AP pelvis x-ray imaging on a trolley: the impact of trolley design, mattress design and radiographer practices on image quality and radiation dose

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Abbreviations

2AFC	Two alternative forced choice
AEC	Automatic Exposure Control
AP	Antero-posterior
APR	Automatically Programmed Radiography
CEC	Commission of the European Communities
CNR	Contrast to Noise Ratio
CR	Computed Radiography
CT	Computed Tomography
DAP	Dose Area Product
DDR	Direct Digital Radiography
DQE	Detective Quantum Efficiency
DRL	Dose Reference Level
ESD	Entrance Surface Dose
ED	Emergency Department
FHD	Femoral Head Diameter
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IRCU	International Commission on Radiation Units and Measurements
MRI	Magnetic Resonance Imaging
MTF	Modulation Transfer Function
NCRP	National Council on Radiation Protection and Measurements
NPS	Noise Power Spectrum
OID	Object to Image Receptor Distance
PA	Postero-anterior
RCR	The Royal Collage of Radiologists
ROC	Receiver Operating Characteristics
SNR	Signal to Noise Ratio
SID	Source to Image Receptor Distance
SOD	Source to Object Distance
TLD	Thermoluminescent dosimeter
VGA	Visual Grading Analysis

Abstract

Background: Major physical and technical differences exist between imaging a patient on an x-ray tabletop and imaging a patient on a trolley. The aim of this thesis was to evaluate the impact of trolley design, mattress design and radiographer practice on image quality and radiation dose for AP pelvis imaging on a trolley in order to optimise this imaging examination. AP pelvis was chosen as the focus of this thesis due to the frequency of this examination on a trolley and the dose implication associated with it.

Materials and Method: An anthropomorphic pelvis phantom was imaged on a commercially available trolley under various imaging conditions using computed radiography (CR). Variables explored were two different mattresses, two different image receptor holder positions, three source to image distances (SIDs) and four mAs increments. Image quality was visually evaluated using a 2 alternative forced choice (2AFC) method with a reference image acquired on the x-ray tabletop using 75kVp, the AEC, broad focus, 110cm SID and 3.2mmAl. Contrast to noise ratio (CNR) was also calculated. Effective dose was established by using Monte Carlo simulation software. Optimisation scores were derived as a figure of merit by dividing effective dose with visual image quality scores.

Results: Visual image quality significantly reduced by an average of 13 % ($p<0.05$) whilst effective dose significantly increased on average by 56% ($p<0.05$) for the images acquired on the trolley with identical acquisition parameters to the image acquired on the x-ray tabletop. For all experimental trolley images, mean image quality scores ranged from 47.4 to 33.2 (45 being the reference image score) and effective dose ranged from 0.08mSv to 0.33mSv (reference effective dose being 0.09mSv). The image with the highest figure of merit (optimisation score) from all trolley images was acquired at 130cm SID, with 20mAs, using the standard mattress and platform not elevated. Magnification variation was also evident on the trolley images with a 12.8mm difference between the image with the lowest and highest magnification level (18%).

Conclusion: From the results it is clear that acquisition parameters used for AP pelvis on the x-ray tabletop are not transferable to trolley imaging and further work needs to be conducted in order to develop a separate exposure chart specifically for trolley imaging.

Chapter 1– Introduction

This chapter introduces background information and the rationale behind the topic selected for this thesis in order to set the scene and introduce important themes. The background information briefly introduces the importance of balancing image quality and radiation dose in medical imaging with the rationale setting out the practical and theoretical issues surrounding trolley imaging and why the antero-posterior (AP) pelvis projection was selected as the focus for this thesis. Previous studies will briefly be considered and how this has influenced and directed the study's aims and objectives. Also an overview of the structure of the thesis is provided at the end of this chapter, to aid the reader's understanding of the subsequent chapters to follow.

1.1 Background

In recent years, concerns have been raised as to the high levels of radiation being delivered for diagnostic x-ray examinations. Given the adverse effects associated with exposure to ionising radiation, it is important to reduce levels where possible (Royal College of Radiologists (RCR), 2015).The interaction of ionising radiation with living cells can cause damage resulting in deterministic and stochastic effects. Deterministic effects are related to high radiation doses and are therefore accompanied by a threshold exposure level below which the effect will be absent, for example, cataract, erythema, and infertility. Increasing the radiation dose means increasing the severity of the effect, rather than the possibility. Stochastic effects are on the other hand probabilistic in nature and it is assumed that any exposure is capable of causing an effect, with no threshold (The International Commission on Radiological Protection (ICRP), 2005). Since this effect is governed by chance, it emphasises the importance of adhering to the *as low as reasonably practical* (ALARP) principle since evidence suggests that harmful effects can happen even at very low doses of radiation. Minimising the radiation risk can therefore be achieved by reducing the patient radiation dose. Reducing radiation dose may however compromise image quality since radiation dose controls the amount of image forming photons that are incident and collected by the image receptor. It is therefore important to maintain a balance between image quality and patient radiation dose; the process used to achieve this balanced is often

referred to in literature as 'radiation dose and image quality optimisation' (Uffmann & Schaefer-Prokop, 2009). This means images acquired should be of diagnostic quality without the radiation dose to the patient being significantly higher than necessary (ICRP, 2006).

Within the United Kingdom (UK), the Ionising Radiation (Medical Exposure) Regulations (IR(ME)R) 2000 requires that all medical exposures using ionising radiation should be justified prior to the exposure, and subsequently optimised. This means that the radiographer must firstly act as the practitioner and **justify** the exposure (Perez, 2013). Justification is the process whereby the clinical benefits and the associated health risks to the individual patient from the x-ray examination is considered (ICRP, 2007). Once the exposure is justified, it is the joint responsibility of the operator and practitioner to **optimise** image quality and radiation dose (RCR, 2015). For this thesis, optimisation of radiation dose and image quality for trolley imaging has been set as the primary focus. The main aspects of optimisation are to firstly identify the level of radiographic quality required to ensure a confident diagnosis from the image. Secondly, careful consideration is required when selecting appropriate x-ray acquisition parameters in order to produce an image of acceptable diagnostic quality whilst reducing the radiation dose where possible. The European Council (2013) have recently drafted new directives (13/59/Euratom) which lays down the basic safety standards (BSS) for protection against the dangers arising from exposure to ionising radiation. These safety standards take into account the recommendations set out by ICRP (2007) based on their patient protection framework. The European Directive (2013/59/Euratom) and ICRP (2007) highlight and strengthen the requirements for justification and optimisation in medical imaging.

There are several parameters to consider for digital radiography examinations in order to enhance image quality and reduce dose. These parameters include collimating the beam to the area of interest, using the appropriate source to image distance (SID), the use of the automatic exposure control (AEC) when available, filtration, the use of appropriate kVp and mAs, and so on (Martin, 2007). The correct use of these parameters is even more critical in digital radiography since overexposure hence a higher radiation dose is less apparent on the resultant images. The transition from conventional film/screen radiography to computed or direct digital radiography (CR/DDR) came with enhanced imaging capabilities including greater dynamic range, wider exposure latitude and post-processing

capabilities (Busch & Faulkner, 2005). Nevertheless, these digital systems also have downfalls. Unlike film/screen, digital radiography does not provide the radiographer with direct feedback on whether appropriate acquisition parameters were used. Digital imaging systems have wide exposure latitude and a linear response to x-ray energies and therefore can compensate and correct the use of inappropriate exposure factors. This can result in a higher radiation dose than necessary being unnoticeably used; this phenomenon is known as '*dose creep'* (Uffman & Schaefer-Prokop, 2009; Lanca et al., 2014). Ma et al. (2013a) explored this phenomenon and found that higher doses could be given to patients without image degradation with even a 10-fold overexposure going visually unnoticed. Manufacturers developed the exposure index (EI) to help overcome this problem as it provides radiographers with feedback on the exposure reaching the detector. The reliance on EI as an indication of overexposure is however dangerous since a wide variety of manufacturer-specific EI's exist causing confusion. There have been attempts to standardise EI however this has not yet been successfully implemented into all clinical departments. The radiographers understanding of EI must also be considered because EI can be affected by a number of factors such as CR processing delay, collimation, detector size, presence of implants and patient habitus (Mothiram et al., 2013).This is worrying in digital imaging and further stresses the need to review and optimise acquisition protocols.

Another point to consider when selecting acquisition parameters for imaging examinations is that inappropriate exposure factors could easily make the difference between a fracture/pathology being identified or missed (Walker, Allen, Burnside & Small, 2011). Consequently it is imperative that radiographers have a comprehensive understanding of how the various acquisition parameters affect patient dose and image quality and how to manipulate them when necessary. This is especially important in scenarios where patients present on a trolley or during portable radiography as acquisition parameters have to be set manually due to the unavailability of both the AEC and the automatic radiography program (APR).The AEC is an important dose reducing instrument in imaging as it takes into account tube potential but also the thickness and density of the body part being imaged which reduces operator errors (Jones, 2008). When the AEC cannot be used to terminate the exposure to ensures radiation dose and image quality control, Martin (2007) believes that exposure charts are essential in this situation.

The above highlights the importance of justification and optimisation in radiography in order to achieve images of adequate quality at the lowest dose possible. Reducing the radiation dose to the patient is vital; however, this reduction can compromise image quality. It is therefore important to optimise the radiation dose in a manner that dose not compromise image quality.

1.2 Rationale

The antero-posterior (AP) pelvis examination imaged on a trolley was chosen as the area to explore and optimise for this thesis due to various reasons including dose implications, the differences between trolley and x-ray tabletop imaging, the emphasis on reducing patient movement for pelvic injuries, and the limited previous published work surrounding trolley imaging in general.

The AP pelvis examination is regularly performed on trolley bound patients in situations such as trauma, post operatively or even portably on the intensive care unit (ICU) / high dependency unit (HDU). Patients are often imaged on the trolley because transferring them onto the x-ray tabletop could cause further harm especially if pelvic precautions need to be maintained for patients with suspicion of multiple injuries (Lee & Porter, 2007). In trauma, the fractured pelvis carries serious risks associated with unstable bony components and vascular damage, requiring movement of the patient to be minimised. Trolleys are fundamental for supporting patients who are unstable, unwell or following trauma situations, helping to significantly reduce moving and handling risks for patients and staff. Pelvic fractures are associated with significant morbidity and mortality with the AP pelvis examination forming an important part of the emergency department's ATLS protocol to quickly assess for life threatening injuries (McConnell, Eyres & Nightingale, 2005). This emphasises the importance of some patients remaining on the trolley for imaging.

Radiographers are therefore often faced with the challenge of producing images of diagnostic quality whilst patients remain on trolleys. Imaging patients on trolleys, especially when having to use the image receptor holder (platform or tray) can cause significant problems for the radiographer (see figure 1 and 2 in section 3.1.3 on page 17). There are a variety of physical and technical variables to consider when imaging patients on trolleys which include the image receptor holder, mattress construction and thickness,

object to image receptor distance (OID), SID, the use of a stationary grid and the unavailability of the AEC. These variables may influence the acquisition parameters selected for trolley imaging since they differ from when imaging on the x-ray tabletop. Yet again, there are no published optimisation studies that explore how these different variables encountered when imaging patients on a trolley impact on image quality and radiation dose.

One of the main principles set out by the European Council Directive (2013/59/EU) was to strengthen and expand on the previous requirements regarding diagnostic reference levels. The application and use of diagnostic reference levels is essential for optimisation of the radiation protection of patients; however for trolley imaging there are no specific national or local dose levels recommended. Tugwell (2014) found that acquisition parameters used for trolley patients are based on exposure charts, APR values which are pre-programmed exposure techniques set on the control panel for average patients being imaged on the x-ray tabletop (Fauber, 2013) and also on the radiographer's professional judgement. The aim of Tugwell's (2014) study was to explore the level of variability between radiographers and working practice when imaging trolley bound patients by means of a departmental questionnaire within three district general hospitals. This study was conducted across North Wales general x-ray departments with a response rate of 65% which accounted for two thirds of the radiographers working within this area. The results of this study by Tugwell (2014) are interesting as considerable variation was found between radiographer's practice and their understanding of different variables when imaging a trolley bound patient. Careful consideration must however be given to these results as it cannot be assumed the same variability and opinions exists in other x-ray departments. One of the most important findings from Tugwell's study was that more than 50% of radiographers increased their exposure factors from the recommended values on the APR system for trolley bound patient without any clear evidence to support this. Tugwell also demonstrated the wide variation that exists in current working practice and the conflicting opinion amongst radiographers as to the optimal acquisition parameters required for imaging trolley bound patients. These findings were the driving force behind this thesis as Tugwell (2014) highlighted the need for trolley imaging to be explored further in terms of the appropriate acquisition parameters required to produce images of diagnostic quality whilst keeping the dose as low as reasonably practical.

Another reason for selecting the AP pelvis projection for this thesis was the associated dose implications as it irradiates radiosensitive organs including the gonads. For those examinations which have previously been found to be high contributors to dose from medical imaging, pelvis is ranked third by the Health Protection Agency (HPA) (Hart, Wall, Hillier & Shrimpton, 2008). AP pelvis and hip examinations expose the gonads to ionising radiation which is a concern for younger age groups as the gonads are highly radiosensitive. This further emphasises the importance of minimising the dose for AP pelvis, especially in trauma situations, where a significant number of younger patients are imaged (Health and Social Care Information Centre, 2013). Lead shielding of the gonads is compulsory practice when imaging the pelvis *except* for the initial imaging such as for trauma since it might obscure important diagnostic information. Consequently the gonads are directly irradiated by the primary beam in these situations (Commission of the European Communities (CEC), 1996).The ICRP (1991) believe the gonads to be the most radiosensitive organ in the body with a weighting factor of 0.2 where there is potential for hereditary damage and cancer induction following radiation exposure. These weighing factor have since been revised and published in ICRP (2007) whereby the tissue weighing factor of gonads have been reduced to 0.08. Careful consideration needs to be given to these tissue weighing data be because according to Tootell, Szczepura & Hogg (2014) not only are these weighting factors averaged across all ages and gender and therefore cannot be applied to individual patients but also the changes are based on the subjective balance between the diverse stochastic endpoints of cancer incidence, cancer mortality, life reduction and hereditary risk. With this in mind, organ doses from a single AP pelvis radiograph can still typically reach 2.1mGy for the testes and 0.52mGy for the ovaries, which are within the primary beam (Wall et al., 2011).This emphasises the importance of reducing radiation dose for AP pelvis especially when imaging young patients of reproductive age in trauma situations.

Trolley imaging plays a vital role in the traumatised patient. From a local perspective, Ysbyty Gwynedd, the hospital where this thesis was conducted, is a district general hospital (DGH) located in North Wales, a catchment which includes Snowdonia National Park. The imaging department of this hospital images many males and females of reproductive ages after trauma from activities including hill walking, rock climbing, mountain biking and so on. According to Talbot, Smith and Dykes (2007), 281 mountain casualties were brought into Ysbyty Gwynedd emergency department in a 42 month

period, 1/3 of these casualties were males under 25 and another third were males between the ages of 26-49. The Mountain Rescue Magazine (2007) carried out a quarterly incident report for England and Wales for attendances to the emergency departments from mountain rescue calls. North Wales was the third highest for most attendances after the Peak District and Lake District. Although these statistics do not specifically indicate the number of patients requiring pelvis imaging, they do highlight the busy workload of Ysbyty Gwynedd's emergency department and also the number of young patients that are potentially imaged on a trolley due to trauma. It is important to remember that the younger population are of greatest concern when exposing them to ionising radiation as they are more sensitive to radiation and the risk of heritable effects from radiation increases with patient age (Busch & Faulkner, 2005,). This further supports the need for exploring ways of optimising radiation dose and image quality for trolley imaging.

1.3 Study focus and structure

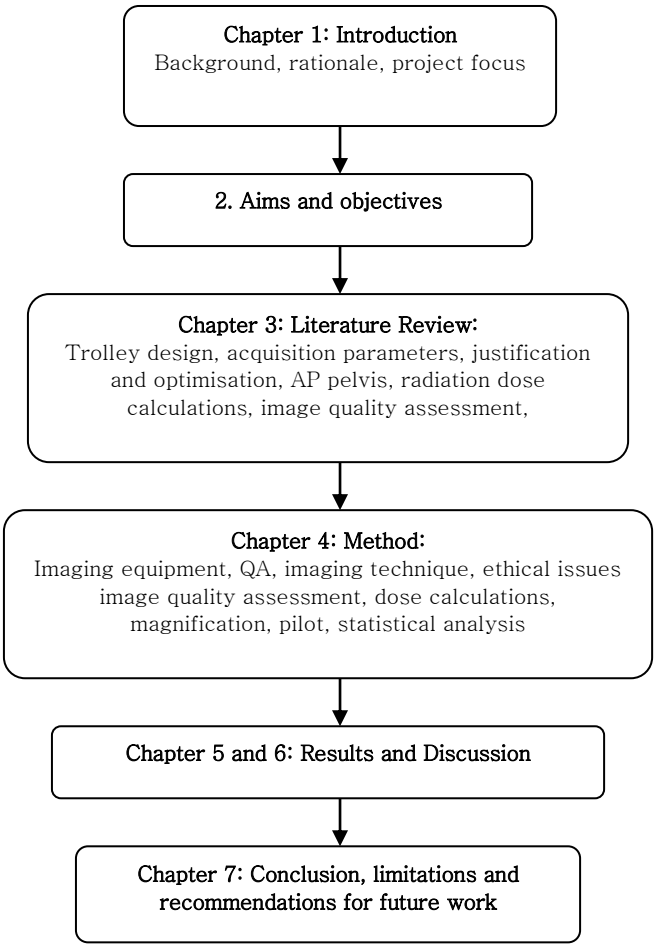

Figure 1 – a flow chart demonstrating the thesis's structure

As briefly discussed in the above section, the focus of this thesis was to explore trolley imaging by establishing how trolley design, mattress design and radiographer practices impacts on image quality and radiation dose. This was achieved by addressing the current gaps in the literature and developing a comprehensive understanding regarding methods of visual evaluating image quality and methods of calculating the risk associated with radiation dose in terms of effective dose (International Commission on Radiation Units and Measurements (ICRU), 1993). The focus of this thesis was shaped initially from the results of Tugwell's (2014) study, which revealed inconsistencies in the utilisation of acquisition parameters when imaging trolley patients. It was also apparent from Tugwell's study that significant variation existed in working practice with a number of radiographers doubling mAs for trolley examinations.

The structure of this thesis is summarised in figure 1.The thesis has commenced with some background information and the rationale behind the topic of interest and will subsequently move onto the aims and objectives (see next chapter). Following on from the aims and objectives, chapter three is a comprehensive literature review which is divided into several sections and aims to build upon the information provided in the introduction. It gives the reader an understanding of how the thesis fits into a broader context and how it informed the method. The first section of the literature review explores different trolley designs and how they may impact on image quality and radiation dose. Next, it reviews individual acquisition parameters and how they might be considered when imaging a trolley bound patient. The AP pelvis projection is subsequently evaluated in term of imaging during trauma and its dose implications. Following this, justification and optimisation is considered, and finally dosimetry and image quality evaluation is critically evaluated.

The fourth chapter is the method section which gives a detailed description of the experimental design for this thesis by providing a clear and complete evaluation of the specific steps taken. These steps include an outline of the imaging equipment and technique used to acquire the reference and experimental images, the use of a pelvis anthropomorphic phantom to acquire these images and a thorough description and justification of the independent and dependent variables chosen for this experiment.

The fifth chapter presents the results under relevant sections and subsections. Following on from the results, chapter six is a detailed discussion of the results by means of summarising, appraising, interpreting and explaining the findings, relating them to the aims and objectives and the existing body of literature. The thesis finishes with a conclusion, summarising the main findings whilst reflecting upon the limitations of the study and the possibility for future work in the area of trolley imaging.

To clarify, the term ***standard*** will be used throughout this thesis when relating to acquisition parameters, techniques or protocols which are the usual or most commonly used in practice. Within the context of this thesis, it is a word that expresses the average or normal requirement and is considered the general agreement as a basis for comparison. Manufactures, the CEC and educational textbooks such as Carver and Carver (2012) and Whitley et al. (2015) are just a few examples where these standard techniques, acquisition parameters and protocols are derived from.

2- Aims and objectives

2.1 Aim

The main focus of this thesis was to analyse and evaluate how trolley design, mattress design and radiographer practices impacted on image quality and radiation dose when imaging the AP pelvis on a trolley. In other words, to evaluate the optimum parameters for pelvis radiography on a trolley.

This aim was achieved by firstly exploring the same acquisition parameters used for AP pelvis on the x-ray tabletop for trolley imaging and subsequently analyse and evaluate whether these parameters were transferable without the need for modification in this situation. Secondly, the aim was to evaluate different acquisition parameters and variables associated with imaging on the trolley in order to optimise image quality and radiation dose for the AP pelvis.

2.2 Thesis objectives

1. Evaluate whether the acquisition parameters utilised for AP pelvis on an x-ray tabletop can be successfully transferred for an AP pelvis undertaken on a trolley

2. Evaluate the impact of two different trolley mattresses on physical and visual measures of image quality and their impact on effective dose.

3. Evaluate how trolley platform position affects physical and visual measures of image quality and effective dose.

4. Evaluate the effect of SID and mAs on physical and visual measures of image quality and effective dose.

Chapter 3- Literature review

The following literature review will critically analyse the background research on the topic of interest by selecting and sourcing the information that is necessary to develop the required context for this thesis. This chapter will explore the literature that is relevant to understanding the basic principles behind image quality and radiation dose optimisation and relate them to AP pelvis imaging and trolley imaging where necessary. This thesis focuses on optimisation which is the balance between acquiring a diagnostic image whilst keeping the dose to a minimum level. This was therefore the recurring theme throughout the literature review. The review presents an overview of the relevant and significant literature in the research area and is divided into various sections including trolley design, pelvis imaging, and image quality and radiation dose calculations. In addition the literature review appraises various optimisation research approaches in order to inform the most suitable method for this thesis and to identify any technical failings and flaws within their design.

Two comprehensive literature searches were conducted for this review. The first search explored specific literature relating to optimisation of trolley imaging however due to the limited number of studies found in this area a second more general search was carried out. The second search was carried out in order to identify any optimisation research in conventional imaging in order to inform the principles behind such experiments. A search strategy was developed for both scopes using the main concepts from the aims and objectives of the thesis. The first search was performed using a systematic approach using several databases including Science Direct and Cochrane with several peer reviewed journal also individually searched including *Radiologic Technology, Radiation Protection Dosimetry and European Journal of Radiology, Radiology, American Journal of Roentgenology, British Journal of Radiology, Radiography, Journal of Medical Imaging*

and Radiation Sciences, and *Medical Physics*. Whilst undertaking a scope of the literature, relevant key words where used including *digital radiography, trolley, stretcher, optimisation, image quality* and *radiation dose.* Boolean operators were also used to collect data with similar themes. Boolean operators are a way of combining keywords to aid the search for literature (Cronin, Ryan & Coughlan, 2008). The second search was identical to the first search with the exclusion of the keywords *trolley* and *stretcher*. Due to the limited literature surrounding trolley imaging (Tugwell, 2014,) no time restriction with regards to publication date was placed on the initial search in order to maximise the likelihood of finding relevant articles. Although digital radiography is very different from conventional film/screen imaging in terms of image acquisition and it's post-processing capabilities, they both still share the same radiographic principles (i.e. collimation, positioning) and involve exposure to ionising radiation (Busch & Faulkner, 2005). This literature search and review did however consider the technological advancements in radiography (transition from film/screen to digital radiography (CR/DDR)) and how this evolvement might have impacted upon the optimisation strategies of various research articles and also the terminology used.

From the above systematic searches, several themes emerged which directed the course of the literature review. This review will firstly consider trolley design and how imaging a patient on a trolley differs to imaging on the x-ray tabletop whilst considering previously published attempts in this area. This includes exploring different trolley manufacturers and comparing various features that are desirable in order to facilitate imaging. Issues including patient condition, SID, mattress thickness and grids will be explored in relation to imaging a patient on a trolley. Following on from this each acquisition parameter will be evaluated individually, to consider their impact on image quality and radiation giving special attention to the AP pelvis projection. Next, imaging the AP pelvis will be explored, considering issues surrounding the AP projection in trauma. This will include a brief introduction to radiation dose implications for this projection and also the importance of acquiring an image of diagnostic quality to increase accuracy of diagnosis and improve patient management. Justification and optimisation will then be discussed and considered by looking at legislation and previous studies in this area. The final two sections of the review chapter consider the various methods available to measure/calculate radiation dose and evaluate image quality whilst critically analysing their advantages and downfalls within previous studies.

3.1 Trolley imaging and design

Patients are often imaged on a trolley as opposed to on a dedicated x-ray tabletop in various circumstances including trauma situations. Considerable differences exist between these two scenarios. The following section considers these differences and their potential impact on image quality and radiation dose. This section also reviews the design of various trolleys available and the challenges faced by radiographers when having to acquire images on the trolley. In order to understand the difficulties associated with trolley imaging, it is important that this review considers all variables associated with this type of imaging prior to investigating optimisation studies relating to trolley imaging.

There are numerous hospital trolleys on the market; some specifically designed for x-ray purposes and others where imaging is not a primary consideration in their design. Manufacturers will offer different designs, each having their advantages and disadvantages. Ideally a medical trolley should combine the requirement of multiple departments' to reduce the need for multiple transfers onto various examination couches e.g. trolley suitable for trauma, transfer, examination, imaging, treatment, and recovery. Stryker (2012) is one manufacturer who offers this flexibility and recently introduced the multipurpose Prime X trolley into practice which combines the requirements of several departments thus helping to provide a continuum of care with minimum disruption to the patient. This flexibility enables patients to remain on *one* trolley for their transportation, treatment and x-ray imaging whilst reducing time, money and the risk of patient and staff injury during transfer from one trolley to another. Literature from Beebe and Myers (2012), Carlton and Adler (2013) and Lee and Porter (2007) all stress the importance of the patient being moved as little as possible when there is concern regarding injures. According to the RCR (2011) on 'Standards of Practice and Guidance for Trauma Radiology in Severely Injured Patients', moving a severely injured patient can cause delays and exacerbate blood loss. The less the patient is moved and the shorter the distance, the greater the chance of survival. For these reasons, patients are often imaged on the trolley rather than being transferred onto the x-ray tabletop to avoid exacerbating undetermined injuries. Nevertheless, according to Carter et al. (1994) there is divided professional opinion as to whether high quality radiographs are achievable if patients remain on trolleys for imaging. Some radiographers believe high quality images are

achievable if patients remain on the trolley whilst others believe that all patients should be transferred onto an x-ray tabletop. This comment made by Carter et al. (1994) was during film/screen era and therefore opinions may have changed following technological advancements. On the other hand, Tugwell (2014) demonstrated uncertainty and conflicting opinion amongst radiographers as to the appropriate acquisition parameters required for trolley bound patients which suggest that uncertainty still exists in this situation.

The above paragraph has focused primarily on patient safety with regards to them remaining on the trolley for imaging as oppose to being transferred onto the x-ray tabletop. Nevertheless, there are literature, including Carver and Carver (2012) and Stryker (2012) who also stress the importance of staff safety during manual transferring of patients. According to Stryker (2012), nursing injuries are expensive for healthcare organisations and can shorten careers with many of these injuries occurring during transferring, repositioning, lifting or moving patients. Therefore, if it is possible to acquire images of diagnostic quality on the trolley, it would benefit both the patient and staff by minimising unnecessary transfer.

3.1.1 Basic trolley design verses top of the range

If the patient remains on the trolley for imaging rather than being transferred onto the x-ray tabletop, there are compulsory features that the trolley must possess to ensure its suitability for imaging. These features are described in various manufacturer brochures e.g. Stryker Prime X Imaging Stretcher (2012), ArjoHunleigh (2014) and in academic radiography textbooks such as Carter et al. (1994) and Whitley et al. (2015) and are summarised in table 1. As seen in table 1, trolleys suitable for imaging requires certain compulsory features however different manufacturers offer additional features in order to improve their design and thus desirability. These additional features are not compulsory but can be obtained at extra cost e.g. lateral cassette holder or thicker mattresses. Table 2 demonstrates the different features and design of five commercially available trolleys. The compulsory features are the minimum specifications required to enable the radiographer to image the patient successfully on the trolley. Whitley et al. (2015) suggested that the imaging department should have close links with the emergency department when purchasing new trolleys to ensure they meet the minimum requirements for imaging.

Radiology should be involved in testing them in order to identify any problems that may be encountered during imaging examinations and whether they are fit for practice.

Compulsory	**Desirable**
A tray or platform beneath the trolley to accommodate a large image receptor and stationary grid	A movable tray or platform underneath the trolley that allows the image receptor to be positioned with no restrictions. (landscape, portrait or angled)
Full length radiolucent trolley top (usually carbon fibre)	Image receptor tracking device
Low attenuating (radiolucent) mattresses	Lightweight with excellent manoeuvrability and designed to reduce pressure ulcers
An adjustable backrest which can be positioned at various angles.	Light and easy assisted tilting back rest enabling various angles for patient position.
A good adjustable height range allowing acceptable SID to be achieved	Lateral cassette holder for horizontal beam lateral examinations

Table 1 - compulsory and desirable characteristics of an imaging trolley (Carter et al., 1994; Whitley et al., 2015; Stryker, 2012; ArjoHuntleighs Healthcare)

Trolley manufacturer	Trolley name	Tray or platform	Mattresses included (mm)	Other mattress options (mm)	Standard Features
Wardray	XRT	tray	50mm	memory foam and pressure relief mattress (no thickness included)	75cm lowest height. Tray rotates through 360 degree and suitable for portrait and landscape images
ArjoHuntleigh	Lifeguard50	platform	65 mm (2½") deep mattress pad with Lectrolite cover or 2-way stretch cover	Bi-Flex® Pressure Re-Distributing Mattress 150mm	56cm lowest platform height range
M.A.S	X-Ray Trauma Trolley	tray	76mm	No information	66cm lowest height. .Full length tracking x-ray cassette carrier
Stryker	Prime X	platform	70mm enhanced comfort mattress	100mm Enhanced Comfort mattress or 100mm or 130 mm Ultra Comfort Mattress	Full length tracking x-ray cassette carrier with film location indicators.

Seers Medical	SM0820	tray	Standard 80mm	100mm memory foam	Alignment guides make positioning the cassette to the patient simple
Seers Medical	SM0830	tray	Standard 80mm	125mm memory foam	

Table 2 - specifications of different commercially available trolleys suitable for imaging

3.1.2 Image receptor holder (also known as trolley 'tray' or 'platform')

A significant proportion of imaging examinations on the trolley, including projections such as AP pelvis, AP spine and supine chest, cannot be acquired with the image receptor directly in contact with the patient due to the potential of exacerbating injuries. Consequently the trolley requires an image receptor holder similar to a Bucky (either a tray or platform) in order to accommodate the image receptor and in some cases a stationary grid. The image receptor holder is also referred to as a trolley cassette holder or platform (Whitley et al., 2015). The design of the image receptor holder varies from one manufacturer to another with some designs preventing angulation or rotation of the image receptor.

There are two different types of image receptor holders, one is designed similar to a Bucky mechanism as found under the x-ray tabletop and is referred to as a tray whilst the other type is referred to as a platform. The trolley tray is a device where the image receptor is placed in a drawer and slid into place prior to an exposure (see figure 2). The platform on the other hand is an opening under the trolley which is parallel to the trolley top in order to accommodate the image receptor (see figure 2 and 3). As opposed to the tray beneath the trolley, the platform offers more flexibility especially if the patient is not central to the trolley or if the image receptor needs to be angled when the patient is not centralised or at an angle on the trolley. The tray can therefore cause practical problems since patients rarely present perfectly centralised on the trolley and often lie obliquely across its central axis (Carver & Carver, 2012). If the trolley has a tray and the patient is not centralised then it requires the patient to be moved to coincide with the tray; this defeats the purpose of imaging on a trolley in the first place. What is also important when considering the trolley

image receptor holder is that the radiographer can clearly visualise the position of the image receptor to ensure accurate alignment relative to the patient before an exposure is made. Carver and Carver (2012) suggested that accurate centring of the image receptor to coincide with the median sagittal place (MSP), area of interest and central ray is complicated since the position of the image receptor underneath the patient is placed there by visual judgment. Radiographers need to see through the gap between the trolley top and the platform to assess alignment of the image receptor to the patient; unfortunately this is not an entirely accurate method of assessing alignment. This problem was also identified in a study by Mutch and Wentworth (2007) where radiographers commented on the difficultly of lining up the image receptor and neonate when using the tray in the incubator. When the image receptor is placed in the image receptor holder of the trolley, whether it is in the tray or on the platform, it increases the OID (see figures 2, 3 and 4). The amount of OID will depend on the trolley design and the manufacturer e.g. the Lifeguard 50 trolley used for this thesis and described in table 2 has an elevating platform in order to reduce the OID and bring the image receptor closer to the patient/phantom (figure 3). The platform for this particular trolley should always be elevated prior to an exposure as per manufacturer operating instructions. A trolley tray on the other hand does not require elevation as seen in figure 2, there are also some trolley platform designs as seen by Stryker (2012) that do not require elevation either (see figure 4). The effect of this increased OID for trolley imaging was one of the main variables explored within this thesis (see section 4.10 and tables 9 and 10 on page 106) because increased OID results in greater geometric unsharpeness which will reduce image detail (Whitley et al., 2015). Whether this decrease in image detail is visually noticeable to observers is another question and will be considered for this thesis.

Figure 2 - Trolley with an image receptor TRAY beneath it (Wardray Premise Limited, 2015)

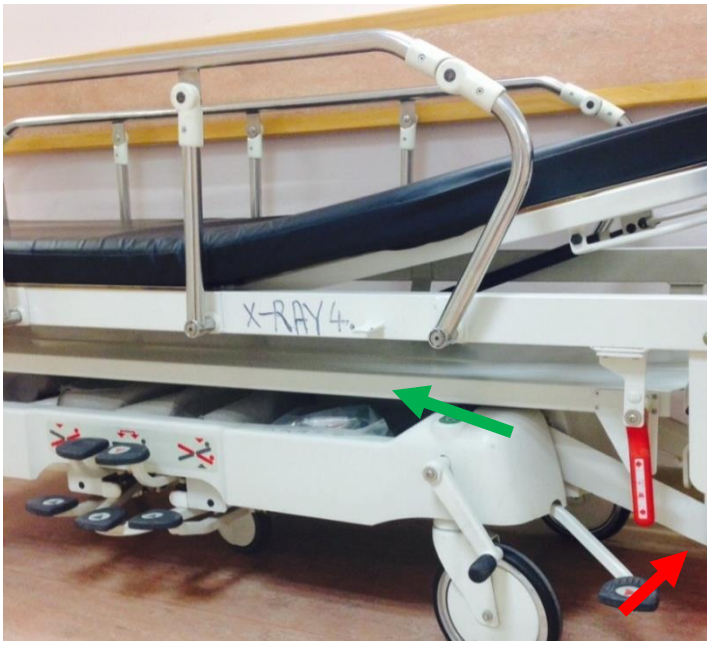

Figure 3 – Trolley with PLATFORM (green arrow) underneath it which can be elevated with the red handle (red arrow) (Lifeguard 50 trolley, ArjoHuntleighs' Healthcare, Sweden)

Figure 4 – Trolley with PLATFORM that does not elevate (Prime X Stryker, Switzerland)

3.1.3 Trolley surface and mattresses

The entire length and width of the trolley surface and mattress have to be radiolucent to allow for x-ray imaging. According to Whitley et al. (2015) metal bars and hinges on the edges of the trolley surface may cause artefacts on images taken using the tray or platform which would be exacerbated when angulation of the tube is required. As seen in table 2, manufacturers have different thickness mattresses and materials; surprisingly they do not specify the density and construction of their mattresses. Most trolleys come with a standard mattress but most manufacturers including ArjoHuntleighs', Wardray and Seers offer a replacement thicker mattress made from memory foam to enhance patient comfort and to reduce the possibility of developing pressure ulcers. Pressure ulcers are injuries that often develop in patients who remain in one bodily position for prolonged periods of time. These wounds are extremely painful and can result in permanent disabilities, and in severe cases, amputation, organ failure, and death (Shoker, 2010). Everton et al. (2014b) demonstrated interface pressure on healthy volunteers when lying supine on the imaging tabletops for more than 20 minutes. This study then suggested that some high risk patients could develop pressure ulcers on imaging tabletops. This is an important consideration because it shows the potential for radiological surfaces to contribute to the development of tissue breakdown hence pressure ulcers and highlights the need to consider the thickness and construction of radiological mattress in order to reduce the patient's likelihood of developing these ulcers. The above is however an assumption based on healthy volunteers data but yet again it would be unethical to use high risk patient to

support such evidence presented by Everton et al (201b). In addition, the risk demonstrated above is further emphasised when imaging on trolley surfaces due to the prolonged time spent on them (see next sub-heading on 'mattress thickness and construction'). It is however important to remember that although a better design and thicker mattress may reduces the likelihood of pressure ulcers occurring, they may also have a negative impact on image quality and radiation dose when patients are imaged on them.

NICE (2011) was one source that considered the potential impact of mattresses used for imaging on radiation dose and image quality. This source from NICE was a recommendation and review document on the Inditherm patient warming mattress for the prevention of inadvertent hypothermia. Within this document, they considered the potential impact of this newly proposed warming mattress on radiation dose and image quality by comparing it to other imaging mattresses which they termed as 'a low-attenuating x-ray mattress' and an 'x-ray trolley mattress'. This was achieved by calculating the aluminium equivalent of these three different mattresses in order to determine their radiation transmission capabilities. Aluminium equivalent is the thickness of aluminium which is required to produce the equivalent x-ray transmission of the mattress in question. It is a commonly used measure in diagnostic radiography to specify the transmission or attenuation of an x-ray beam through an object. NICE (2011) estimated that the low attenuating x-ray mattress was 0.2mm Al equivalent whereas the x-ray trolley mattress used was 1mm Al equivalent. Even though this document shows a considerable difference in Al equivalent between an x-ray tabletop mattress and trolley mattress, NICE do not specify the make, type or thickness of these mattresses used. It is therefore difficult to generalise and put this information into context since there are several commercially available mattresses for x-ray tabletops and trolleys on the market. In addition, manufacturers do not ordinarily specify the Al equivalent of their mattresses therefore it is also difficult to compare the estimations from the NICE guidelines to the mattresses described in table 2. NICE went on to commented that the Inditherm mattress does not affect x-ray image quality or radiation dose however this was an observation made by only confirming that clinical practice hadn't changed when using this new mattress. No empirical evidence was documented to support this statement. NICE also stated that no literature search was conducted for this new product as they did not believe it would produce any useful information over and above the users' comments. From an empirical perspective, the lack of scientific evidence for these assumptions regarding image quality

and radiation dose is unacceptable and the conclusion made by NICE was merely based on word of mouth from users.

Having explored the design of different trolleys suitable for imaging, it is apparent that imaging a trolley bound patient differs significantly from imaging on the x-ray tabletop. The main differences that may influence and require the modification of acquisition parameters include mattress thickness and attenuation, AEC availability, grid type and geometric factors.

- **Mattress thickness and construction**

In comparison to the mattresses used on x-ray tabletops, trolley mattresses tend to be thicker and of different materials (they may also have a different linear attenuation coefficient) in order to meet required standards for tissue viability, infection control and durability purposes, since patients can remain on a trolley for long periods of time (Dawkins, 2012).In NHS England, the number of patients waiting on trolleys in the emergency department has tripled in four years (Donnelly & Sawer, 2014). This problem is also apparent in Wales where headlines such as "*War hero, 89, kept waiting on trolley for 34 hours in A&E"* are printed by the Wales News Service (2015). Pressure ulcers are more problematic in elderly patients who have suspected neck of femur fracture because they are more susceptible to these sores (Haleem, Heinert and Parker, 2008).Due to this complication, patients are usually transferred onto a thick pressure relieving mattress on admission and are consequently imaged on these mattresses (Vickery, 2001).

As already discussed in section 3.1.3, NICE (2011) suggested that a standard low attenuating x-ray mattress is equivalent to approximately 0.2mm aluminium whereas an x-ray trolley mattress is equivalent to approximately 1.0mm Al. This reflects large differences between the transmission and attenuation properties of these mattresses and thus could have implications on image quality and radiation dose. Another point to consider is that some x-ray departments do not use mattresses on their x-ray tabletops. When manufacturers such as Siemens Healthcare and Philips Healthcare launch new x-ray rooms, the advertising images do not demonstrate a mattress. This is because radiographic mattresses are sold separately (see figure 5 as example). This could mean that the APR system and exposure chart seen in imaging departments are based on imaging techniques performed without the used of mattresses. Everton et al. (2014a) commented that

radiological surfaces are designed by manufacturers to be radiolucent and any mattress added to this would add to patient dose. Another study by Everton et al. (2014b) highlighted that in some cases x-ray tabletops do not include a mattress and therefore patients are imaged on the hard surface. From an image quality and radiation dose perspective, acquiring images without a mattress is better as it is one less object for the x-ray beam to travel through. However Everton et al. (2014b) did highlight the potential for the development of pressure ulcers if patients remain on the tabletop for long periods of time without a mattress. Everton et al. also demonstrated a significant difference in pain and comfort levels between the two imaging surfaces (a surface with and without a mattress) and therefore excluding mattresses from imaging tabletops may result in more patient movement caused by discomfort during imaging.

The fact that two different mattresses are available on the Lifeguard 50 trolleys (the trolleys used in the hospital where this thesis was conducted) and the lack of empirical evidence demonstrating their effect on image quality and radiation dose, these two mattresses became one of the main independent variables for this thesis.

Figure 5 – Philips DigitalDiagnost System (Philips Healthcare, UK)

- **Automatic exposure control (AEC)**

For certain radiography examinations, the AEC is utilised as an x-ray exposure termination device (Manning-Stanley, Ward & England, 2012). AEC is considered a dose reducing and

image quality standardising device since the exposure terminates when the image receptor has received sufficient exposure. It takes into account the thickness of the body part being imaged, the tube potential and reduces user error (Jones, 2008). The use of the AEC is recommended by both the CEC (1996) and ICRP (2007) when imaging the AP pelvis. However when imaging a trolley bound patient, the AEC system is not available and therefore requires the radiographer to set their own exposure factors based upon exposure charts and clinical judgment. According to Ma et al. (2013a) dose creep can occur in examinations where the AEC is not feasible where radiographers may use higher mAs than necessary to ensure image quality is adequate on the first attempt. The unavailability of the AEC on trolley for AP pelvis is therefore one major difference that exists between imaging on the trolley as oppose to the x-ray tabletop.

- **Grid type**

A radiographic grid is a device used to reduce scattered radiation from reaching the IR and will be discussed in more detail in section 3.3.7 on page 39. Radiographic grids can be movable/oscillating or stationary. An oscillating gird is found incorporated into the x-ray tabletop Bucky and moves during an exposure in order to minimise the shadows of the gridlines on the resultant image. It is the most desirable type of grid as it helps minimise grid artefacts (Bushong, 2013).Nevertheless, this type of grid is unavailable when imaging a trolley bound patient therefore a stationary grid has to be used. A stationary grid does not move during an exposure and is fitted onto the image receptor prior to exposure. In comparison to an oscillating grid, the opaque strips found in a stationary grid are so thin and so close together that the grid can remain stationary without the shadows of the strips being sufficiently visible to interfere with the image detail of the film (e.g. Lysholm grid)

The major difference therefore between imaging on an x-ray tabletop and the trolley is the fact that the grid used for trolley imaging does not move. However there may potentially be further differences between an oscillating grid and a stationary grid subject to grid design. Different acquisition parameters are needed depending on the grid type, grid frequency and grid ratio, for example, the lower the grid ratio, the lower the image quality since more scatter radiation is able to reach the image receptor (Whitly et al., 205).

Nevertheless, a higher grid ratio requires more mAs resulting in increased dose (Allisy-Roberts & Willaims, 2008).

Grids today (whether they are oscillating or stationary) are generally focused which means all of the lead strips are aligned in a tilted fashion toward a centring point. These grids have a minimum and maximum SID tolerance in order to avoid grid cut off artefact (Whitley et al., 2015). The radiographer must therefore be accurate when measuring SID to avoid this cut off due to misalignment or lead strips shadow visualisation on the resultant image (Carroll, 2014; Fauber, 2013). The focus tolerance of the grid can become problematic when imaging a trolley bound patient for AP pelvis for two reasons. Firstly, an increased SID may be required for trolley imaging to compensate for the magnification caused by the mattress and image receptor holder. The radiographer in this situation has to consider how much they can increase SID before gird cut off becomes apparent. Secondly, accurate measurement of SID can be difficult for trolley imaging in comparison to x-ray tabletop imaging since it requires manual measurements of SID using a measuring tape; this accuracy was tested during the pilot study of this thesis and is discussed further in 'geometric factors' below.
In conclusion, even though moving grids are considered essential if radiographs are to be unaffected by grid lines, images produced on trolley bound patients can be of equal high quality, providing that the correct acquisition parameters are employed for the grid used.

- **Geometric factors**

As already discussed at the beginning of this section, trolleys tend to have thicker mattresses to those used on x-ray tabletops and therefore the patient would potentially become closer to the x-ray tube resulting in decreased source to object distance (SOD) and increased OID. This increase in OID is exacerbated further when the image receptor is placed in the image receptor holder beneath the trolley (see figure 6). Carver and Carver (2012) supported this notion and commented that OID is greater on a trolley in comparison to the table Bucky setup. By placing the image receptor in the image receptor holder beneath the trolley and with the patient laid on a thicker mattress it considerably increases magnification. It is therefore important that the height of the trolley can be lowered in order to maintain the required SID and reduce magnification. This is especially important when undertaking a supine chest due to magnification of the heart (McConnell, 2011).

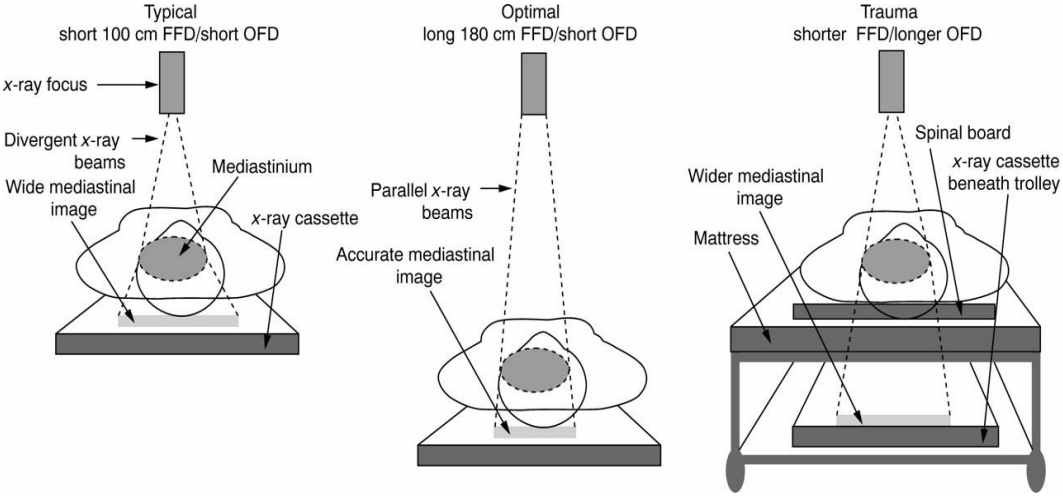

Figure 6 - figure demonstrating how changing SID and OID in various circumstances including on a trolley influence magnification (Gleeson, Spedding, Harding and Caplan, 2001)

Another geometric factor to consider is when using the x-ray tabletop Bucky the tube housing has indicators that confirm if the source and image receptor are aligned to the MSP and whether the correct SID has been achieved. These indicators are governed by sensors which illuminate and automatically notify the radiographer when there is correct alignment (source and image receptor) in all planes (long axis, short axis and distance) (see figure 7). Papp (2010) believes that these indicators are important to avoid cutting off important anatomy, to avoid grid cut-off but also to ensure consistency in radiographic practice. However, for trolley patients the alignment of the image receptor, patient and source is done by sight and also the SID can only be measured manually using the measuring tape incorporated into the light beam diaphragm (LBD). This requires the radiographer to measure SID at the side of the trolley and then position the tube over the patient as seen in figure 8. Inaccuracies in these measurements are demonstrated in the pilot study within the method section on page 75. This issue was also realised by Carlton and Adler (2013) where they suggested that the primary cause of repeated mobile exposures was failure to measure SID accurately.

Figure 7 - source to image receptor alignment indicators illuminated on x-ray tube housing

Figure 8 - a radiographer measuring SID at the side of the trolley before repositioning the tube and image receptor to the midline

3.2 Previous published studies specific to trolley imaging

According to both Carter et al. (1994) and Tugwell (2014), there are conflicting opinions in clinical practice with regards to techniques and acquisition parameters required for successfully imaging trolley bound patients. Some radiographers believe that high quality radiographs are achievable on trolleys if the correct acquisition parameters are selected, but others believe that all patients should be transferred onto an x-ray tabletop which incorporates a moving grid. Evidence suggests that seriously injured or unstable patients should be moved as little as possible and therefore should remain on the trolley during imaging examinations where possible (Beebe & Myers, 2012; Lee & Porter, 2007; Dunn, Gwinnutt & Grey, 2007). The radiographer and medical staff need to make an informed decision on whether the patient is well enough to be transferred onto the x-ray tabletop giving consideration to the safety of the patient as well as image quality and radiation dose implications.

A comprehensive literature review revealed limited previous published work on imaging trolley bound patients, especially ones investigating the effects of the trolley design on image quality and radiation dose. From the first search strategy as described at the beginning this chapter, only three studies were found that met the search criteria.

The first relevant study found was conducted by Gleeson et al. (2001) where they explored supine chest imaging on trolleys and the impact of components such as the mattress and image receptor holder on magnification of the mediastinum. Similar to the current thesis, Gleeson et al. identified problems when imaging trolley bound patients and wanted to determine the effect trolley imaging had on magnification in supine chest imaging. The problems identified by Gleeson et al. included the introduction of advanced trauma life support (ATLS) which sees patients being pre-packaged on spinal boards and placed on a trolley with a thick mattress consequently inhibiting the placement of the image receptor directly behind the patient for imaging. The introduction of the spinal board, the thick mattress and the image receptor holder beneath the trolley has therefore increased the distance between the image receptor and the area being imaged. Gleeson et al. wanted to explore this increased OID which has exacerbated magnification in order to determine its

effect on the diagnosis of thoracic trauma in chest imaging. '*Radiographic techniques have to be adapted when imaging trolley bound patients*' was one of the concluding statement made within this study however no recommendations were made with regards to how and what adaptations. When calculating magnification, Gleeson et al. compared the effect of six commercially available trolleys on mediastinal diameter however the name of the trolley manufacturers were anonymous. The six trolleys caused different distances between the spinal board and the image receptor holder, ranging from 7.1 to 12.9 cm. This suggests a large variation in trolley design between manufacturers resulting in varying magnification level when imaging on different trolleys at identical SIDs. The study also commented on magnification differences between *shallow* and *deep* trolley image receptor holders however these definitions are not elaborated upon in the text and therefore the difference between these types of image receptor holders could not be determined. It can be assumed however that the deeper trolley trays have larger distances between the patient and the tray (increased OID). This study by Gleeson et al. (2001) was carried out more than 10 years ago yet no follow up research study was found that addressed the issues raised by this study. In addition, the impact of trolley design on chest magnification was the only outcome measure for this study and therefore the dose implications of the trolley and its effect upon image quality was not considered.

Linsenmaier et al. (2001) conducted an experimental study exploring how different spinal boards affected image quality, the attenuation and transmission of radiation and dose area product (DAP).Spinal boards are devices that are frequently used in trauma to immobilise the spine in case of significant injury. From an imaging perspective these boards need special consideration since they are another additional object placed in-between the patient and the IR and are therefore in the path of the x-ray beam. Linsenmaier's study found that radiation transmission was similar for all boards but with DAP differing by up to 59 %. This study did not however compare the difference in radiation transmission and DAP between the spinal boards and the absence of a spinal board. Five different spinal boards were compared to each other which helped to indicate the optimum spinal board to utilise for imaging rather than the impact different spinal boards have on image quality and dose compared to imaging without the boards. Linsenmaier et al. demonstrated that the spinal boards' increased DAP and also had an impact on image quality due to image artefacts. Similar to Gleeson et al. (2001), the study did not consider whether and how acquisition parameters should be modified when imaging with the patient lay on a spinal board.

On the downside, the information from this study by Linsenmaier et al. (2001) was obtained from only the abstract as opposed to the full text since the article was written in German with only the abstract having been translated to English. Careful interpretation of the information provided is therefore required since the in-depth detailed description and analysis of the method and results are missing and there may also be inconsistencies between what has been reported in the abstract and what has been stated in the full paper (Siebers, 2001). Also this study was conducted in Germany in 2001 where the use of spinal boards was considered gold standard. Nevertheless, recent research has been conducted which questions the use of spinal boards. Log rolling the patient on to a spinal board should be avoided according to Conrad et al. (2012) as it can exacerbate injuries. Theodore et al. (2013) demonstrated that patients had better neurological outcomes when spinal immobilisation was not used with further studies including Lance et al.(2011) and Vanderlan, Tew and McSwain (2009)finding that delay in resuscitation when using immobilisation had detrimental effects on patients.

Although the study by Linsenmaier et al. (2001) is outdated and does not specifically explore trolley imaging, it does however demonstrate that spinal boards (an object that lies in-between the patient and the image receptor) increases dose to the patients and produce artefacts on the resultant images. These findings strengthens the current thesis argument that acquisition parameters need to be carefully considered when imaging a trolley bound especially if an object such as a thick mattress is used and if the image receptor has to be placed in the image receptor holder which is beneath the trolley (beneath the mattress and trolley top).

Mutch and Wentworth (2007) was the third article found that explored a similar imaging situation to this current thesis. Their study investigates the effects of an image receptor tray underneath neonatal incubators on image quality and radiation dose. The main aim of this study was similar to the current thesis which was to study the effect of placing the image receptor in a dedicated slot under the patient in comparison to the standard method of imaging which in Mutch and Wentworth's case was a direct exposure (image receptor placed in contact with the neonate).

Premature newborns are placed in incubators in order to maintain suitable environmental conditions. Neonates often require imaging where the radiographer acquires the images with the neonate remaining in the incubator. Similar to trolleys, there are a variety of different incubators available, each having their own design. Some incubators have a dedicated image receptor holder beneath them in order to reduce the risks associated with placing the image receptor directly behind the neonate. The difference between these two scenarios was investigated by Mutch and Wentwroth (2007). They found that in comparison to placing the image receptor directly behind the neonate, the mattress and image receptor holder mechanism caused a 49% reduction in image receptor dose although this did not equate in a 49% increase in neonate dose. When allowing for the inverse square law, the difference in distances (OID) between a direct exposure and the image receptor placed in the image receptor holder would account for one-fifth of the reduction in image receptor dose. This means that the remaining reduction must have resulted from attenuation by the materials between these two imaging conditions. In addition, this large reduction in image receptor dose did not result in deterioration in image quality; there was minimal effect.

The results of Mutch and Wentworth's (2007) study are interesting and they demonstrate the potential impact of absorbing materials in the path of the x-ray beam on image recepor dose; however these results cannot be fully accepted due to several methodological limitations including the radiation dose calculations and image quality assessment.

The radiation dose quantity used in Mutch and Wentworth's (2007) study was image receptor dose. This quantity is not a universally accepted dose quantity and has limited use in optimisation studies. It is also not cited in radiation protection reports such as those from ICRP (Petoussi-Henss et al., 2010). From a radiation protection perspective, image receptor dose does not consider the risk to the patient and it is also not fully understandable in terms of its correlation with image quality (Mattsson & Soderberg, 2013).

Exposure indices or index (EI) is the commonest method in digital radiography of gaining information regarding the exposure received by the image receptor. Digital radiography manufacturers have developed EI as a measure of the estimated exposure reaching the image receptor (Mothiram, Brennan, Lewis, Moran & Robinson, 2014). Shepard et al. (2009) considers EI to be an indicator of whether the noise levels are acceptable and an

indirect indication of digital image quality. The large reduction in image receptor dose found between the direct exposure and image receptor holder dose by Mutch and Wentworth (2007) may therefore impact on image quality. Uffmann and Schaefer-Prokop (2009) suggested that in digital radiography, image noise is inversely related to the amount of image receptor dose. Hess and Neitzel (2012) went on to propose that any absorbing material between the patient and the detector reduces the image forming radiation and therefore reduces contrast to noise ratio (CNR); and to compensate for this, the dose may need to be increased. Nevertheless, Mutch and Wentworth (2007) found that the reduction in image receptor dose did not impact upon image quality. Having said this, they used a Leeds Test Object to quantify the degree of threshold contrast in each image using the author of the study as an observer to assess this. Not only could this introduce bias into the study but it can also introduce subjectivity due to the relaxed and unstructured nature of the visual evaluation. It would have been beneficial to use more than one independent observer to assess the images using stricter image criteria with repeated measurements taken at time intervals in order to ascertain intra and inter-observer variation (Cohen, McDaniel and Wagner, 1984).In addition, a Leeds Test Object does not resemble patient clinical imaging and therefore according to Tapiovaara (2006) this method may not always be suitable for evaluating different imaging systems or imaging techniques, since their contrast could behave differently to the contrast of clinically relevant details with a changing radiation quality.

The above three studies were found when specifically searching for optimisation studies surrounding trolley imaging. Nevertheless, none of these studies attempted to optimise image quality and radiation dose. They did however identify challenges when imaging in situations where objects and an OID where present between the patient and the image receptor (i.e. spinal boards, trolley mattress). They also highlighted and emphasised the importance of studying imaging conditions and techniques that vary from standard imaging techniques in order to understand their effects on image quality and radiation dose. This is important because the APR system and exposure charts found in imaging departments are programmed for standard clinical examinations and do not take into consideration these changes that occur in clinical practice e.g. increased OID and objects placed in the path of the primary beam. Although according to George et al. (2004) the APR system and exposure charts should only be used as a guide to help the radiographer's clinical judgment as to the appropriate exposure factors required for each examination. It is the

radiographer's responsibility to modify these parameters when necessary; however this can be challenging if there is no empirical evidence to suggest or support how and when modification is necessary. This limited empirical evidence can result in a wide variation in exposure factors for examinations as clinical judgment is highly subjective but also it may contribute to the dose creep phenomenon since Tugwell (2014) found that numerous radiographers increased their exposure factors for trolley bound patients without evidence from research to support this. This is therefore one of the main driving forces behind conducting this thesis as there was an apparent gap in the current literature on imaging trolley bound patients.

3.3 Acquisition parameters

Before consideration can be given to justification and optimisation of radiographic examinations, it is important that acquisition parameters are individually explored in order to understand how they can be used and manipulated in order to optimise radiation dose and image quality. This section will evaluate the primary acquisition parameters and consider how they impact on image quality and radiation dose, giving special attention to the AP pelvis projection.

In radiography, many interlinked acquisition parameters govern image quality, as well as the radiation dose to the patient. With regards to general digital radiography, these parameters include kVp, mAs, collimation and centring beam, filtration, focal spot size, object to image receptor distance, use of grid, air gap technique, source to image receptor distance, and image post-processing. When conducting an optimisation study, acquisition parameters are usually modified to identify how they impact image quality and radiation dose. Most optimisation studies including Ma et al. (2013b), Heath et al., (2011) and Davey and England (2015) focus on varying one acquisition parameter at a time due to the time implications and the complexity of conducting a factorial based experiment whereby a combination of acquisition parameters are varied together. Below is a review on the functions of different acquisition parameters and how they might affect image quality and/or radiation dose:

3.3.1 Milliampers per second (mAs)

Tube current, measured in milli amperes (mA), is the unit used to express the number of electrons travelling in the current through the x-ray tube from the cathode to the anode (Bushberg, Seibert, Leidholdt, Boone & Goldschmidt, 2002). The number of x-ray photons is not only controlled by variation in mA, but also by the time over which the cathode is permitted to generate electrons, hence why x-ray intensity is measured as milli amperes per second (mAs). mAs is the main controller of radiation dose quantity that reaches the patient and the image receptor, and hence is the key controller of image signal to noise ratio(Carver and Carver, 2012). A low mAs value results in low image density, characterised as noise on the resultant image. Therefore, the higher the mAs, the more x-ray photons are produced, due to the higher number of electrons travelling through the x-ray tube, consequently increasing the dose (Fauber, 2013).

Unlike kVp, mAs has a linear relationship with dose and therefore the higher the mAs, the higher the radiation dose. It is therefore important to consider ways of reducing mAs where possible to reduce patient dose. This should be done by considering image quality as well as radiation dose since low mAs can result in low image density presenting as noise (i.e mottle) (Carroll, 2007). A compromise is therefore required with regards to mAs between patient dose and image quality.

3.3.2 Tube voltage (kVp)

kVp is the main controller of the penetrability of the x-ray photons which in turn determines the contrast on the resultant image. The higher the kVp, the higher the x-ray photon energy resulting in higher penetrability through the tissue causing less visibility of image contrast (Fauber, 2013). High kVp exposures can introduce more scatter and hence more noise into the image (Walker et al., 2011).

There have been many attempts to optimising kVp for various examinations using digital imaging. The results of these studies present conflicting evidence as to whether a high or low kVp technique should be employed in various circumstances. Seeram, Davidson, Bushong and Swan (2013) conducted a systematic review on kVp optimisation using CR and found that lower kVp was favoured. Geijer, Norrman and Persliden (2009) found that a

reduction in kVp to be beneficial for both reducing dose and improving image quality for lumbar spine x-ray examinations. Tingberg and Sjostrom (2005) found similar results, where visual image quality increased with decreasing kVp for both chest and pelvis. Others have also found a decrease in image quality with increasing kVp but have also witnessed a reduction in effective dose too. Lanca et al. (2014) found a reduction in visual image quality for pelvis imaging with increase kVp but also discovered a reduction in effective dose at higher kVp. This reduction in effective dose at higher kVp is supported by various studies including Lorusso, Fitzgeorge, Lorusso and Lorusso (2015), Martin (2007) and Ramanaidu, Kumar, Ng, George and Maria (2006) who suggested that instead of being absorbed into the patient as lower kVp radiation beam would, higher kVp is able to penetrate and exit the patient's tissues, resulting in a lesser dose delivered/absorbed by the patient.

The above paragraph highlights the importance of understanding how radiation dose has been measured or calculated in various studies as this may influence the results and how they are interpreted. There are many different quantities that can be used to express the amount of radiation delivered to a patient and the understanding of the principles, advantages and disadvantages of each will aid in their analysis (Sprawls, n.d). Radiation dose quantities and calculations are discussed in more detail in section 3.6 on page 55.

It is also important to consider the corresponding mAs used in the kVp optimisation studies as they are closely related. This is why numerous optimisation studies have explored the effect of mAs on radiation dose and image quality in conjunction with varying the kVp settings (Sun, Lin, Tyan and Ng, 2012; Brindhaban and Khalifah, 2005). Some of these studies including Allen, Hogg, Ma and Szczepura (2013), Reis et al. (2014), Lanca et al. (2014) who investigated the use of the '10 kVp rule' where it is suggested that halving the mAs whilst simultaneously increasing kVp by 10 significantly reduces patient dose and has no major impact on visual image quality. This '10 kVp rule' has however been challenged by authors including Herrmann et al. (2012) and Bontrager (2010). They suggest a different rule whereby increasing the kVp by 15% rather than by 10 with a corresponding decrease in mAs; this is known as the '15 percent rule'. This change in rule was proposed because a 10 kVp increase at 50kVp produces a greater change in contrast in comparison to a 10 kVp increase at 100kVp whereas the 15% rule maintains the same density effect across all exposure factors (Johnston & Fauber, 2015).

In conclusion, choosing the optimum kVp and mAs depends upon various factors including the body size being examined, image receptor, type of information required and image display. There is never a one size fits all answer to these parameters.

3.3.3Focal spot

Focal spot is the area on the anode surface where the electron beam strikes and is usual described in terms of the line focus principle (Ball, Moore & Turner, 2012). The line focus principle explains the relationship between the anode surface known as the actual focal spot (size of the area being bombarded by the electrons) and the effective focal spot which is the size of the emitted x-ray beam projected towards the area being imaged. The focal spot size can be set by the radiographer prior to an exposure as broad or fine (Fauber, 2013). Fine focal spot sizes range from 0.5 to 0.6 mm, whereas broad focal spot sizes range from 1.0 to 1.2 mm. The choice of fine or broad focal spot is determined by adjusting the filament size that is engaged in electron production (Fauber, 2013). From an optimisation perspective, focal spot size can impact on image quality since the selection of a fine focal spot reduces geometric unsharpness on the resultant image and thus improves image detail (Gorham & Brennan, 2010). Nevertheless, using a fine spot can impact on tube life since the concentrated heat dissipated on the anode surface from the electron bombardment can degrade it (Johnston & Fauber, 2015)

There have only been a few studies conducted on the impact of different focal spot sizes on image quality and radiation dose. The use of fine focus has been advocated in various literatures (Dowsett, Kenny & Johnston, 2006; Carver and Carver, 2012) because physical and theoretical evidence suggests increased penumbra and reduced image detail with broad focus. However, recent optimisation literature for specific imaging examinations has questioned whether this physical and theoretical evidence has any impact on visual image quality in clinical practice. Ma, Hogg and Norton (2014) found no difference in image quality between fine and broad focal spot sizes at different kVp and mAs settings when imaging the hand. Gorham and Brennan (2010) supported these findings and found no significant differences between images of the AP knee and lateral ankle produced at fine and broad focal spot sizes. Interestingly both of these studies explored projections that are traditionally acquired using fine focal spot sizes and yet again found not difference in

image quality between both focal spot sizes. These findings by Ma et al. and Gorham and Brennan therfore questions the relationship between physical (mathematical) and visual (clinical) measures of image quality which will be further considered in section 3.7on page 61 and as part of the method chapter.

3.3.4Filtration

There are two types of x-ray beam filtration, inherent and added. When the x-ray photons are produced they have a range of energies some of which are of no benefit to image production and only increase dose to the patient. Inherent filtration is the filtration that happens by design when the x-ray beam passes through various structures e.g. the glass of the tube, cooling oil and tube head before it exits the tube. It is however common practice to add further filtration to the x-ray source in the form of aluminium or copper sheets in order to minimise unwanted low energy photons (Aird, 1988). The low-energy x-rays are absorbed by the filters instead of the patient and this reduces the radiation dose to that patient. Aluminium (Al) is the most commonly added filter material. Other common filter materials include copper and plastic (e.g., acrylic) (Bushberg et al., 2002). As the inherent filtration is not constructed of aluminium, the total filtration is measured in aluminium equivalent thickness. A total filtration of at least 2.5 mm aluminium or aluminium equivalent is recommended by the National Council on Radiation Protection and Measurements (NCRP) (1989) and supported by investigators including Behrman and Yasuda (1998),van der Plaats and Vijlbrief (1980). Total filtration tends to be similar for both fixed and mobile x-ray units with both having to meet the minimum aluminium equivalent as recommended by NCRP (1989).

3.3.5Source to image distance (SID)

SID was previously referred to as film to focus distance (FFD), or also nowadays referred to as focus to receptor distance (FRD). It is the linear distance from the focal spot of the x-ray tube to the image receptor. According to the inverse square law it affects contrast and if doubled, the intensity of the x-ray beam will be reduced by one-fourth (Carroll, 2007). SID also affects magnification and distortion on the resultant image i.e. magnification will reduce if SID is increased; in clinical practice each projection has a suggested standard SID

in order to reduce variability and provide consistency in image quality (Bontrager & Lampignano, 2014; Fauber, 2013)

For AP pelvis imaging, the recommended SID varies between literatures, especially in the last ten years because more studies have been conducted exploring the effect of increasing SID as a method of reducing radiation dose, whilst maintaining image quality. The CEC (1996) has a recommended range of SIDs for certain projections rather than a definitive value, with the recommended range for pelvis being in the order of 100-150cm. This recommended range is substantial especially when considering the potential impact of different SIDs on radiation dose as found in recent literature (Tugwell et al., 2014; Heath et al., 2011). Several studies have been conducted to explore whether increasing SID without altering OID reduces dose whilst maintaining an image of diagnostic quality (Heath et al., 2011; Tugwell et al., 2014; Poletti & Mclean, 2005; Farrell et al., 2008; Woods & Messer, 2009). These studies explored SID values of up to a 160cm and found them to be successful in reducing dose, however, it is important that the grid's tolerance range with regards to SIDs are considered in order to avoid grid cut-off and thus artefacts on the resultant images.

3.3.6Object to image distance (OID)

OID is the distance from the object being exposed to the image receptor. It is another factor that influences magnification. Magnification is the enlargement (size distortion) of the actual exposed areas on the resultant image (Hendee & Ritenour, 2002).The closer the object being imaged is to the image receptor (reduced OID), the less the magnification, and the better the detail and image resolution (Poletti & McLean, 2005; Fosbinder & Orth, 2011).For an exposed body part to have no magnification the OID must be zero. This is however not possible when imaging humans since their three dimensional shape means there will always be a distance between the exposed body parts and the image receptor (Fauber, 2013).

In the context of this thesis, OID can become a substantial problem when imaging on the trolley since for numerous examinations the image receptor is placed in the image receptor holder underneath the trolley and also the mattresses tend to be thicker (see section 3.1on page 13). Some trolley designs including the Lifeguard 50 have an elevating platform as

opposed to a tray to accommodate the image receptor in which the platform requires elevation prior to an exposure in order to reduce the OID. Tugwell (2014) found that over 20% of radiographers did not always ensure platform elevation prior to an exposure which would further exacerbate the problem of increased OID on a trolley. There will always be a trade off in trauma trolley imaging situations and radiographers are often forced to choose which factors to sacrifice: a slight increase in unsharpness and magnification, a slight loss of contrast, some distortion of anatomy or the clipping of anatomy if SID is not appropriately increased (Carroll & Bowman, 2013).

3.3.7Grid

A radiographic grid is a device used to reduce image noise by absorbing scattered radiation that exits the patient before it reaches the image receptor. A grid is utilised when patient thickness and density (size of the area being imaged) will cause excess scattered radiation. This is especially important with CR as imaging phosphor plates are sensitive to scattered radiation. A radiographic grid is composed of high x-ray transmitting material, as well as high x-ray absorbing material, each aligned alternately. Grids can either be used as a stationary grid or a moving grid. Moving grids which are incorporated into the x-ray table Bucky are also known as oscillating grids since they move backwards and forwards during an exposure in order to blur out the shadows of the lead strips in the image (Fauber, 2013). Stationary grids are used in situations where moving grids are not practical, for example during ward examinations or when patients are imaged on a trolley. The specifications of different grids can vary based on their strip frequency (number of strips over the length of the grid), ratio (strip height to the distance between two strips), focus (strip alignment), and pattern (strip orientation). It is important for the radiographer to understand the specification and imaging implications of different grids as it will influence the acquisition parameters required. On the down side, grids absorb some useful x-ray photons which means their utilisation comes with an increased dose due to the need for more x-ray photon production to achieve the same signal to noise ratio as without a grid (Schueler, 1998).

There have been various optimisation studies to determine whether a grid is required for certain areas of the body or whether they can be excluded in order to reduce dose. A study by Keating and Grange (2011) compared image quality and dose for AP cervical spine with and without grid and found that even though dose savings where recognised without

the grid, image quality was significantly deteriorated. Bell, Erskine and Warren-Forward (2003) also explored the cervical spine but with the lateral projection rather than the AP. From their retrospective study, it was found that radiation dose for the lateral projection increases with the use of grid and they recommended that image quality is sufficient without their use in this situation. The use of a grid for cervical spine imaging has always been fairly controversial. Carver and Carver (2012) suggest a grid should only be used for certain patient's sizes when imaging the AP cervical projection, whereas a grid is not advocated for the lateral projection. Bontrager and Lampinano (2014) also recommend no grid for the lateral cervical spine as there is a naturally occurring air gap for this projection, however, they do recommend a grid for the AP projection.

The current thesis focuses on the AP pelvis which is a body part that has traditionally always required a grid (Whitley et al, 2015; Carver & Carver, 2012; Bontrager & Lampinano, 2014). The pelvis is a dense and thick structure and therefore benefits from a scatter removing device, however one study found explored the use of 'no grid' in adult AP pelvis imaging. Chan and Fung (2014) explored an air gap technique as oppose to a gridded technique. The air gap technique was found to be useful in reducing dose whilst maintain image quality however the method of achieving the air gap was not practical for clinical practice as it would require the patient to be elevated using a small Perspex block or a complete re-design of the x-ray tabletop Bucky system. In addition, the problem with studies exploring grid verses no grid is they usually only consider one or two types of grid whereas Sandborg, Dance, Carlsson and Persliden(1993) suggested the choice of grid characteristics is important for optimising imaging performance. Different types of grids have different tradeoffs when considering image quality and reducing dose i.e. grids with higher ratios eliminate more scattered radiation however they tend to increase patient exposure and x-ray tube loading and require more precise positioning.

3.3.8Air gap

Scattered radiation can also be reduced by introducing an air gap between the patient and the image receptor (a deliberate OID). Practically, an air gap is an OID of typically 15 to 45 cm (Schueler, 1998).Patient exposure will be lower when using an air gap in comparison to a grid since Trout, Kelley and Larson (1975) found that air gap technique requires almost the same dose as when the image receptor is in contact with the subject (which

requires less dose than that when using a grid). This technique also requires an increased SID to compensate for the air gap space in order to reduce image magnification. Fauber (2013) identified this as a drawback owing to the inverse square law yet as previously mentioned many studies have found increasing SID to be a successful dose reducing technique which does not impact significantly on image quality (Tugwell et al., 2014; Heath et al., 2012). In addition, Chan and Fung (2014) advised the use of an air gap for AP pelvis imaging as it reduced dose and still produced an image of diagnostic quality, nevertheless, their method of producing and maintaining this air gap required specialised equipment which would be unfeasible in clinical practice.

3.3.9 Post-processing

Unlike film-screen radiography, digital imaging allows for post-processing. Post processing is one of the greatest advantages of CR and DDR as it allows for the manipulation of raw data after acquisition in order to enhance the visibility of the details within an image. This function is usually integrated within the workstation and can be used for manipulating the images such as annotations added, borders applied, shadows masked, images can be flipped/ rotated, inverted and magnified, images can be conjoined for examinations, contrast and density can be enhanced, and images can be sent for archiving, or deleted (IAEA, 2012).

This above section considers the different functions of acquisition parameters, their importance in image production and display and their influence on radiation dose to the patient. It is important when conducting optimisation studies to consider how dose can be reduced whilst still maintaining an image of diagnostic quality but also ensuring that the technique used can be transferable and feasible in clinical practice. A degraded image may require a repeat exposure which defeats the importance of the dose reducing technique in the first instance. It is important to select appropriate acquisition parameters that considered the balance between image quality and radiation dose.

3.4 The Pelvis

Having reviewed trolley design, the difference between imaging on a trolley to x-ray tabletop, and the different acquisition parameters that can affect radiation dose and image

quality, this section explores the AP pelvis projection, anatomy, dose implications and the image acquisition parameters involved for this examination on the trolley.

The pelvis comprises of the hip bones, sacrum, and coccyx. Each hip bone contains three bones which are the ilium, ischium, and pubis (see figure 9). The pelvis forms the base of the spine in addition to the socket of the hip joint (acetabulum).The hip joint is a ball-and-socket-style joint created by the femur. Several gastrointestinal and genitourinary organs are situated within the pelvic ring with also large nerves and vessels passing through to reach the legs; see figure 10 (Shier, Butler & Lewis, 2008; Shaw, 2005). The pelvis provides attachment for muscles that balance and support the trunk and move the legs, hips, and trunk. With all these vital structures situated within the pelvic cavity, a pelvic fracture can cause substantial bleeding, nerve injury, and internal organ damage. The commonest group of individuals at risk of pelvic fractures are young adults especially those involved in sports and the elderly population with osteoporosis. The majority of pelvic fractures involve high energy forces such as from road traffic accident (RTA), crush accident or fall (Garg, 2010). Other than trauma, the most common clinical indications for a pelvis x-ray are osteoarthritis, multiple myeloma , perthes, slipped upper femoral epiphysis (SUFE) and osteomylitis (Carver and Carver, 2012).

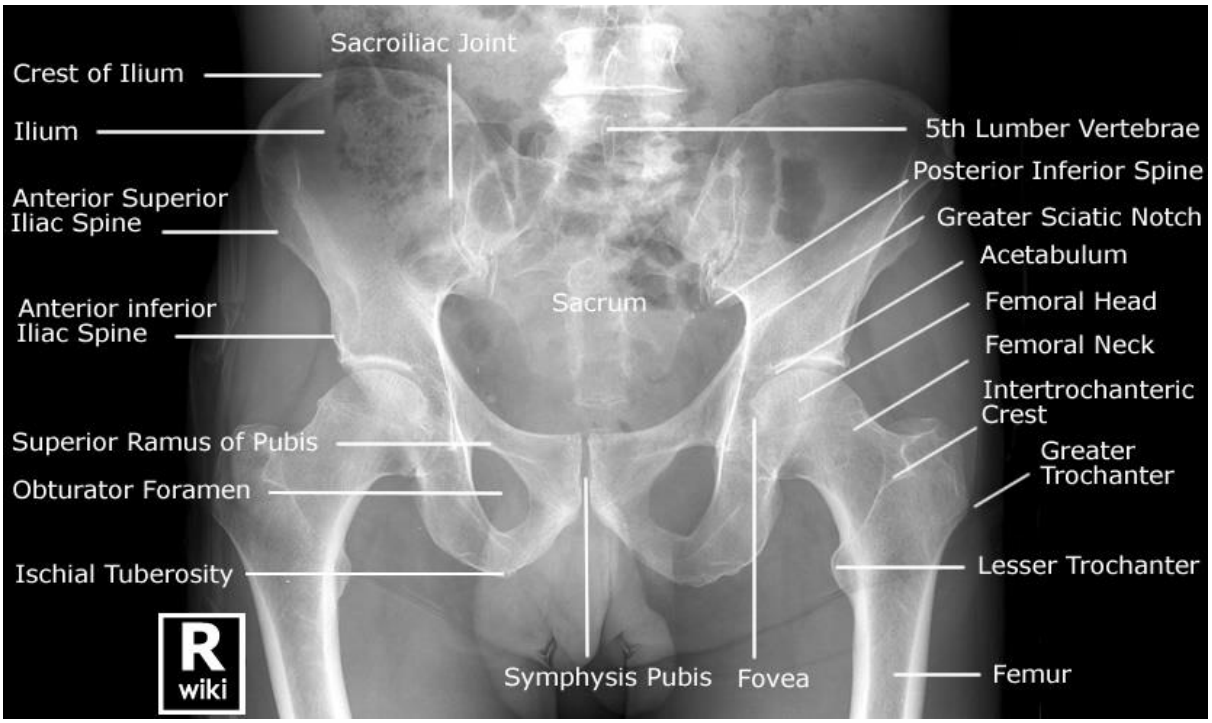

Figure 9 – AP pelvis with bony structures labelled (Pelvis Radiographic Anatomy, n.d.)

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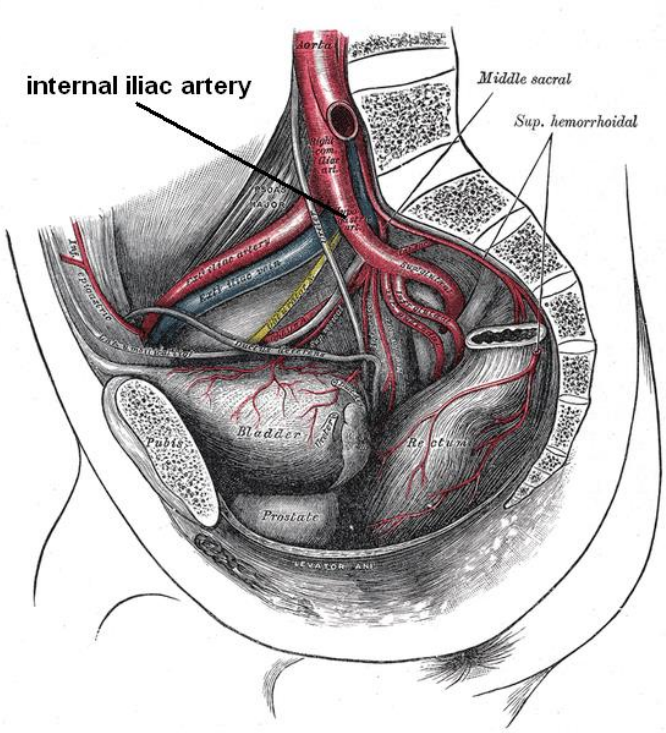

Figure 10 – internal structures of male pelvis (Drake, Vogl and Mitchell, 2014)

3.4.1 Imaging the pelvis on a trolley

This section considers issues when imaging the pelvis on a trolley. For conventional pelvic imaging, some patients are imaged on a dedicated x-ray tabletop however in trauma situations the patient is either imaged on the trolley in the resuscitation room using a mobile radiography unit or in the x-ray department, again on the trolley. This is because transferring them onto the x-ray tabletop may exacerbate pre-existing injuries.

Pelvic fractures are one of the potentially life-threatening injuries that should be identified during the primary survey in patients sustaining major trauma. Suspicion, identification and management of a pelvic fracture in early stages are crucial to decrease the possibility of death fromhypovolaemia as a result of significant loss of blood and fluids. (Lee & Porter, 2007). Haemorrhage causes death in 40% of all pelvic trauma victims and the primary cause of death (60% of fatal cases) in unstable pelvic fracture (Cryer, Miller, Evers, Rouben & Seligson, 1988; Heetveld,Harris, Schlaphoff & Sugrue, 2004; Poole & Ward, 1994). Documented mortality rates range from 6.4% to 30% depending on the type of pelvic fracture, haemodynamic status, and the severity/complexity of associated injuries (Grotz et al., 2006). This highlights the severe consequences of pelvic trauma, the importance of early diagnosis with imaging playing a vital role in the diagnosis of pelvic fractures.

Patients often present to the x-ray department for pelvis imaging on a trolley or require an AP pelvis in the resuscitation room as part of the imaging trauma series. Patients who require a pelvis x-ray on a trolley are predominantly those who have had some form of trauma i.e. RTA, fall or sport injury, however imaging a patient on a trolley for a pelvis can occur in other situations too such as for post-operative rays. The role of the AP projection in the identification of pelvic injury is wide spread in practice and is still recommended by the ATLS protocol as an early diagnostic adjunct in the resuscitation of blunt trauma patients. This protocol has however been challenged by many studies including Kessel et al. (2007) and Obaid,Barleben, Porral, Lush and Cinat (2006) who argue that the role of CT is vital in these situations. They compared the specificity and sensitivity of AP pelvis x-ray image to CT pelvis and found little value for pelvis x-ray image in stable multiple trauma patients. Obaid et al.(2006), Chmelová et al. (2006) and Guillamondegui et al.(2002) however suggested that the role of the AP pelvis x-ray was

beneficial in polytraumatized, hemodynamically unstable patients since the images can be performed in the resuscitation room therefore eliminating the need for transfer. In addition these studies argued that the AP pelvis can easily identify major life threatening fractures. According to The National Clinical Guideline Centre (2011), a fracture which is not evident on radiographs is likely to be undisplaced and therefore will not cause major bleeds and complications. They also agreed with Cannon, Silvestri and Munro (2009) and found that plain radiographs are usually sufficient for diagnosis as they are approximately 90% sensitive for hip fracture. Falchi a Rollandi (2004) agreed with this by suggesting that conventional radiographs are, in the majority of situations, satisfactory to determine the type of pelvic injury. Even though CT has been proven to be more sensitive in detecting pelvic injuries, it does not signify that pelvic x-ray images are insensitive. Chmelová et al. (2006) found plain x-ray images to be sensitive in detecting most pelvic injures; they did however propose that CT examination could reliably replace plain x-ray, particularly if acceptable image quality could not be generated for the AP pelvis. The word '*if*' in this latter sentence with regards to image quality is interesting since it indirectly suggests that image quality for AP pelvis on a trolley can be poor and unacceptable. It can be assumed that trolley imaging can therefore hinder the diagnostic value and the sensitivity of pelvis radiographs on the trolley highlighting the importance of recognising why these issues arise and identify whether/where image quality can be improved. In addition, it must be remembered that radiographs are the most widely available imaging technique (available 24 hours a day) for the diagnosis of hip fractures. Image acquisition takes approximately five minutes which is quick and also there is widespread experience in image interpretation of x-ray images making the AP pelvis desirable in this situation (The National Clinical Guideline Centre, 2011).

The above argument regarding conventional imaging verses CT for pelvic imaging in trauma questions the sensitivity of x-ray imaging and highlights the need to improve image quality in order to increase the diagnostic value of AP pelvis x-ray images. The importance of acquiring a high quality AP pelvis is further emphasised by studies that question the need for a horizontal beam lateral hip projection in trauma situations. Naqvi, Iqbal, Reynolds, Braithwaite, Banim (2012), Leong et al. (2012) and Korim, Reddy, Gibbs and Wildin (2012) have all questioned the usefulness of the horizontal beam lateral hip projection in providing additional information to a high quality AP pelvis projection and have gone on to suggest that it may be surplus to requirement in trauma. If the horizontal

beam lateral was excluded in trauma situation, this would place further reliance on the quality and diagnostic value of the AP projection.

According to Uffman and Schaefer-Prokop (2009), a number of international working groups introduced the concept of image quality classes depending upon the clinical indication and the demand of the diagnostic question. A non-displaced fracture was one of two occasions where high image quality was necessary to ensure detection. Diagnosing pelvic/hip fractures is particularly important due to the high dependence on the integrity of the hip in the daily life of most people. If pelvic image quality is poor on a trolley bound patient a confident diagnosis might not be made; consequently the patient may require additional imaging which will involve additional radiation dose. In some cases, the patient may be sent back to the imaging department for supplementary views/repeat radiographs or the clinicians may wait for a day or so to see whether the patient's clinical signs are still suggestive of a fracture. This again may result in further imaging, including a repeat AP pelvis or the use of modalities such as MRI or CT to look for an occult fracture (National Clinical Guideline Centre, 2011). This delay in diagnosis not only has patient management implications but it also has financial and capacity implications for the imaging department. Hip fracture is a common problem and requires efficient and precise diagnosis. It has significant morbidity and mortality rates, which worsens as time from injury progresses.

3.4.2 Dose consideration for pelvis imaging

The importance of acquiring an image of diagnostic quality for pelvic imaging has already been discussed however the radiation dose implications of this projection also need to be considered. The balance between image quality and dose is a process of equilibrium; dose should be reduced but not to a level where it impacts upon image quality / fracture detection. If image quality is not optimal, further imaging may be necessary which not only increases dose but also impacts on patient diagnosis and management. European figures identified pelvic and hip radiography to be third biggest contributor to dose from medical imaging in the UK, with an annual frequency of 39 per 1000 of population (Hart et al., 2008). Pelvic radiography is a high dose examination that irradiates radiosensitive organs such as the gonads, bladder and bowel; consequently there have been many attempts to reduce the amount of radiation to patients from this examination (Heath et al., 2011; Tugwell et al., 2014; Chan & Fung, 2014). The radiosensitive organs are exposed to the primary beam in trauma imaging as lead shielding is not recommended to ensure that

important diagnostic information is not obscured (Doolan, Brennan, Rainford & Healy, 2004).The ICRP (2007) believe the gonads to be one of the most radiosensitive organ in the body with a weighting factor (103) of 0.08 with the potential for hereditary damage and cancer induction present following radiation exposure. In addition, Frantzen et al. (2012) commented that gonad shielding is an effective method to reduce dose to the gonads with the dose to the testes reduced by about 95% and the dose to the ovaries by about 50% with its use. This gonad shielding technique and thus reduction in dose is not possible in trauma situations and therefore other methods of optimisation for this projection needs consideration. Also, this information emphasises the importance of reducing radiation dose for AP pelvis especially when imaging a young patient of reproductive age. According to the statistics from the Health and Social Care Information Centre (2013) there are a significant amount of young patients imaged in trauma situations.

An additional point to consider when imaging the pelvis in trauma situations was argued by Chan and Fung (2014) where they believed that the radiation dose from pelvic imaging was of concern if the patient suffers from a fracture and repeated follow up images of the pelvis over a long period of time for monitoring may be necessary. This causes concerns of unavoidable accumulative low radiation dose to the gonads region of the same patient increasing the likelihood of stochastic radiation effects. This is worrying especially when considering the data from the dose survey studies by Mettler, Huda, Yoshozumi and Mahesh (2008) and Muhogora et al. (2008) disclosing that on average a single projection of an adult AP pelvis examination delivers an effective dose of 0.6-0.8 mSv to the patient which is approximately six times as much as general chest x-ray.

The above section highlights the dose implications associated with AP pelvis imaging and the risks of imaging the gonads without shielding, however the dose implications associated with the alternative imaging method which is CT pelvis is significantly higher. In comparison to the effective dose associated with AP pelvis imaging (0.6-0.8mSv), a helical CT pelvis results in an effective dose of approximately 6.2mSv (Tjiang and Richardson, 2011). This dose is significantly higher than the dose delivered for AP pelvis imaging highlighting the importance of optimising the AP pelvis projection on the trolley as it may result in improved image quality and thus reduce the possibility of the patient requiring a high dose CT scan.

3.5Justification and Optimisation

Having reviewed the influence of different acquisition parameters on image quality and radiation dose and considering the use of pelvis imaging in trauma situations, this section considers the justification and optimisation of medical exposure in general radiography. The appropriate use of acquisition parameters and the knowledge on how they can affect image quality and radiation dose received by the patient forms the basic principles behind justification and optimisation (Malone et al., 2012; ICRP, 2007).

Following the discovery of x-rays, the use of radiation for diagnosis and treatment of human diseases expanded worldwide. During these early days when x-rays were first used in medical imaging, radiation dose to the patient was given only minor consideration. Nevertheless, due to the increase in the number of examinations performed and emerging data on the long term risks of cancer arising from ionising radiation exposure, more attention has been focused on keeping the doses received by the patient to a minimum (Seeram et al., 2013). The European Directive (2013/59/Euratom) have recently been revised taking into consideration the recommendations set out by the ICRP (2007) whereby scientific evidence and operational experience set out the basic safety standards (BSS) for protection against the dangers arising from exposure to ionising radiation. The goal of radiation protection is to minimise the probability of stochastic risks and to prevent the occurrence of deterministic effects (these effect will be discussed further in section 3.6 on page 55). To achieve this goal, the ICRP (2007) have developed a framework that is guided by three main principles: justification, optimisation and dose limitation.

3.5.1 Justification

Justification of a medical exposure can be described as the process of ensuring that imaging using radiation is necessary and that benefit versus risk has been considered. When deciding upon an appropriate procedure utilising ionising radiation, the **benefit to risk balance** must be carefully considered (Malone et al., 2012). Factors to consider are not confined to those associated with radiation; consideration must be given to other risks such as the costs and benefits of the imaging method. At times the radiation burden will only be a small component to consider as it is important that other types of detriment are reflected upon such as the available resources, accessibility and patient values. Justification

therefore goes further than the scope of radiological protection. Within the UK, the Ionising Radiation (Medical Exposure) Regulation (IRMER) (2000) requires the practitioner to be responsible for the justification of every medical exposure taking into account the characteristics of the individual patients involved. The ICRP (2007) and IAEA (2009) recommend a multi-level (1-3) approach to justification of medical exposure (see figure 11). Level 1 of justification refers to the general/overarching justification of the use of ionising radiation in medicine; level 2 is where justification is performed in accordance to a generic clinical condition i.e. for patients with a given clinical condition, or for a group of individuals at risk to a given condition that can be detected whereas level 3 is justification on an individual patient basis. Level 3 involves taking into account the benefit to risk associated for a particular/individual patient, considering more personal information such as age, previous imaging and so on (Perez, 2013). In order to achieve these different levels, there are evidence-based referral guidelines such as those issued by the Royal College of Radiologists (2012a) in the UK, the American College of Radiology (2015), CEC (1996) in place to assists referrers in making the most appropriate imaging decision and thus ensure that patients are referred for procedures that are beneficial and necessary. Perez (2013) commented that some referrals for imaging might be wasteful and harmful because of defensive medicine and concerns about malpractice litigation. Physicians may react to the threat of litigation by requesting more x-ray imaging referrals and more diagnostic tests to ensure all avenues have been cleared by means of ruling out causes of symptoms rather than to diagnose.

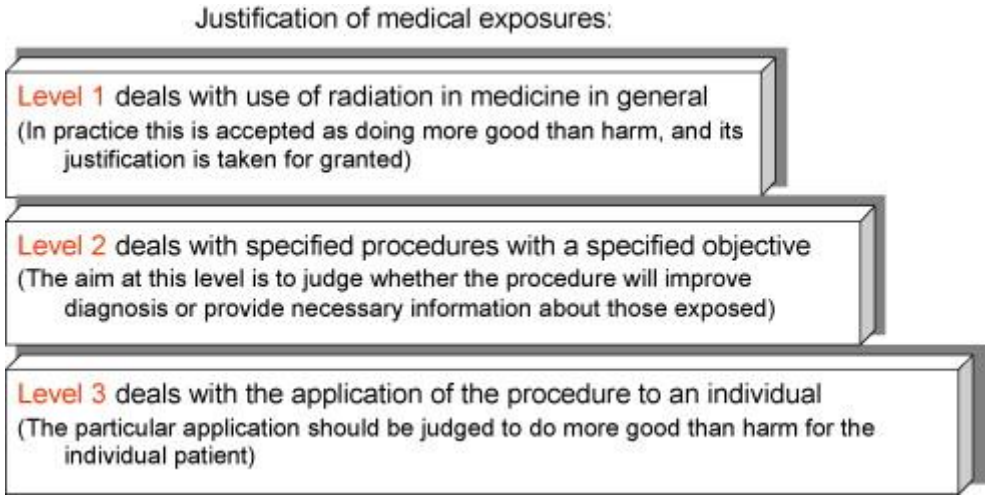

Figure 11 – the justification levels of medical exposure set out by ICRP 2007 (Holmberg et al., 2010)

Although optimisation is the primary focus of this thesis, the process of justification has also been considered. As discussed in section 3.4.1.on page 44, trolley imaging in trauma is controversial and the use of other imaging modalities such as CT is favourable in certain circumstances. Justification plays a vital role in trauma situations especially when having to decide upon the gold standard imaging technique for patients on an individual basis. The decision of whether to acquire an AP pelvis x-ray in the resuscitation room verses using CT imaging is a decision made in the justification process (outweigh benefit to risk). This justification process will be based on various factors including, age of patient, dose implications, patient condition i.e. polytraumatised, hemodynamically unstable patients, and so on (Cannon et al., 2009). The justification process also considers image quality and how this might impact on diagnosis. Currently, CT is much more sensitive than conventional imaging when detecting pelvic fractures in trauma but this may change slightly if AP pelvis imaging on a trolley is optimised as suggested for this thesis.

3.5.2 Optimisation

Optimisation is one of the prime ideologies in the radiation protection framework set out by the ICRP (2007). The essential aspects of optimisation are to firstly identify the level of radiographic image quality that is required to make a diagnosis and to answer the clinical question. Subsequently the radiographer must decide upon the technique that provides that level of image quality with the lowest amount of patient dose. This means it is the responsibility of the radiographer to obtain images which are adequate for clinical purpose whilst keeping the dose to a minimum (adhering to the ALARP principle) (Martin, 2007). The European Directive (2013/59/Euratom) has recently updated their safety standards for radiation protection where the requirement for optimisation has been highlighted and strengthened (ICRP, 2007). In addition, diagnostic reference levels (DRL's) and specific training requirements for new techniques have also been emphasised as a significant feature of optimisation (ICRP, 2007). These changes made by the European Directive strengthens the requirement and importance of this thesis because no specific training is provided for trolley imaging and no specific DRL's are in place for imaging a patient on a

trolley. DRL's are derived from national and local data for common x-ray examinations. Currently, no DRL's exist for projections acquired on trolley bound patients. It has already been discussed in section 3.1(on page 13) that major differences exist between x-ray tabletop imaging and trolley imaging and therefore it cannot be assumed that the DRL's and techniques used for standard conventional imaging is transferable to trolley imaging. This is why one of the main aims of the current thesis is to evaluate whether the acquisition parameters used for AP pelvis on an x-ray tabletop is exchangeable to pelvic trolley imaging and then subsequently optimise image quality and radiation dose for this imaging technique by exploring variables such as the mattress thickness and image receptor holder.

There are a reasonable number of published studies in medical imaging on AP pelvis optimisation where different acquisition parameters such as kVp, mAs and beam geometry have been adjusted in order to determine their effect on image quality and radiation dose. There is often a trade-off between image quality and radiation dose, with some dose reduction techniques having a positive effect on image quality, whilst others degrade contrast or increase image noise. It is therefore imperative not only to reduce dose but to optimise each imaging technique, maximize its effectiveness, and verify the right balance between patient dose and image quality (Chan & Fung, 2014). The radiographer has considerable influence over patient dose and image quality and therefore can use certain measures to balance the two. These measures include collimation, scatter removal (grids), exposure time, filters and so on (Morrell, 2006).

For this thesis, AP pelvis is the examination being explored and optimised because of its frequency in trauma situations on a trolley and its dose implications as already discussed in section 3.4 on page 46. Researchers have employed various combinations of acquisition parameters to reduce the dose for AP pelvis x-ray examinations. One of these studies included Chaparian, Kanani and Baghbanian (2014) who reported significant reduction in effective dose and risk when the pelvis projections was acquired in a postero-anertior (PA) position as oppose to the standard AP position. This is supported by similar studies using different imaging examinations including the lumbar spine, whereby the PA position reduced effective dose and the dose to radiosensitive organs which are located anteriorly in the body (e.g. gonads) (Davey & England, 2015; Brennan & Madigan, 2000). Nevertheless, this dose reducing method cannot be utilised in trauma situations because of the impracticality and dangers of laying a potentially injured patient in prone position. Not

only can the prone position exacerbate pelvic injuries but also a traumatised patient would need to be in a supine position to allow for nursing care, medical evaluation and insertion of central lines (Fridrich, Krafft, Hochleuthner & Mauritz, 1996).

Another study that aimed to optimise image quality and radiation dose for AP pelvis was Chan and Fung (2014) who investigated the use of an air gap technique in comparison to utilising a grid. Their findings suggested that the 'no grid' technique increased image noise but yet produced suitable image quality with considerable dose reduction. On the other hand, this study evaluated image quality using a visual grading analysis (VGA) method combined with the CEC image quality criteria (1996) which is based on film-screen image quality and therefore does not take into account features relating to digital imaging such as contrast, noise and sharpness (Mraity, England & Hogg, 2014a). In addition, Chan and Fung (2014) acknowledge that the method used to produce an air gap is unrealistic in clinical practice due to potential for injury of the patient. If this air gap technique was utilised for AP pelvis, it would have to involve a total re-design of the x-ray tabletop and Bucky system. In conclusion, Chang and Fung (2014) commented that this air gap technique may only be useful for examinations where a high level of image quality is not required to answer the clinical question such as for follow up examinations to confirm the positions of pins and nails or for monitoring bone alignment. This thesis however aims to optimise image quality and radiation dose for AP pelvis in trauma situations whereby high image quality is required to rule out significant injuries and to potentially detect occult undisplaced fractures (Uffman & Schaefer-Prokop, 2009). According to Mraity et al. (2014a), when defining image quality the intention of the image should be considered since the quality of an image can be defined in terms of its acceptability for answering the primary clinical question. It is therefore important that optimisation techniques are employed carefully because they may not be suitable for some clinical indications where high image quality is necessary for confident diagnosis.

Several studies including Heath et al. (2011), Tugwell et al. (2014) and Farrell et al. (2008) have also explored the effect of increasing SID for AP pelvis as an optimisation method to reduce dose to the patient whilst maintaining image quality. All studies found increasing SID to be a simple, cost-effective and successful technique to reduce effective dose whilst maintaining diagnostically acceptable images at SIDs of up to 140-150cm. Nevertheless, even though these studies demonstrated the advantages of this method, it still needs to be

explored further in clinical practice. All previous studies except for one (England et al., 2015) were completed using anthropomorphic phantoms and therefore the results need to be confirmed using patients of various body habitus in clinical practice taking into account the grid cut off ranges of the various different grids available in clinical department. England et al. (2015) went one step further and trialled this technique in clinical practice using patients. This study demonstrated the benefits of increasing SID for the AP pelvis but again had a few flaws which should be considered before the findings can be implemented into routine clinical practice. England et al. did not set specific SID values for the test group, the SIDs were based on the maximum achievable height of the radiographer. This 'maximum achievable height' can significantly vary between radiographers and therefore consideration must be give to the variability between magnification level of different patients or images acquired of the same patient by different radiographers. This is worrying considering that AP pelvis images are used to help plan and measure implants for orthopaedic surgeries. The use of a calibration ball has been suggested to eliminate the variation in magnification and allow for identical scaling of images. Nevertheless, this may not be reliable if the calibration ball is not placed in the correct position as seen in the study by Boese et al. (2015).

In addition, careful consideration must be given to all the above studies who have investigated increasing SID to reduce dose but claim that the decrease in radiation dose had no major impact in image quality. Vladimirov (2010) suggested that with increasing awareness of the need for radiation protection, there has been a paradigm shift from the principal "image quality as good as possible" to "image quality as good as needed". This philosophy needs reviewing because according to Uffman and Schaefer-Prokop (2009) by the time observers visualise a high level of noise, diagnostic information may have already unnoticeably disappeared.

Another different and interesting optimisation study found was that by Manning-Stanley et al. (2012) who investigated how different orientations and AEC chamber selection impacted upon image quality and radiation dose for AP pelvis. This study, along with all other optimisation studies on AP pelvis, conducted their experiments using the standard method of imaging the AP pelvis which is supine on the x-ray tabletop. Manning-Stanley et al. demonstrated the advantages of using the AEC for dose reduction and image quality optimisation, but unfortunately this optimisation technique cannot be considered for this

thesis due to the unavailability of the AEC on trolleys. This further highlights the importance of conducting an experimental optimisation study for AP pelvis on a trolley since the previous optimisation studies for AP pelvis have been conducted using the x-ray tabletop disregarding the fact that the AP pelvis is often imaged on a trolley.

3.5.3 Digital imaging system's impact on optimisation

Today, most imaging departments use digital imaging systems as opposed to film/screen whether this is CR or DDR. There are many benefits of digital imaging that make it preferable to film/screen technology, such as the ability for digital storage and transfer of images, non-chemical processing, reusability, wider exposure latitude and post-processing algorithms (Ching, Robinson & McEntee, 2014). These new capabilities offer flexibility in being able to provide diagnostic image quality in conditions where incorrect exposure factors have been used which avoids repeat exposures and additional dose to the patient (Walker et al., 2011). Nevertheless the advantage of this wider exposure latitude and post-processing algorithms in adjusting the image to a standard displayed optical density (OD) can hide and compensate for exposure errors. Digital systems are much more tolerant of inappropriate techniques because of the high latitude of digital detectors and phosphor plates making it possible to use unnecessary high exposure with a resultant good or even perfect image quality. This phenomenon in digital imaging has been branded as 'dose creep'. Dose creep can be described as the ability to increase dose without it being visual noticeable on image quality. Digital systems are not as tolerant to mistakes when exposure is low because if the receptor dose is considerably reduced the images appear noisy due to photon deficiency. Therefore the inverse correlation between dose and image quality is eliminated with digital systems. Unlike film-screen, 'film blackening' as an indicator of overexposure, no longer exists. Even a 10-fold overexposure can go unnoticed which is worrying (Uffmann & Schaefer-Prokoft, 2009). Ma et al. (2013a) also found that the largest over-exposure factor was 139 (ratio of maximum E to minimum E that produce images of
acceptable quality) for chest before the image became visually unacceptable.

Although digital imaging systems significantly differ from film/screen radiography, guidelines and codes of practice implemented for film/screen such as those issued by NCRP (1989) are still valid for digital radiography. These codes of practice include

techniques such as appropriate collimation, appropriate SID, selection of focal spot size, and patient positioning which all influence dose and image quality. These principles are important especially in an emergency department setting such as for this thesis where many of the above-mentioned parameters including mAs and SID are set manually and rely on radiographer clinical judgment. Unfortunately, as previously mentioned there is a tendency to handle these principles less precisely, based on the fact that digital technology is more tolerant to dose variations and offers more options to retrospectively modify image quality by processing. This is even more worryingly for this thesis because the AEC is also unavailable for trolley imaging and according to Ma et al (2013a), the phenomenon known as dose creep is more common in examinations where the AEC cannot be used because radiographers tend to use higher mAs to ensure the image is acceptable on first attempt. This re-enforces the importance of providing radiographers with exposure charts for various examinations to assist them when selecting appropriate acquisition parameters.

3.6 Radiation dose calculations

The above section highlights the importance of justification and optimisation of image quality and radiation dose in medical imaging. This next section investigates the different dose quantities and the equipment and calculations available to estimate them. Firstly, the importance of quantifying and calculating radiation dose is highlighted and then the means of estimating dose quantities are discussed. In current optimisation studies, authors use different dose quantities and calculations in their methods depending on the research question and aims. Below is a brief summary of the different dose measurements used in research studies and the advantages and disadvantages of each method, bearing in mind that some doses can be directly estimated from instruments whilst others need to be estimated using mathematical models (ICRU, 1993).

In radiology, there are two fundamental reasons for estimating the radiation dose delivered to patients. Firstly it provides a way of setting and checking standards of good practice, ensuring compliance with regulatory requirement. This means that recorded doses can be used to compared against DRLs, identify whether a dose greater than necessary was delivered to the patient and to evaluate different techniques or equipment (RCR, 2008). Secondly, radiation dose estimation can be used to determine and assess the associated risk to the patient from the imaging exposure (Wall et al., 2006). When ionising radiation

interacts with living cells, it can cause the chemical bonds to be modified or split. Individual cells can frequently repair this damage, but the repair process is occasionally faulty, resulting in mutations (Alpen, 1998). Changes to these cells can result in deterministic effects or stochastic effects. Deterministic effects can occur if ionising radiation reaches a specific threshold with the severity of the effect increasing as the dose increases. The radiation doses associated with this thesis (AP pelvis on trolley) is however primarily concerned with protection against radiation-induced cancer and hereditary disease which is known as the stochastic effect. Stochastic effects are probabilistic in nature and it is assumed that any exposure is capable of causing an effect, with no threshold (ICRP, 2005). Since this effect is governed by chance, it emphasises the importance of adhering to the ALARP principle because evidence suggests that harmful effects can happen even at very low doses of radiation. Chan and Fung (2014) expressed concerns regarding this stochastic effect when imaging the pelvis in trauma situations as multiple follow up examinations may be required and therefore a high cumulative dose to the pelvis organs including the gonads. It is essential that radiation dose to the patient can be measured or estimated in order to check standards of good practice but also to estimate the risk associated with the absorbed dose to the organs and tissues of the patient (Wall et al., 2011).

There are three interrelated measures of radiation that this thesis will consider - **exposure**, **absorbed dose**, and **equivalent dose/effective dose**.

3.6.1 Exposure

Exposure is a dosimetric measure of the strength of the radiation field at a point in air before it interacts with a patient (IAEA, 2012). The main advantage of this unit is that it is direct and easy to measure but also it is a practical dose quantity for the periodic inspection of patient doses for common examinations within the imaging departments. The main limitation is that it is only valid for deposition in air and does not reflect upon the risk associated with the measure or the energy absorbed by the tissue (Tootell, Szczepura & Hogg, 2014). Examples of commonly used exposure dose quantities in literature are DAP and ESD.

Dose area product (DAP)

DAP is the absorbed dose to air (or otherwise referred to as the air kerma) averaged over the whole x-ray beam area. DAP reflects not only the dose within the radiation field but also the area of tissue irradiated which correlates well with total energy directed at the patient. It has the advantages of being easily measured since a DAP meter is permanently mounted onto the x-ray tube in front of the collimators (Tootell et al., 2014).This makes it useful when doing retrospective analysis of dose as it is recorded for every examination. The recording of the total examination DAP in conventional radiography is a requirement of IRMER (2000) which states that the operator should record DAP on the request card to aid in exposure audits and the ongoing monitoring of exposure factors. The DAP meter consists of an ionising chamber which needs to intercept the entire x-ray field for accurate readings. This dose quantity is considered to be sufficient for checking and comparing effectiveness of modifications to technique or equipment that are introduced to reduce dose (Engel-Hills, 2006). It is sometimes used in optimisation studies as a dose quantity (Ekpo, Hoban & McEntee, 2014; Keating & Grange, 2011; Shaw et al., 2013), it is also commonly used by authors including Allen et al. (2013), Reis et al. (2014), Ma et al. (2013a)as a means of calculating effective dose (discussed further on in this section 3.6.6 on page 59). According to Faulkner, Broadhead and Harrison (1999), DAP measurements correlates reasonably well with stochastic effects.

Entrance surface dose (ESD)

ESD is another direct measure of radiation dose and is described as the absorbed dose to air on the x-ray beam axis at the point where the x-ray beam enters the patient or phantom, including backscatter (Tootell et al., 2014). The ESD, in particular, is recommended as the most appropriate dosimetry quantity for simple x-ray projections since it meets the three basic conditions set out by the International Atomic Energy Agency (IAEA) (2004) which are: *simple to measure, permits direct measurement on patient during the examination, and is representative of the dose received by the patient.* It is also recommended by the Commission of the European Communities (CEC) (1996) in the document on quality criteria for the most common radiographic images. In addition, the measurement of ESD permits easy comparison with published diagnostic guidance or reference level (Škrk, Zdešar & Žontar, 2006; Wall, 2006; Ofori, Antwi, Scutt & Ward, 2012). Although knowing the surface entrance exposure to a patient does not give a complete description of the radiation delivered to all tissues, it does provide useful information for several

purposes. It can be used to compare a variety of imaging techniques with regards to radiation delivered to patients, particularly for the same anatomical coverage and also to calculate the absorbed dose to the tissues and organs (Sprawls n.d.).

ESD can be measured with either TLDs or ionising chambers. TLDs have the advantage of being small and easy to place on the patient surface without obscuring any anatomy. They also can detect small amounts of radiation compared to ionising chambers which is especially useful if interested in measuring scattered radiation. They have been used successfully to calculate ESD in various optimisation studies including Mekis et al. (2010), Clancy, Brennan and McEntee (2010) and Egbe, Heaton and Sharp (2010a/b). The use of TLDs however can be time consuming to read and require careful calibration and handling for accurate results. Ionising chambers on the other hand have high accuracy and reproducibility with the necessary correction factors well understood (Attix, 1986).Though less sensitive than TLDs, ionisation chambers are a valid ESD measurement tool according to Cherry & Duxbury (1998). However they are bulky and therefore can obscure diagnostic information if used on patients, however if used on phantoms, two exposures can be made under equal conditions, one for image quality and the other to calculate the ESD. This ensures the field of view is clear of any artefact/objects when image quality is evaluated. Ionising chambers have also been used to measure ESD by literature including Sun, Lin, Tyan and Ng (2012), Davey and England (2015) and Keating and Grange (2011) with some literature using ESD to calculate effective dose (Chan & Fung, 2014; Poletti & McLean, 2005).

3.6.2 Absorbed Dose

Absorbed dose is a quantity that implies the amount of energy from ionising radiation imparted upon a given part of tissue. In other words, it is the amount of radiation absorbed by an object (Tootell et al., 2014).This dose quantity is a pure physical descriptor of energy transfer due to the ionising radiation. Quantities relating to radiation outside of the human body, such as those described previously (ESD and DAP), are relatively easy to measure because a measuring device can be positioned at the location of interest. However, absorbed dose in tissue cannot be measured directly by any practical methods as it is not reasonable to insert them into internal tissues or organs. Therefore, the absorbed dose in

body tissues is usually determined by indirect measures (Sprawls n.d.). Absorbed dose is rarely described as an individual quantity in literature as it is usually estimated and subsequently used to derive equivalent or effective dose my multiplying it with radiation or tissue weighing factors e.g. equation 1.

Equation 1:

Effective Dose (Gy) = Absorbed Dose (Gy) x $\mathbf{W_T}$

3.6.3 Equivalent dose, effective dose and effective risk

The quantities that have already been considered for measuring radiation dose are physical measures and are expressed in terms physical quantities such as energy. These quantities do not however consider the potential occurrence of biological effects or the biological impact of the radiation on the body from the amount of radiation absorbed. According to Giordano (2009), radiation may not produce the same biological impact each time for the same or different patient even if the dose or energy delivered to that individual is no different than before, therefore it is important that other factors are considered when discussing the possible harmful effects of radiation doses from medical imaging. This is why calculations are carried out to convert absorbed dose into equivalent or effective dose in order for the consideration of the stochastic health risks from the radiation dose.

Equivalent dose takes into account the type and energy of the radiation and is obtained by applying a radiation weighting factor (W) to the absorbed dose. Radiation weighting factors are published by ICRP (2007) which reflect the potential biological damage of various radiation types. It can be considered a less fundamental quantity than absorbed dose but it is useful for indicating the health risk of radiation exposure.

In the past few years, effective dose has been the most commonly used dose quantity in medical imaging optimisation studies. Effective dose has been advanced by the ICRP over the years as a key radiation protection calculation to meet the requirement of appropriate quantification of radiation exposure. It has been utilised for setting the basic principles of radiological protection such as controlling dose limits for stochastic effects and for use in dose optimisation (Pradhan, Kim & Lee, 2012). Effective dose takes into account the type

and amount of exposed tissue and the relevant tissue weighting factors (how sensitive a particular area in the body is to radiation). It is an indicator of the risk of inducing stochastic effects, such as cancer (ICRP, 2007; Harrison & Lopez, 2015). Tissues within the body have different sensitivities to radiation which means a dose applied to one area of tissue within the body carries a higher risk than the same dose applied to another. This allows comparisons of the risks associated with different imaging techniques or modalities (Tootell et al., 2014). These tissue weighting factors have been developed and adapted within ICRP 103 with the latest tissue weighing factors published in ICRP (2007). These weighing factors were derived using data that was assessed and analysed by The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) on cancer risks from follow-up studies of the Japanese atomic bomb.

The estimation of effective dose can be made with commercially available computer programs such as the PC based Monte Carlo (PCXMC) program (STUK, Helsinki, Finland). Monte Carlo is a common simulation method of calculating effective dose (and risk) associated with the radiation to the patient. The PCXMC program allows the user to input the necessary radiographic parameters such as field size and projection, tube voltage and beam filtration in order to calculate effective dose. The utilisation of this software is supported by a vast body of literature including Schultz, Geleijns, Spoelstra and Zoetelief (2003), Helmrot, Pettersson, Sandborg and Altén (2007), Ma et al. (2013a), Allen et al. (2013) and Chan and Fung (2014) which have shown that PCXMC results agree well with dose measurements and calculations with other phantom models. The application of effective dose is useful when comparing imaging techniques and modalities as it provides referrers, practitioners and operators with data that allows them to make decisions during the referral, justification and optimisation of medical imaging procedures. However, effective dose should not be used to calculate the risk of the exposure to an individual (Pradhan et al., 2012). Brenner in a number of publications including (e.g. Brenner 2008, 2011, 2012) questioned the reliability of effective dose due to its subjective assumptions and uncertainties involved in its estimation. Effective dose does not reflect the major age / gender dependencies in radiation sensitivity. It is also confusing to most users and unnecessarily hard to interpret. However, Dietze, Harrison and Menzel (2009) commented that the revision of the tissue weighing factors in 2007 by the ICRP was in response to the publication of more reliable cancer incidence data rather than a change in the committee's emphasis. Whatever the reason, it is clear that these revisions do have an impact on

effective dose calculations making comparisons to older data difficult. Nevertheless, although many authors, including Martin (2011), Dietze et al. (2009) and Balonov and Shripmpton (2012), appear to relate with the concerns raised by Brenner (flawed for risk estimation especially on an individual patient basis), optimisation studies continue to use this quantity due to the fact that there is no other simpler way for the estimation of risk from radiation exposure (Pradhan et al., 2012).

With these criticisms regarding effective dose in mind, Brenner proposed an alternative risk estimation that could be applied to individual patients; this is referred to as effective risk. Effective risk considers the life time risk of cancer induction from an absorbed dose of radiation (Brenner, 2008). In comparison to effective dose, effective risk replaces the use of tissue weighing factors with organ-specific radiation-induced cancer risk, such as those published by The Nuclear and Radiation Studies Board or more recently by Wall et al. (2011).The lifetime risk figures are calculated from stronger data as they are based directly on epidemiological studies and not determined by a committee. This therefore eliminates the subjectivity associated with committee-generated weighting factors and would offer a more instinctively interpretable quantity relating to risk with less potential for misuse (Tootell et al., 2014)

3.6.4 Detector dose

Detector dose does not offer a measure on the radiation dose received by the patient but it can give an indirect indication of image quality. Detector dose, sometimes referred to as image receptor dose, is the air kerma measured directly behind the patient in front of the image receptor (Hess & Neitzel, 2012). This means it is the dose received by the image receptor to form the image after absorption and penetration through the subject/patient. According to Uffman and Schaefer-Prokop (2009), in digital radiography, image noise is inversely related to the amount of detector radiation dose.

3.7 Image quality assessment

Having reviewed and critiqued different quantities and means of calculating radiation dose, this section evaluates various methods of measuring image quality. It considers both

physical and visual means of assessing image quality whilst reflecting upon the benefits and limitations of each method and their use in previous optimisation literature.

To allow for optimisation of the imaging procedure, it is important that image quality can be measured and assessed as to whether or not the images are satisfactory for their intended purpose. The purpose of medical imaging is to demonstrate patient anatomy and pathology adequately to enable reliable and accurate diagnosis (Morrell, 2006). It's about acquiring an image of diagnostic quality whilst keeping dose as low as reasonably practical (ALARP). A variety of methods are available for measuring the performance of imaging systems, some involve the use of physical measures whilst others involve the participation of human observers. Evaluation of image quality can be made by either considering the quality of the data acquired by the imaging device or that of the displayed image. When addressing the problems of quality control of imaging instrumentation, the former is generally the commonest method due to their high objectivity and unbiased measure of image quality e.g. CNR or MTF (Krupinski, 2010). However these measures are limited due to the fact that they only measure one specific characteristic of device performance. The latter on the other hand involves the use of human observers to analyse test pattern and subjectively judge what is visualised. This allows for observer assessment of the displayed data and therefore is a closer representation of the clinical situation. The drawback is that human observers can be subject to agreement inconsistency not only when using multiple observers but when re-testing the same observer(intra and inter variability) (Vennart, 1997); this makes the use of observers to achieve reliable and valid data challenging.

The next section considers the different physical measures used to assess image quality, computer modelling and the different observer performance methods also used to assess image quality.

3.7.1 Physical measures

Physical measures of image quality are used to determine the technical performance of imaging systems and they have the advantage of being an objective and repeatable means of assessing image quality (Morrell, 2006). They enable the performance of an imaging system to be characterised by measuring certain physical parameters and combining them

according to the requirement of a particular imaging task. These measures include contrast to noise ratio, modulation transfer function and detective quantum efficiency and they can be used as the quality assurance measures to certify the imaging system is performing with suitable accuracy and consistency (Vennart, 1997). These measures give reproducible results and indicate what can be accomplished in controlled conditions without the influence of human bias.

The primary quality-related features in imaging are contrast, sharpness and noise. A number of complementary metrics are available to assess the performance of digital x-ray imaging systems using physical measures. These include CNR, MTF, Noise Power Spectrum (NPS) and Detective Quantum Efficiency (DQE)

CNR is frequently used as a measure to estimate image quality and can be defined by the following equation:

$$\frac{S1 - S2}{\sigma 2}$$

Where S1 is object signal intensity, S2 is the background intensity, and σ2 is the standard deviation of the background intensity (Vladimirov, 2010; Tang et al., 2012 and Desai, Singh & Valentino, 2010). CNR has been used to measure image quality by authors including Hess and Neitzel (2012), Mori et al. (2013) and Martin (2007) in the process of optimisation and has been deemed to be acceptable for evaluating image quality. In comparison to signal to noise ratio (SNR) which is described by Doyle, Gentle and Martin (2005) as the ratio between the object signal intensity and the pixel standard deviation in the background, CNR considers the signal intensity of the background in comparison to the object signal intensity and therefore gives more information on the visibility and differentiation between structures. SNR is limited as it does not consider the effect of noise on our ability to visualise objects within an image since visibility depends on contrast (the difference between signals). An overexposed image may contain a high SNR but demonstrates no valuable information on the structure of interest (Vldimirov, 2010; Lyra, Kordolaimi & Salvara, 2010).

The ability of an x-ray detector to produce high-quality images is determined largely by the **MTF** and **DQE** of the system. MTF has long been the accepted metric for evaluating the spatial resolution of an imaging system; MTF is the ability of the detector to transfer the modulation of the input signal at a given spatial frequency to its output. It is a valuable measure of true or effective resolution, as it accounts for contrast over a range of spatial frequencies (Körner et al., 2007). DQE on the other hand is one of the primary physical measures related to image quality in radiography and refers to the efficiency of a detector in converting incident x-ray photons into an image signal. It combines the effects of modulation, spatial frequency and noise of an image receptor and can be utilised to compare various receptors in a more general manner than MTF alone. DQE involves the physical evaluation of an image detector and it's usefulness in quantifying the detector's characteristics including its sensitivity and noise sources (Ertan et al., 2009). The DQE is a measure of the combined effects of the signal (related to image contrast) and noise performance of an imaging system, generally expressed as a function of spatial frequency. NPS is another physical measure of image quality used to quantify the noise characteristics and patterns in all frequencies of the image, and provides a more complete description of noise in an image.

The above physical measures are all objective methods of assessing image quality and are therefore reproducible. Nevertheless the use of these measures in clinical medical imaging needs careful consideration as they may not reflect upon the entire imaging chain (display of image). Also, a study from Dobbins, Samei, Ranger and Chen (2006) demonstrated that even though these physical measures are objective in nature, different techniques exists to calculate each metric and therefore careful consideration must the given when comparing them with other published work.

3.7.2 Computerised modelling

Computer modelling was another method found in the literature that could determine image quality. For this method computer software is developed for mathematical simulation of the imaging process. The calculations are most commonly performed using a Monte-Carlo computer program with its simulations appearing to be an efficient means of

optimising imaging techniques as done by studies including Ullman et al. (2004) and Poletti and McLean (2005). These computer programs work on the basis of simulation by modelling various aspects of the clinical procedures, enabling large-scale studies to be carried out quickly and easily, comparing various combinations of imaging parameters. Nevertheless, because they simulate the clinical situation, they can create situations that are not practical or clinically possible such as that shown by Poletti and McLean (2005) where SID of up to 10metres were explored for the lateral lumbar spine. Even though this distance demonstrated dose reduction, it would require an increase in x-ray tube loading, performed in an extremely large room, with a flexible x-ray tube. Another downside is that computer modelling can be time consuming since you have to test and validate the program by comparing it to measurements performed on an actual x-ray system (Morrell, 2006).

From what has already been discussed regarding methods of assessing image quality, physical measures and modelling have been deemed useful for optimisation and characterising the intrinsic performance of imaging systems. Nevertheless, both methods rely on generalisations or assumptions, and therefore their accuracy in determining clinical imaging performance is limited. The results of modelling studies must be confirmed empirically, prior to introducing new techniques into clinical practice. In addition, they do not predict the behaviour of the human observer and therefore do not take into consideration the display and observation steps of the imaging process resulting in little information regarding direct clinical implication (ICRU 1996).

3.7.3 Observer performance methods

"*Medical image quality is related to the subjective interpretation of visual data"*

(Martin, 2007).

Observer assessment of image quality as highlighted by Martin's quote above, involves the use of human subjects to visualise structures on displayed images and make a judgment. There are numerous means in which this can be conducted and will be discussed in the below sections. The first observer performance method involves visual detectability of physical measures such as contrast and spatial resolution using test objects. It is the visual

evaluation of physical parameters such as line pairs/mm-spatial resolution testing using contrast detail analysis and physics phantoms (test objects) such as the Leeds TOR CDR (see figure 12).The other observer performance methods can then be grouped into two categories, one category involves lesion detection and the other involves the visibility of anatomical structures. Both these methods are used to evaluate the entire imaging sequence and provide an assessment of clinically relevant image quality (Vladimirov, 2010; Sun et al., 2012)

Contrast detail

Contrast detail test objects provide a quantitative measure of image quality by means of sensitometric measurements, detail detectability and checking resolution limits in order to determine equipment performance. Although these cannot be used directly to predict clinical image quality because of their simplicity in comparison to anatomic structures, they still provide useful information of threshold contrast detail detectability and equipment performance. The use of contrast detail images is a practical approach adopted for routine quality control constancy testing. The visual appreciation in such experiments is usually performed by an appropriate observer / observers. The most common objects used are the Leeds test objects (see example in figure 12). Contrast detail tests offer a quick and simple check for large variation in system performance and can rank systems according to their contrast and noise characteristics (Morrell, 2006). However, they have limited accuracy and reproducibility in identifying absolute threshold contrast since it suffers from significant intra- and inter-observer variation, since detail visibility is dependent upon observer's visual and cognitive decision thresholds. This can lead to variations between even the most experienced observers, and also between viewing sessions, especially if the sessions have long time intervals (Ullman et al., 2004, Sandborg et al. 2001b).

Figure 12 – TOR CDR Leeds Test Object used in radiography (Leeds Test Object Ltd, North Yorkshire, United Kingdom).

Kupinski (2012) commented that medical radiographic images are acquired for specific purposes and it is important to consider the clinical indication in order to evaluate the level of image quality required. Customary measures such as resolution, noise and contrast are of secondary importance as they do not essentially correlate with task performance. Instead, the quality of an imaging system or the processing of image data is assessed by the performance of appropriate observers in completing medically relevant evaluations. Image quality must therefore be judged in terms of the extent to which a class of images allows real observers, such as radiologists, to decide correctly the state of health or disease of a patient from evaluating their images (ICRU, 1996).An important goal in medical imaging is the assessment of image quality in a way that relates to clinical efficacy.

According to Burgess (2011), human observer performances are often performed by forced-choice methods. Forced choice methods can be applied to both lesion detection methods and methods that evaluate the visualisation of anatomical structure. 2AFCis a discrimination assessment where two stimuli (standard and comparison) either side by side, or one at a time, is displayed and the observer is required to make a judgment on which image contains optimal image quality or the abnormality/lesion(Abbey & Eickstein, 2002). Green and Swets (1966) described a 2AFC experiment similarly where two stimuli are demonstrated in a trial, and the observer has to identify the stimulus that contains the target of interest; this assesses the psychophysical visual opinions of the observers who are presented with two separate stimuli displayed side by side on dual monitors (Pelli & Farell, 1995). Forced choice methods can also contain more than two stimuli and is know as 4

alternative force choice (4AFC) or multiple alternative forced choice (MAFC) methods. These are simple extensions on the 2AFC method with more than two decision alternatives (Burgess, 2011). These forced choice methods are sensitive to small changes in image quality and has found to be easy and quick to complete, offering additional consistency in responses when compared to other observer performance methods (Lanca et al., 2014; Ulrich & Miller, 2004). In addition, forced choice experiments minimise some aspects of observer bias, since observers have to identify the position of a known object, from a number of possible locations resulting in numerical values. This can improve the reliability of the test results (Mansson, 2000).

This next section considers image quality assessment methods that use visual/clinically relevant techniques including lesion detection (ROC analysis) and visual evaluation of anatomical structures using visual grading analysis (VGA).

Lesion detection studies

Lesion detection studies are most often performed using a receiver operating characteristic (ROC) to demonstrate the diagnostic accuracy of imaging examinations yet again there have been some studies who have used eye-tracking methodology to determine the visual search strategies of different observers (Manning, Ethell, Donovan & Crawford , 2006; Cooper et al., 2009) whilst others have used both methods in a single study (Reed et al., 2011).

ROC analysis originates from Signal Detection Theory, where the detection of low contrast signals in a noisy background is explained (Mansson, 2000). It is a type of forced choice methodology where in its simplest form the observer is presented with a series of images, some which are normal and others which contain pathologies (usually lesions). It is therefore a binary decision between the ‘absence’ and ‘presence’ of diseases. Consequently a graph can be plotted from the true positive rate (sensitivity) verses the false positive rate (specificity). This binary ROC method has many drawbacks which includes the poor reflection of the clinical situation, it requires a vast amount of images in order to generate statistically relevant results, it cannot handle multiple tumours/lesions in a single image and it does not consider the location of the lesions therefore the observer can presume the presence of a lesion without having to indicate its position within the image (Morrell, 2006).

In order to overcome these drawbacks, numerous more realistic methods have been developed including localisation ROC (LROC) where the lesions present in the image need to be pointed out by the observer to ensure a true positive score. Free-response ROC (FROC) expands upon LROC where a random number of lesions may be used in each image and also the observer is required to use confidence ratings rather than a binary decision regarding the presence and location of the lesion/s. Alternative FROC (AFROC) analysis is simply an alternative way of analysing FROC data and has been described and utilised in recent studies (Kashani et al., 2010; Metz, 2006; Thompson, Manning & Hogg, 2007). The most advanced ROC method is the jackknife free-response ROC (JAFROC) analysis which overcomes the shortcoming related with ROC by increasing its statistical power of evaluation (Chakraborty, 2005). For this reason, it is frequently used in recent optimisation studies (Jessop et al., 2015; McEntee et al., 2013; Fletcher et al., 2015).

ROC analysis methods are a well-established method for determining the diagnostic accuracy of clinical images and considered robust in comparing the diagnostic accuracy of radiological tests. Nevertheless, ROC trials can be very time consuming as they are based on the establishment of truth for all cases requiring large sample size in order to produce statistically significant results. This can lead to considerable observer fatigue and reliability issues (Burgess, 2011; Vladimirov, 2010; Tapiovaara; 2006).

Visualisation of anatomical structures

Visualisation of normal anatomical structures is an accepted, well-established, valid, and straightforward method for visually assessing image quality (Seeram et al., 2014). Observers are required to make judgments on the clarity of visualisation of anatomical structures within a radiograph. In VGA, observers are asked either to rate each image against a reference image (relative VGA), or to grade images according to their individual value (absolute VGA). Tingberg et al. (2005) suggested that the relative VGA method, where the images are compared to a reference image can provide much more consistent results than the latter absolute VGA method. Although subject to intra and inter observer variability, VGA methods are sensitive to small changes in image quality and is characterised by attractive simplicity and powerful discriminating properties (Mansson, 2000). In comparison to ROC, VGA is associated with visualisation of normal anatomical structures as opposed to pathology and therefore questioned with regards to its clinical

significance. However several authors including Sund, Båth, Kheddache and Månsson (2004) and Tingberg et al. (2005) advocate that the visibility of normal anatomy is strongly correlated to the detectability of pathological structures. This means that if the visibility of normal anatomy deteriorates, for example, by the use of a different diagnostic technique, then the visibility of pathological structures will also deteriorate. This is a reasonable assumption. VGA can be considered a more general evaluation of image quality as it is based on different types of structures rather than on a specific type of lesion. It has been successfully used for comparing various imaging techniques within an x-ray department (Almén et al., 2000; Tingberg et al., 2004; Tingberg & Sjöström, 2005). This method can also be referred to as a 2AFC methodology (Tingberg et al., 2000).

The above VGA method is considered highly subjective which introduces bias. To address this problem, VGA is most often coupled with a formal image quality criteria. These criteria allow for the scoring of the images and sets out the diagnostic requirements against which the observer can judge the images. The purpose of image quality criteria is to identify the necessary requirements for suitable diagnostic image quality. They are based on the degree of visualisation of important anatomical structures. The observer's perception of an image is determined by their own expectations and preferences but an image quality criteria helps the observer to focus on the visibility of pre-defined anatomical structures. This helps minimise bias and observer variability through focusing their attention upon certain features within the image (Martin, 2007). In most published optimisation studies, the criteria used is often based on The European Commission CEC (1996) '*European Guidelines on Quality Criteria forDiagnostic Radiographic Images'* which is a set of criteria based on common radiographic procedures (Ma et al., 2013; Mekis et al., 2010; Allen et al. 2013; Davey & England, 2015). Nevertheless, individuals need to be cautious when utilising these criteria as they were developed for film-screen images and therefore many of the benchmarks do not apply in the digital environment. In addition, important aspects of image quality relating to digital imaging are missing from the criteria such as noise. Mraity et al. (2014a) recently evaluated a new method for developing and validating image quality criteria for visual grading assessment. The methodology was based upon psychometric theory which provided an approach to establish the reliability and validity of a grading scale using a large sample of volunteers. Mraity et al. (2013, 2015) used this method to develop a new psychometric image quality scale for the AP pelvis projection which has been used in recent literature to visually assess

image quality (Lanca et al., 2014). This scale will be discussed in more detail in the method chapter, section 4.4.2 on page 95. Mraity et al. (2014b) has also developed another psychometric scale for the PA chest x-ray projection using the same methodology. In comparison to previous scales, these newly developed criteria take into consideration factors involving digital imaging but also the robust methodology utilised considers the internal validity and reliability of each proposed criteria for visual/perceptual image quality assessment.

3.7.4 Inter and intra-observer variability

One of the downfalls of observer performance methods is the potential for inter- and intra-observer variability when interpreting medical images. Within methods such as ROC and VGA, the observers are required to set their level of agreement/confidence on how clearly the anatomical structure or pathology is seen within a certain image. This approach uses observer judgment and therefore it is highly susceptible to inter-and intra-observer variation (Krupinski, 2010). Intra-observer variation relates to the degree of agreement for one observer when taking repeated measurements whereas inter-observer variation is the degree of agreement amongst more than one observer for the same task/measurements (Cheong et al. 2010). According to Ma et al. (2014) perfect agreement in visual evaluation of image quality can be difficult to accomplish for numerous reasons and variability will exist when any measurements are made on medical images. Providing the observer with training sessions can help ensure consistency and accuracy and thus increase observer agreement.

The importance of using multiple observers when evaluating image quality is highlighted by many authors including Ma et al. (2014), Burgess (2011) and Obuchowski (2004). There are many statistical methods to assess observer agreement with most image quality optimisation studies in general radiography using the intra-class correlation coefficient (ICC) (Allen et al., 2013; Heath et al., 2011; Manning-Stanley et al., 2012; Ma et al., 2013; Chan & Fung, 2014). Other statistical methods can be used such as Pearson's correlation coefficient (Egbe et al., 2008; Decoster, Mol & Smits, 2015) or kappa statistics (Al-Khawari et al., 2010; Johnson & Kline, 2010; Tang et l, 2012). According to Manning-Stanley et al. (2012) various guidelines exist for the interpretation of these statistical methods. Rosner (2006, 2010) seems to be a common reference used in many studies (Manning Stanley et al., 2012;) where it is suggested that an ICC value of less than 0.40

indicates poor reproducibility, between 0.40-0.75 indicating fair to good reproducibility, and an ICC value of greater than 0.75 showing excellent reproducibility. Ma et al. (2014) questioned these values and suggested a standard level agreement should be set when assessing visual image quality. This however would take considerable work and trials as the optimal level of agreement is 1 (perfect agreement) but this would never be the case with human observational performances. Also, Rosner (2006, 2010) has set these values as a general interpretation and therefore they may not be relevant or robust enough for medical imaging evaluation as the level of agreement when diagnosing a patient needs to be high to avoid error in interpretation. Errors in interpretation can lead to litigation against the interpreters (Robinson et al., 1999).This potential for error in diagnosis emphasises the importance of producing a high diagnostic quality image to ensure the interpreter can formulate a confident diagnosis.

To conclude, the two above sections on ‘radiation dose calculations’ and ‘image quality assessment’ demonstrate the importance of being able to measure dose and image quality in order to perform optimisation studies. Optimisation involves finding the balance between image quality and patient radiation dose which would not be possible without suitable methods of measuring and calculating them. There are various means of measuring and calculating radiation dose with effective dose having become the commonest method used in optimisation studies as it gives an indication of risk. With regards to image quality, although time consuming, observer performance studies using anthropomorphic phantoms and human observers have been found to be valuable and the most commonly used method when evaluating image quality as it reflect more closely that of clinical practice.

3.8 Anthropomorphic phantoms

The harmful effects of radiation have been discussed in section 3.6 on page 55 which emphasises the requirement of the ALARP principle and the need to justify and optimise each patient exposure. In the UK, the ALARP principle is a legislative requirement which ensures that the clinical objective of the examination is met with the lowest possible risk to the patient. This issue restricts the use of patients in research involving radiation especially if new innovative and different techniques are to be explored. There have been some optimisation studies carried out in general radiography on various anatomical regions using

human subjects including Brennan and Nash (1998), Bartholomew, Denton, Shaw and Marshall (2004) and Egbe et al. (2008) where the patients are imaged as part of a clinical trial and the results are compared to other patients imaged in the same trail. This type of study is beneficial in one respect as it is most clinically relevant however it does make analysing results difficult due to the differences that exist between patients. Patients present in different shapes and sizes and therefore require adjustment in exposure factors and techniques. This would make the interpretation of the results from such optimisation studies difficult as parameters cannot be controlled (many confounding factors) (Martin, 2007). Some studies have used cadavers (Gorham & Brennan, 2010) or animal tissue (Keating & Grange, 2011) for optimisation studies in order to explore various acquisition parameters. This method overcomes the issues discussed with regards to patient as the area exposed is consistent and the harmful effect of radiation does not apply. Nevertheless, it is very difficult to find an appropriate cadaver, there are strict regulations and restriction regarding The Human Tissue Act of 2004 and it is also dependent upon the preservation of the bodies as they can decompose and dehydrate causing inconsistency to real human tissue (Bell, 2006). In addition, Schramek et al. (2013) commented that the frequently used embalming fluid to perverse the bodies contains small amounts of formalin which produces artefacts that severely deteriorate image quality.

Due to these problem of using patients or cadavers for optimisation experiments, the majority of optimisation studies including Chan and Fung (2014), Lanca et al. (2014), Manning-Stanley et al. (2012), Davey and England (2015), use anthropomorphic phantoms. Anthropomorphic phantoms are used in radiography to evaluate and analyse image quality and/or dose. They are constructed from tissue-equivalent materials that represent various parts of the human body. Studies as stated above have demonstrated the value of using such phantoms to investigate experimental conditions initially without exposing humans to radiation. These phantoms have similar physical properties to human tissue, such as density and attenuation coefficients and have the advantage of being able to simulate clinical imaging conditions without irradiating humans (Moores, 1993; Winslow et al., 2009). Martin (2007) commented that these phantoms are useful because they are comparable to human anatomy and can be imaged multiple times using different exposure factors. This means that unlimited number of exposures can be performed on them, allowing for a more reliable comparison of the same anatomy under different imaging conditions. Ullman (2008) stated that anthropomorphic phantoms play an important role in

the assessment of image quality; they permit unlimited repetitions of x-rays demonstrating the effects of changing technical factors. In addition, Tapiovaara (2006) commented that evaluating images of phantoms in a clinical imaging task can be better characterised with its variability reduced. This is why many studies have demonstrated the value of using an anthropomorphic phantom initially to test experimental conditions without exposing patients to excessive radiation (Tang et al., 2012; Ma et al.. 2013; Clancy et al., 2010; Manning-Stanley et al., 2012). Their disadvantage however is that they lack the variations in human anatomy with respect to body composition and anatomical backgrounds as seen in the clinical environment. The ICRU (1996) did however suggest that image quality and radiation dose study methods need to be a compromise between realism and convenience. Conversely, it is important that the results of phantom studies are verified by actual patient studies before being fully implemented into routine clinical practice (Vassileva, 2004).

As briefly described in section 3.7.3on page 65, there are other more simple phantoms that can be used to verify system performance in optimisation studies; these are often referred to as physics phantoms. When used in optimisation studies, they are first line investigations of system performance and quality assurance that require further verification after being conducted. They also do not simulate real patient anatomy thus cannot be translate directly to clinical practice (Sun et al., 2012; Mutch & Wentworth, 2007).

3.9 Summary

The main purpose of this above chapter was to reflect critically on the literature and to develop a comprehensive understanding of the background information required to help contextualize the research and ultimately inform the research method. The review of the literature confirmed the limited studies exploring trolley imaging and absence of optimisation research investigating acquisition parameters in this area. Nevertheless, the review did identify a number of different optimisation studies in general radiography with several of these papers seeking to reduce radiation dose for the AP pelvis projection using techniques such as air gap (Chan & Fung, 2014), increasing SID (Heath et al, 2012; Tugwell et al, 2014) and AEC orientation (Manning-Staley et al, 2012) . The latter sections of this chapter also reviewed different experimental methods used to determine radiation dose and image quality with consideration given to the benefits and limitation of these measures. The importance of optimisation was highlighted throughout the literature

review, where studies focused on acquiring a diagnostic image whilst reducing the dose with the ALARP principle in mind. Lastly, this literature review as a whole confirmed the value and necessity of conducting and optimisation experiment on trolley bound imaging as proposed in this thesis.

Chapter 4 - Method

This chapter gives a detailed description and justification of the methods applied to achieve the research's aims and objectives. The chapter begins with a brief overview of the method by outlining the main parameters and variables utilised. Following this there will be in an-depth explanation of the main methods utilised and why they have been selected. Imaging equipment, quality control measures and the imaging techniques used are reviewed in detail. Both independent and dependent variables are discussed and evaluated, along with the problems encountered during the pilot study and how these problems were amended for

the main method. Finally, the statistical methods utilised to analyse and make sense of the data are defined.

4.1 Overview

The research method utilised for this thesis was an experimental approach, which was carried out under controlled conditions in an attempt to maximize objectivity and increase the study's validity and reliability. The study manipulated independent variables in order to evaluate their effect upon the dependent variables. An experimental approach was deemed the most suitable method in order to address the aims and objectives of the study. This type of method offers precision and control where objectives are met through a deductive approach thus generating quantitative data allowing for statistical analysis (Burns, 2000). The aim of the experiment was to discover new knowledge surrounding image quality and radiation dose optimisation when imaging trolley bound patients since there is limited previous evidence surrounding this topic. Data from the literature and current technological developments were considered when deciding upon the most appropriate and robust equipment, parameters and techniques to use for this experimental study.

The main objective of the thesis was to assess and evaluate whether the same acquisition parameters used for AP pelvis on the x-ray tabletop can be used for trolley imaging bearing in mind the differences between imaging on the tabletop and trolley. The remaining objectives aimed to optimise image quality and radiation dose on the trolley by exploring the effect of the mattresses, platform position, mAs and SID on image quality and radiation dose.

To achieve these objectives; the method involved imaging an anthropomorphic pelvis phantom in the AP position using a computed radiography (CR) system. The use of an anthropomorphic phantom allowed for repeated exposures to be made which would have been unethical to achieve on humans. All images were acquired using a ceiling suspended x-ray tube in a standard trauma x-ray room. A reference image was acquired on the x-ray tabletop using standard acquisition parameters for AP pelvis whereas the experimental images were acquired on a commercially available trolley suitable for imaging. The reference image was acquired to allow for visual comparison to all the experimental images. The experimental images were acquired in different imaging conditions on the trolley where four independent variables were manipulated. These included the use of two

different mattresses (standard and Bi-Flex), two different image receptor holder positions (elevated and not elevated), three SID values, and four mAs values. Prior to the commencement of the main experiment, a pilot study was conducted to assess and determine the suitability of the proposed method and to ensure that no problems were encountered with data analysis.

Five dependent variables were used for this experiment in order to evaluate the effect of the independent variables on image quality and radiation dose. These included two image quality measures, two radiation dose measures and the magnification level of the acquired images. Image quality was determined by calculating contrast to noise ratio (CNR) and also by visual evaluation of image quality using a 2 alternative forced choice (2AFC) method. Radiation dose was established by using Monte Carlo simulation software to derive effective dose (mSv) and also by using an ionising chamber to establish ESD. The magnification level of the images was assessed by measuring the right femoral head diameter of each image. All of these outcome measures generated quantitative primary data enabling statistical analysis of the data.

As previously stated, two different image quality measures were used for this thesis (physical and visual) in order to provide complementary information allowing for correlation measures
to be performed. Special emphasis and attention was given to the visual evaluation method due to its significance in simulating image evaluation within clinical practice. This visual image quality assessment was conducted using a 2 alternative forced choice (2AFC) method (Yu, Carter & McCollough, 2013; Abbey & Eckstein, 2002; Ulrich & Miller, 2004) and bespoke software (Hogg & Blindell, 2012). Five observers were asked to visually assess the clarity of anatomical structures of images acquired on the trolley (experimental images) in comparison to a reference image. This was done using dual monitors, side by side, and a validated psychometric image criteria scale for AP pelvis. Nevertheless, the objective physical measure was useful to compliment and support the visual evaluation, mainly because the experiments used anthropomorphic phantoms (i.e. no anatomical variation) and digital images (i.e. pixel based).CNR was the physical measure of image quality where the mean pixel value and standard deviation of that pixel using a specific and consistent region of interest was measured and calculated using ImageJ (National Institutes of Health, Bethesda,MD) (ImageJ, 2014).

Two radiation dose measures were also attained in order to compare and complement each other. Effective dose is the principle dose quantity for this thesis as it is a useful measure of the overall risk to the patients from ionising radiation. It is based on a mathematical model which takes into account the type and amount of exposed tissue in order to calculate the risk associated with the radiation dose to the patient. ESD derived with an ionising chamber is the second measure of radiation dose used for this thesis. This is measured in order to support the data from effective dose because ESD provides a direct measure of the radiation dose entering the patient at skin level as oppose to a mathematical simulation calculation. ESD is also useful since it will directly demonstrate the variation that exists between different imaging conditions especially since OID hence SOD varies between these conditions (Tootell et al., 2014).

4.2 Imaging equipment

4.2.1 Quality assurance (QA) and Quality Control (QC)

A variety of imaging equipment was used throughout the experiment making QA thus QC a vital part of this thesis. QA is a program aimed at maintaining optimal diagnostic image quality whilst ensuring minimal risk and distress to patients. One of the most important aspects of this program is the QC tests that are conducted periodically. QC includes a series of standardised tests which detects anomalies or variance in x-ray equipment function from its original level of performance. If carried out correctly and routinely, it will identify problems and errors thus allowing for timely corrective response to maintain x-ray image quality (Périard & Chaloner, 1996). It is important that QC tests are undertaken as per departmental QA protocol in order to identify potential errors. Herrmann et al. (2012) stated that systematic errors within digital imaging equipment can affect both image quality and radiation dose until the problems are identified and corrected.

Routine QC was performed prior to utilising all equipment for this experiment in accordance to the guidelines and recommendations set out by the American Association of Physicists in Medicine (AAPM) (2006), the Institute of Physics and Engineering in Medicine (IPEM) (Hiles, Mackenzie, Wall & Scally, 2005) and the National Council on

Radiological Protection and Measurements (NCRP) (1988) with the frequency of these tests also conducted in accordance with their recommendations. Routine daily QA was performed on the equipment before commencing the experiment; these checks are described following the description of each piece of equipment below. In addition to daily QA procedures, the imaging department where this experiment was conducted followed the recommended standards for routine performance testing of diagnostic x-ray imaging systems with level 'A' tests performed in house and level 'B' tests performed by qualified medical physics experts (Hiles et al., 2005). Any equipment performing outside tolerance levels were not used for this study. Records of all QA checks are documented within the department and therefore were analysed prior to using the equipment to ensure that they fell within manufacturer's specification (see appendix I).

4.2.2 X-ray Unit

All exposures were performed using a ceiling suspended x-ray unit used in general and trauma situations. The room consisted of a Philips Bucky Diagnost x-ray unit with an Optimus 50kW high frequency generator, a total filtration of 3.2mm Al equivalent and a 1mm broad focal spot (Philips Healthcare, Netherlands). These characteristics are consistent with the minimum requirements of general x-ray equipment (Holm, 2000) and in line with Dowsett et al. (2006). The Philips x-ray unit was equipped with a PTW-Freiberg Diamentor
E DAP meter (PTW-Freiberg, Freiberg, Germany)**.** Prior to the conduction of the pilot study, a mobile unit (Shimadzu MobileArt Plus) was to be utilised for comparison to the x-ray unit. However, problems were encountered in the pilot study and therefore only the x-ray unit was used for the main method (see section 4.10 on page 106 for more details about the problems).

Radiation output tests were performed on the above x-ray unit using methods suggested in IPEM, report 91 (Hiles et al., 2005) with a DAP meter. Set kVp and mAs values were used and the average dose reading for three exposures were recorded and immediately compared to the recommended reference levels whilst ensuring they fell within the ±10% manufacturer tolerance level.

4.2.3 Image receptor and reader

The same 35cmx43cm Fuji IP HR-V image receptor made from Barium Flurohalide (BaFX) phosphor was used throughout the study in order to maintain continuity and minimise potential error that would result from variations in the sensitivity of different image receptor. The image receptor was processed using a Fuji FCR Capsula XII with 50-micron resolution which was monitored before and after each experiment for sensitometric compliance (Fujifilm Medical Systems, Japan). This image receptor and reader are commercial products that are universally used in imaging departments (Jones et al., 2011; Keating & Grange, 2011) and are equipment that are used as examples by the AAPM (2006) in their report on 'Acceptance Testing and Quality Control of Photostimulable Storage Phosphor Imaging Systems'. The daily QA program for a CR system was based primarily on verification of processor sensitometry and general system condition. As recommended by AAPM (2006), a visual inspection of the imaging plates was carried out to check for cleanliness and then a primary erase was performed on the image receptor to ensure that no fogging or ghosting artefacts would be present on the acquired images (Long, Frank and Ehrlich, 2013).

4.2.4 Trolley

The experimental images were acquired on a Lifeguard 50 trolley (Lifeguard trolley range, ArjoHuntleigh, UK) using two different mattresses and will be further discussed with regards to technique in section 4.3.2 below). The Lifeguard trolley ranges are commonly used in clinical practice and are commercially available (see figure 14 for main components). They are used in the three district hospitals of North Wales and are also used in other hospitals across the UK including Nottingham, Forth Valley and Salford Royal (Briody & Walker, 2013; Thompson, 2012; Stone, 2012). The Lifeguard 50 trolley has a fully radio-translucent mattress trolley top, has an elevating x-ray platform, which can be accessed from both sides of the trolley enabling flexible positioning of image receptors (ArjoHuntleigh, 2014). The Lifeguard trolley can be sold with either a standard 65mm mattress or a thicker foam mattress (Bi-Flex) used to reduce pressure sores as described below:

Standard mattress

The Lifeguard 50 trolley is sold with a standard 65 mm deep mattress pad (see figure 15). This mattress is the mattress available on the x-ray department's trolleys where this thesis was conducted. The construction of this mattress is not specified by the manufacturer and no previous published work has been conducted to explore the mattress materials and how they differ from general x-ray mattresses that are used on x-ray tabletops (ArjoHuntleigh Healthcare, UK).

Bi-Flex mattress

ArjoHuntleigh's Healthcare offers an alternative mattress that is compatible with the Lifeguard 50 trolley at additional cost. This mattress is known as the Bi-Flex pressure re-distributing mattress which is double the thickness of the standard mattress (130mm) (see figure 16). This Bi-Flex mattress is required for areas such as the emergency department where patients remain on the trolley for long periods of time. The emergency department would always purchase a Lifeguard trolley with the Bi-flex mattress due to tissue viability concerns (Dawkins, 2012). According to ArjoHuntleigh' Healthcare UK, this mattress has been developed using two layers of foam, with the base layer made of higher density foam whilst the top layer is made from lower density foam. This mattress construction has resulted in a comfortable and more stable design, which maximises pressure redistribution, thereby reducing the likelihood of pressure ulcers. ArjoHuntleigh Healthcare UK stated that this mattress has been tested for x-ray translucency but this statement was not supported by empirical evidence and therefore cannot be translated into clinical practice (Lifeguard trolley range, ArjoHuntleigh, UK).

Due to the limited manufacturer information regarding the specific materials and density of these two mattresses above (standard and Bi-Flex), a small preliminary experiment was conducted prior to the main experiment in order to discover their attenuating properties. This experiment was carried out in the same x-ray room using the same equipment as for the main experiment whereby the two trolley mattresses (standard and Bi-Flex), the x-ray tabletop mattress and the use of 'no mattress' was compared.

The experiment was conducted on the Lifeguard 50 trolley using a 10cm Perspex block to simulate an attenuating dense object (similar to a patient) with the mAs determined from

the given AEC value using no mattress and 66kVp. The AEC in this situation gave an mAs of 4 which was then used throughout this small experiment. Dose measurements were performed at the centre of the image receptor position (which is on an elevated platform) in order to determine detector dose. The measurements were made using an Unfors Calibartion device (Unifors Equipments US) with the dose measurement taken in microGrays (µGy). Three reading were taken for each measurement and the average calculated. The results were as follows:

- On average, there was a 14% difference in detector dose between no mattress and Bi-Flex mattress (see figure 13)
- On average, there was an 8% difference in detector dose between the x-ray tabletop mattress and Bi-Flex mattress.
- On average, the was a 7% difference in detector dose between both trolley mattress (standard v Bi-Flex)
- On average, there was no % difference in detector dose between x-ray table top mattress and standard mattress

Note* Standard deviation was negligible for the above values and are therefore not visible on figure 13

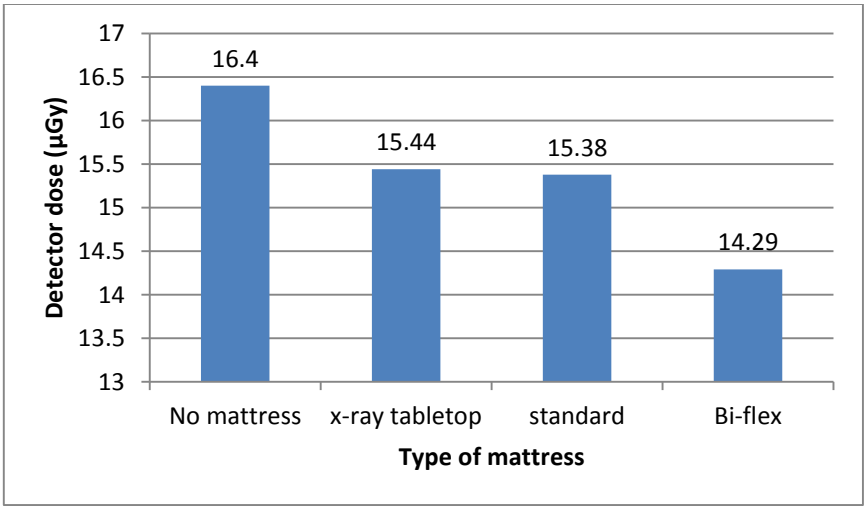

Figure 13 – figure demonstrating the difference in detector dose between different types of mattresses

Detector dose is the dose received by the image receptor to form the image after absorption and penetration through the patient and other objects in the path of the beam, With this and

the results of the small experiment in mind, it can be seen that the thicker Bi-Flex mattress absorbs more of the primary beam than the other mattresses (Hess & Neitzel, 2012).

For this thesis, both the standard (65mm) and Bi-Flex (130mm) mattresses were used for comparison.

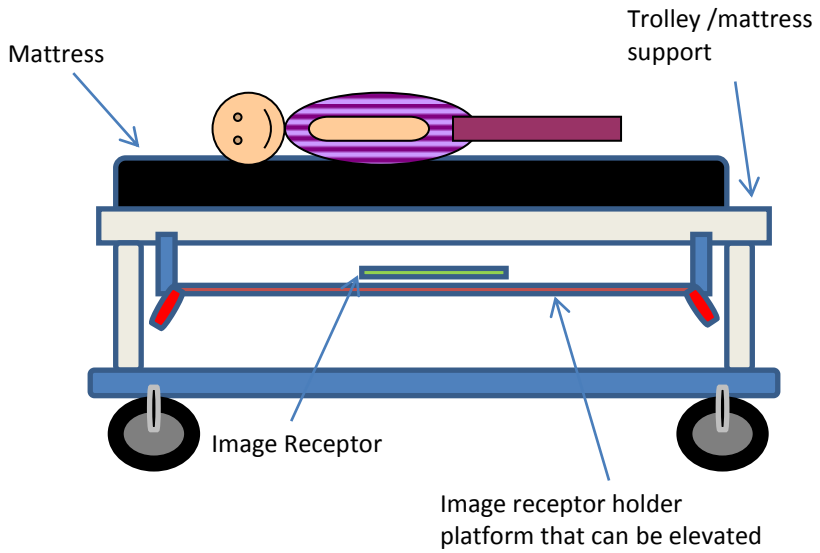

Figure 14 - diagram of key components of the Lifeguard 50 trolley

Figure 15 - the Lifeguard 50 trolley with the standard 65mm mattress (ArjoHuntleighs Healthcare, UK)

Figure 16 - the Lifeguard 50 trolley with the Bi-Flex pressure redistributing mattress (ArjoHuntleighs Healthcare, UK)

4.2.5 Anthropomorphic phantom

As already discussed in section 3.8 of the literature review on page 72, the harmful effects of radiation restricts research involving patients and therefore anthropomorphic phantoms are commonly used instead as they simulate human anatomy and permit unlimited exposures to be performed on them. Anthropomorphic phantoms allow for a comparable evaluation and analysis of image quality and/or radiation dose (Winslow et al., 2009).

For this study, a pelvic anthropomorphic phantom (Rando SK250 sectional lower torso) was utilised (see figure 17). This phantom is made of tissues-equivalent materials with a human natural skeleton embedded inside simulating the real human body (Phantoms, 2014). The phantom includes the lumbar vertebrae, pelvic girdle, upper third of the femora and a hollow space in the midline reproducing the sigmoid flexure (see figure 18).

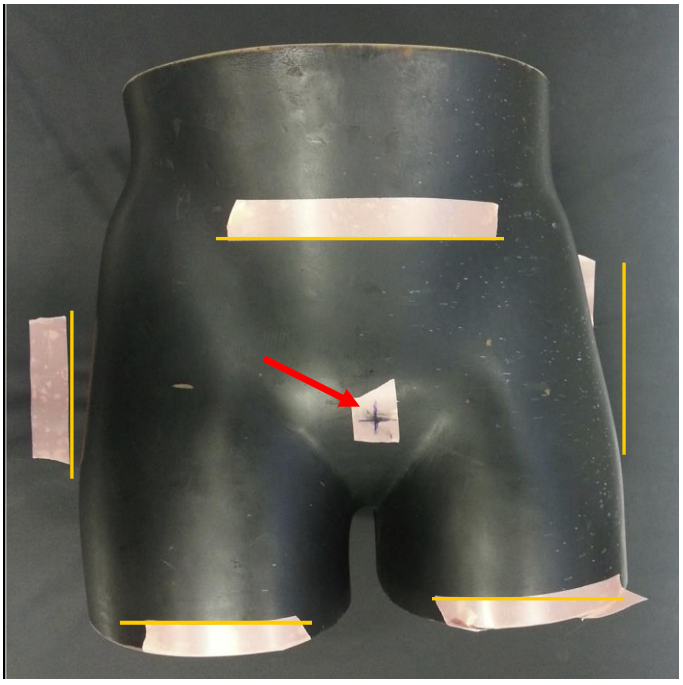

Figure 17 - anthropomorphic pelvis phantom used for the study, which is marked with a centring point (red arrow) and collimation borders (yellow lines)

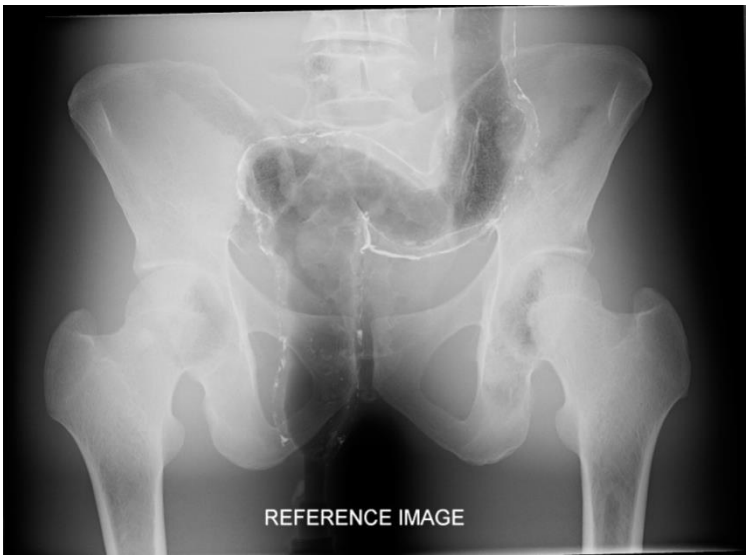

Figure 18 - AP pelvis acquired on the Rando SK250 sectional lower torso

4.2.6 Display monitors and ambient light conditions

High quality 24.1 inch NEC (EA243WM) monitors with a resolution of 5 megapixels was used to display the images for both visual evaluation and for making physical measures of image quality. This monitor resolution is generally used to interpret clinical images with their specification meeting the minimum requirements for primary diagnostic display devices used for clinical interpretation and recommended by The Royal College of Radiologist (2012b). Monitors were calibrated for Digital Imaging and Communications in Medicine (DICOM) grayscale standard display function which was also to the recommended specification of the Royal College of Radiologists (2012). To determine the dual screen's display quality consistency a visual pattern check proposed by the AAPM in report 93 was undertaken prior to each observer undertaking a visual evaluation of image quality (Samei et al., 2005a). Lighting conditions were maintained at a dimmed and consistent ambient level throughout the visual image quality experiment in accordance with the European Guidelines on Quality Criteria for Diagnostic Radiographic Images (Allen et al., 2013).

4.3 Imaging technique

All images were acquired using a Rando SK250 sectional lower torso anthropomorphic pelvis phantom as discussed above. The phantom was positioned on the x-ray tabletop and

on the trolley as for a standard supine AP pelvis examination consistent with Williams (2006), ensuring the median sagittal plane was coincident with, and at right angles to the tabletop and trolley top (see figure 19). Centring point and collimation were fixed throughout the experiment and therefore were marked with adhesive surgical tape on the phantom's surface to improve repositioning and thus consistency (see figure 17). The centring point was fixed in the midline, half way between the ASIS and the upper order of the symphysis pubis in accordance with educational textbooks including Carver and Carver (2012) (see figure 17)

Figure 19 - images demonstrating the positioning of the phantom for an AP pelvis on the trolley with the image receptor placed on the platform below.

4.3.1 Reference image

The reference image was acquired on an x-ray tabletop to allow for comparison to the experimental images acquired on the Lifeguard 50 trolley. The acquisition parameters used to acquire the reference image on the x-ray tabletop were those typically employed in clinical practice and recommended in various published work as demonstrated in table 3.

Reference image	Parameters used
kVp	75
SID	110cm
mAs	AEC dependent
AEC	Outer (cranially orientated)
Grid	Movable (70cm-^{1},12:1 ratio)
Focal spot size	1mm (Broad)
Filtration	3.2mm Al equivalent

Table 3 - acquisition parameters used to acquire the reference image

The kVp used to acquire the reference image was 75 as this is widely used in clinical practice, in accordance with Aldrich, Duran, Dunlop and Mayo (2006), within the recommended range suggested by Carver and Carver (2012) and the CEC quality criteria(1996) and also commonly used in optimisation studies for AP pelvis (England et al., 2015; Harding et al., 2014). A 110cm SID was employed as it is standard practice in the hospital where the current experiment was conducted and is consistent with other studies including Lanca et al. (2014) and Woods and Messer (2009) who used the same SID for their AP pelvis reference image. The SID (110cm) was also within the recommended range of Bontrager and Lampignano (2014) and the CEC (1996). Outer AEC chambers were selected for the reference image and directed toward the 'head-end' of the phantom (cranially orientated). This position is widely used in clinical setting (Williams, 2006; Shephard, 2003; England et al., 2015; Heath et al., 2012; Chan & Fung, 2014) and the use of the AEC for AP pelvis is recommended by both the CEC (1996) and the ICRP (2005). The use of the AEC determined the mAs of the reference image which was 16 in this case. The grid incorporated into the tabletop Bucky was used for the acquisition of the reference image. This grid was a generic oscillating grid with a strip density of 40 lines/cm and a 12:1 ratio (Manning-Stanley et al., 2012). Broad focal spot size of 1mm was selected in accordance to Lanca et al. (2014) and Heath et al. (2011).

To summarise, the reference image was acquired using a 110cm SID, outer AEC chambers, 75kVp, an oscillating grid mounted into the x-ray table Bucky and a broad focal

spot size (1mm). These acquisition parameters are consistent with standard practice and are pre-programmed into the system at this particular clinical area. The word ‘standard practice’ or ‘standard acquisition parameters’ is a recognised term and used in optimisation literature including Lorusso et al. (2015) and Kroft et al. (2007) to describe what is already common practice in their clinical institution.

4.3.2 Experimental image acquisition conditions

Image	Mattress type (Bi-Flex/Standard)	Platform position (elevated/not elevated)	mAs	Grid (Y/N)	SID (cm)
Ref	Tabletop	n/a	16	Y	110
1	**St**	**elevated**	**16**	**Y**	**110**
2	**St**	**not elevated**	**16**	**Y**	**110**
3	St	elevated	20	Y	110
4	St	not elevated	20	Y	110
5	St	elevated	25	Y	110
6	St	not elevated	25	Y	110
7	St	elevated	32	Y	110
8	St	not elevated	32	Y	110
9	St	elevated	16	Y	120
10	St	not elevated	16	Y	120
11	St	elevated	20	Y	120
12	St	not elevated	20	Y	120
13	St	elevated	25	Y	120
14	St	not elevated	25	Y	120
15	St	elevated	32	Y	120
16	St	not elevated	32	Y	120
17	St	elevated	16	Y	130
18	St	not elevated	16	Y	130
19	St	elevated	20	Y	130
20	St	not elevated	20	Y	130
21	St	elevated	25	Y	130
22	St	not elevated	25	Y	130
23	St	elevated	32	Y	130
24	st	not elevated	32	Y	130

Image	Mattress type (Bi-Flex/Standard)	Platform position (elevated/not elevated)	mAs	Grid (Y/N)	SID (cm)
25	**Bi**	**elevated**	**16**	**Y**	**110**
26	**Bi**	**not elevated**	**16**	**Y**	**110**
27	Bi	elevated	20	Y	110
28	Bi	not elevated	20	Y	110
29	Bi	elevated	25	Y	110
30	Bi	not elevated	25	Y	110
31	Bi	elevated	32	Y	110
32	Bi	not elevated	32	Y	110
33	Bi	elevated	16	Y	120
34	Bi	not elevated	16	Y	120
35	Bi	elevated	20	Y	120
36	Bi	not elevated	20	Y	120
37	Bi	elevated	25	Y	120
38	Bi	not elevated	25	Y	120
39	Bi	elevated	32	Y	120
40	Bi	not elevated	32	Y	120
41	Bi	elevated	16	Y	130
42	Bi	not elevated	16	Y	130
43	Bi	elevated	20	Y	130
44	Bi	not elevated	20	Y	130
45	Bi	elevated	25	Y	130
46	Bi	not elevated	25	Y	130
47	Bi	elevated	32	Y	130
48	Bi	not elevated	32	Y	130

Table 4 - the acquisition conditions for all images within the main method (with images highlighted in blue demonstrating the images acquired using the same acquisition parameters as the reference image).

Once the reference image was acquired, the experimental images were acquired on the Lifeguard 50 trolley in various imaging conditions. Images were acquired using two mattresses (standard 65mm and Bi-Flex 130mm) for comparison. The trolley also has an image receptor holder (platform) which should be elevated prior to an exposure to reduce object to image distance (OID). See section 3.1.4 above on page 20 for clarification. In clinical practice, this platform should always be elevated, however, after conducting the

current practise questionnaire (discussed in section 3.2 on page 28), it was apparent that radiographers do not always ensure that the platform is elevated. For this reason, images were acquired with and without the elevation of the platform for comparison. All images were acquired with a commercially available stationary grid (Lysholm, Sweden) with a grid ratio of 10:1 and strip density of 40 lines/cm (Sandborg et al., 1993). This was employed due to the unavailability of the oscillating grid (situated within the x-ray tabletop Bucky) when imaging on the trolley. Initially, images were to be acquired with and without a grid for comparison however this idea was eliminated following the preliminary experiments. Table 4 highlights (blue) four images which were acquired using the same acquisition parameters as the reference image. These four images were analysed separately in order to explore whether the imaging acquisition parameters used for x-ray tabletop imaging were directly transferable to trolley imaging for AP pelvis.

The *current practices questionnaire* by Tugwell (2014) revealed that some radiographers for trolley imaging would double their mAs for chest and pelvis examinations from the exposure factors recommended for x-ray tabletop imaging. For this reason, it was decided that four different mAs settings would be used for the main method in order to evaluate the effect of this practice highlighted by Tugwell on image quality and radiation dose. The initial mAs used was derived from the AEC reading of the acquisition parameters used to acquire the reference image which was 16. Lanca et al. (2014) and Tugwell et al. (2014) used the same principle for their AP pelvis studies where the average mAs value derived from the AEC system was used for their initial manual exposure (reference). The other mAs values used for this thesis were 20, 25 and 32 which are the customary increments found on control panels with 32mAs being double the mAs used to acquire the reference image (16mAs).

Three different SIDs of 110cm, 120cm and 130cm were used for this study, the latter two were used to compensate for increased OID and thus reduce magnification on the resultant images. According to Carver and Carver (2012) increasing SID to compensate for OID reduces image magnification and improves geometric unsharpness. By keeping the three SID's identical for all imaging conditions allowed for easier comparison of results. A 110cm SID was used the same as for the reference image with a 120cm and 130cm used to reduce magnification but also to help reduce radiation dose as found by Heath et al. (2011), Woods and Messer (2009) and Tugwell et al. (2014). A 130cm SID was considered the

maximum practical and achievable SID to use due to the effective range of the stationary grid with regards to grid cut off. Also Heath et al. (2011) and Tugwell et al. (2014) found that image quality started to deteriorate at higher SID values. Initially, only two SID values were going to be used: a 110cm, being the same as the reference image and one other SID where the OID of each trolley imaging condition was added to the 110cm SID in order to compensate for each condition independently. It was already established before the pilot study that this method would not compensate for magnification in some conditions because OID was too large and it would be physically impossible to achieve the required SID for some conditions to keep magnification identical to the reference image. Nevertheless, it was still considered and experimented upon during the pilot phase (see section 5.10 for further details).

Collimation was adjusted to the region of clinical interest for each SID to include the iliac crest, greater trochanters and proximal one third of the femora in accordance with Carver and Carver (2012) as demonstrated on the resultant image in figure 20. This area of clinical interest was marked with tape in order to maintain the collimation size for all exposures (figure 16). This allowed for the same area of coverage at the surface of the phantom to ensure the collimation did not affect radiation dose or image quality. Collimation was therefore adjusted accordingly when SID was increased because the amount of scattered radiation hence patient dose varies when different volumes of tissue are irradiated (Davey & England, 2015).

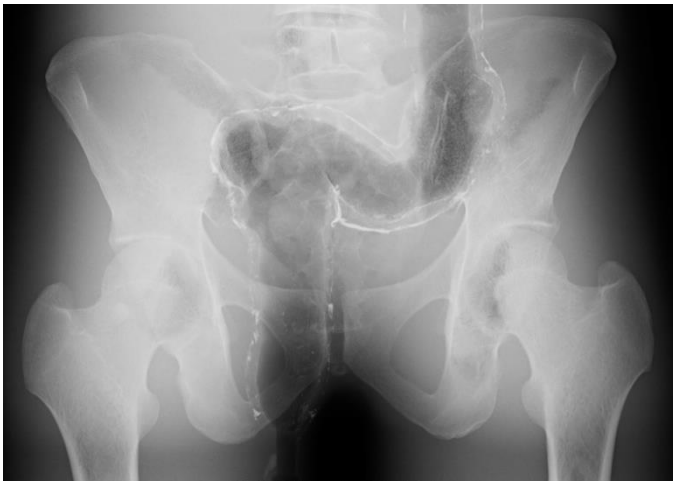

Figure 20 -figure demonstrating the anatomy included within the collimation borders (greater trochanters, iliac crest and upper third of femora)

4.3.3 Post processing

The images were post-processed digitally by the computer system using Fuji auto processing mode that adjusts both the density and contrast accordingly (Fujifilm Medical Systems, USA). Before the examination is undertaken, the radiographer selects the anatomical region for the radiographic exposure; this predetermines the post processing function based on the area which is being imaged. Post processing is generally undertaken automatically by the computer system and is called 'auto mode processing' by Fujifilm. The automatic processing samples the image data on the image receptor and uses the Exposure Data Recognizer (EDR) to determine optimal imaging conditions for viewing. This is achieved by creating a histogram from the raw image data of useful signal levels to determine the final pixel values that is consistent with the anatomical region of interest predetermined prior to the exposure, which was an adult AP pelvis for this thesis (Lo & Puchalski, 2008). Once the image has been automatically post-processed, no alteration was permitted i.e. no adjustment of window width and level was allowed during the experiment. Digital imaging has created many possibilities when it comes to post processing, with capabilities such as filters and density values to enhance and change the appearance of the image, although these are beyond the scope of this study.

4.4 Visual evaluation of image quality

Visual evaluation of image quality using observer performance methods can be grouped into two categories: observer performance methods based on lesion detection or methods based on visibility of anatomical structures/bony landmarks of interest (dependent upon the area being imaged) (Tingberg, 2000). Both of these methods are described in detail above in section 3.7 on page 61. Observer performance methods based on lesion detection are usually carried out using receiver operating characteristics (ROC) methods or eye tracking methods whereas methods based on visibility of anatomical structures are typically conducted using visual grading analysis (VGA) (Manning et al., 2006). Forced choice methods i.e. 2AFC or mAFC can be applied to both lesion detection tasks and the methods based on visibility of anatomical structures. 2AFC is a widely and successfully used method in optimisation studies (Tugwell et al, 2014; Lanca et al., 2014, Yu et al., 2013; Ma et al. 2014).

A VGA method using a reference image as a comparison to the experimental images is called relative VGA. This requires the evaluation of the visibility of anatomical structures against the same structures within the reference image. VGA can also be carried out on an absolute scale with no comparison image. This means the visual perception is based on an independent assessment thus increasing the likelihood of bias since different observers may have different opinion or expectancy of image quality (Tingberg et al., 2000). In a study by Tingberg et al. (2004) it was found that in repeated readings of the same images using an absolute VGA method, the radiologists changed their opinion on the visibility of a structure in about one in four, on average. It is noted that the relative VGA method, where the experimental images are compared to a reference image, provides much more consistent results and leads to less decision variability in comparison to the absolute VGA method. Tingberg et al. (2004) supports this and suggested that VGA is sensitive to small changes in image quality, especially if paired images are used.

4.4.1 2AFC/ relative VGA method

When considering the evidence from section 3.7 and the above paragraph, a 2AFC task in conjunction with relative visual grading analysis was used for this thesis, where a known target (which is the reference image) was distinguished from a known alternative (the experimental images acquired on the trolley in various imaging conditions). This method was chosen for this study as it is sensitive to small changes in image quality and has found to be easy and quick to complete, offering additional consistency in responses when compared to other simple visual grading methods (Lanca et al., 2014; Tingberg et al., 2004). According to Mantiuk et al. (2012), it is also time-efficient and reduces bias in comparison to other methods since it has the smallest measurement variance. This is because the reference image serves as a fixation point in the rating scale for the observers rather than the quality of the images being based on subjective and inconsistent impression of quality (Tapiovaara, 2006; Månsson, 2000).

Observers were presented with two images simultaneously on dual monitors, one a reference image (x-ray tabletop image) and the other a comparison (experimental trolley images). The observers were required to score the comparison image(s) against the reference image using a visual grading scale and image criteria discussed below. As

indicated in section 4.2.6 on page 86, two side by side 5 megapixel monitors (as per guidance with the IPEM (Hiles et al., (2005; RCR, 2012b)) were used for this study with the reference image remaining in the left monitor and all other acquired images (comparisons) displayed in random order in the right monitor.

4.4.2 Image quality criteria

The 2AFC method was used in conjunction with image quality criteria. These consist of items or statements regarding anatomical structures of different radiographic projections. By providing observers with a set of items/criteria, it reduces bias, variability and subjectivity as it focuses their attention upon specific features within the image (Thornbury, Fryback, Patterson & Chiavarini, 1977, Vucich, 1979; Dobbins 2000). Until recently, The CEC (1996) was responsible for the only published criteria for visual image quality assessment. This is why their criteria has been utilised in many studies that assess visual image quality including Allen et al. (2013), Davey and England (2014), Chan and Fung (2014) and Mekis et al. (2010). Nevertheless, the CEC quality criteria were developed in an era of film, therefore many of the criteria do not apply in the digital environment, and other important aspects of image quality relating to digital imaging are missing.

Recently, Mraity (2015) generated a new psychometric image quality scale for AP pelvis. This scale was systematically developed using a robust methodology, ensuring internal reliability and validity. The internal consistency of the scale was assessed by Cronbach's Alpha coefficient with any item/criteria scoring less than 0.7 excluded. The initial scale comprised of 24 items, all items having a Cronbach's Alpha coefficient of between 0.803 and 0.913 demonstrating a high level of internal reliability. The number of anatomical items within the scale was 15 (out of 24). These items relate to how clearly a given structure is visualised in an image whereas the remaining nine items relate to procedural and technical factors. These nine items were excluded for this study since according to Mraity et al. (2013, 2015) removing the nine items does not adversely affect the scale's psychometric properties. The compact correlation factor was found to be high for these 15 remaining anatomical items (0.7-0.9) reflecting a good construct reliability. Mraity et al. (2013, 2015) supports the use of the shorter 15 item scale and for this reason it was used for this thesis (see table 5).

	Item
Anatomic region	1. The right lesser trochanter is visualised
	2. The right hip joint is visualised
	3. The right iliac crest is visualised
	4. The right greater trochanter is visualised
	5. The left hip joint is visualised
	6. The left lesser trochanter is visualised
	7. The left iliac crest is visualised
	8. The left greater trochanter is visualised
	9. The pubic and ischial rami are visualised
	10. The proximal femora are demonstrated
	11. The left femoral neck is visualised
	12. The right femoral neck is visualised
	13. Both acetabula are visualised clearly
	14. The body of L5 is sufficiently visualised
	15. The exposure factors are sufficient
Diagnostic accuracy	**16. This image is sufficient for diagnostic purposes**

Table 5 – visual image quality criteria

To score the items 1 to15 on the image quality criteria, a 5-point Likert scale was used where '1' indicated much worse than the reference image, '2' slightly worse, '3' equal to, '4' better than, and '5' much better than the reference image. This meant that the image quality scores for each image would range from 15 to 75. An image scoring 45 indicated equal quality to that of the reference image (15 items multiplied by 3 'equal' = 45), a score of > 45 was considered an improvement in image quality and anything lower than 45 considered a decrease in image quality. For the image quality assessment, the 2AFC software was set up in a way that observers visualised both the statement and score assigned to that statement e.g. 'slightly worse (2)'. This was clarified to the observers within the task instructions.

An additional item was included at the end of the 2AFC image criteria scale, which was a binary decision (yes or no answer), rather than on a 5-point Likert scale. For this item, the observers considered the diagnostic quality of each experimental image, deciding whether they were acceptable or unacceptable for diagnostic purpose. This was included within the image quality criteria because an experiential image that scores lower than the reference images does not necessarily indicate that it is not sufficient for diagnostic purposes.

4.4.3 Image display

Bespoke software (Hogg & Blindell, 2012) was used to conduct the 2AFC visual evaluation task. The reference image was permanently displayed on the left monitor while the trolley images (experimental) were displayed in random order on the right monitor (see section 6.1 for monitor specifications).The 2AFC software enables the observer scale scores to be captured and subsequently exported to Excel once the task is finished. The observers were blinded to the acquisition parameters of each image. The software also prohibits the observers from adjusting window width or zooming, thereby helping to reduce bias and variability. The above ensured that any differences in visual perception were due to image acquisition parameters rather than post processing. This technique is consistent with Ma et al. (2013).Viewing distance was not controlled or restricted for this study, since this would not reflect what happens in clinical practice. This is consistent with recommendations from Mantiuk et al. (2012).

4.4.4 Observers

The images were analysed visually by five diagnostic radiographers with more than five years clinical experience in accordance to Chan and Fung (2014). In addition, numerous optimisation studies including Lanca et al., (2014), Reis et al., (2014), Ma et al. (2013), Allen et al., (2013) used five radiographers as observers in their image quality assessment. Burgess (2011) suggests the need for approximately four trained observers to carry out this type of assessment; however no literature exists to indicate the definitive number of observers required for visual image quality assessment. Obuchowski (2004) did however suggest that for a phase 1 studies, where a new diagnostic technique or test is explored, that 3 observers are ideally required to allow for inter-observer comparison. Ludewig, Richter

and Frame (2010) also commented that the reliability of visual image quality assessments may be improved by using multiple observers and averaging their scores.

Radiographers who work in the general diagnostic department were invited to take part. It was important that the observers worked in general x-ray and evaluated image quality as part of their daily responsibilities rather than a radiographer who worked in specialised areas such as CT or MRI and had limited time spent in the general department visualising x-ray images. Radiographers were chosen as observers since they acquire and subsequently assess image quality using their professional judgment to decide whether they are diagnostic or not. According to the SCoR (2013b), radiographers make important clinical decisions based on careful consideration of all factors pertinent to the examination. In addition, for trolley imaging, the interpreters, that being a radiologists or an emergency department medical practitioners, do not see the images immediately and therefore it is the radiographer who makes the initial clinical decision regarding the diagnostic quality of the images. It was therefore felt appropriate to recruit experienced radiographers to assess the image quality for this thesis.

Before the image quality analysis commenced, each observer undertook a training session, which included using the 2AFC method to evaluate five randomly selected images from the available 48 experimental images. A training session was suggested by Mantiuk, Tomaszewska and Mantiuk (2012) as it allows observers to familiarise themselves with the task and typical images but it also allows them to ask questions to clarify their role before commencing the main experiment/task. The observers were also presented with a set of instructions regarding the image quality task. Lastly, due to the number of images and the number of items to score, the observers were permitted to take a short break after assessing half of the data set in order to minimise the effect of tiredness and fatigue on their eyes (Alers, Bos & Heynderickx, 2011). According to Pinto and Brunese (2010), perceptual errors, in general, are related to various psychophysiological issues, including level of observer alertness, observer fatigue, duration of the image quality task and any distracting factors.

4.5 Ethical issues

Ethical approval was granted from The Ethics Panel of the University of Salford since five observers were required to complete the image quality assessment (see appendix II). Observers were approached by invitation letter and a participant information sheet. Once the observers agree to participate in the study, they signed a consent form to acknowledge that they fully understood what was required of them (see appendix III). This experiment was in compliance with statutory regulations (IRMER) at the hospital where it was conducted.

The study was conducted taking into account all ethical issues ensuring compliance with the Declaration of Helsinki and with Good Clinical Practice (GCP). The study has also been guided by the Professional Conduct published by the Society and College of Radiographers (2013a). The researcher complied with the requirements of the Data Protection Act (1998) with regards to the collection, storage, processing and disclosure of personal information. All observers were given a unique study number and no personal details were retained. Data arising from the 2AFC task was stored on password-protected computer.

4.6 Contrast to noise ratio (CNR)

Visual evaluation of image quality was the main outcome measure for this thesis as it simulates more closely the observations made on images in clinical practice. Nevertheless an objective physical measure of image quality was also derived to support this visual data by means of calculating CNR. The primary quality-related features in imaging are contrast, sharpness and noise and therefore CNR is considered a good reflection upon two of these factors related to the quality of an image. CNR has been used successfully as a measure of image quality in various optimisation studies (Hess & Neitzel, 2011, Mori et al., 2013, Martin 2007). In comparison to SNR, CNR takes into consideration the effect of noise on our ability to distinguish objects within the image because visibility depends on contrast (the difference between signals). A highly exposed image may have a high SNR but show no useful information on that image (Vladimirov, 2010). CNR does not however include the display and observation steps of the imaging process and therefore does not truly reflect what happens in clinical practice. This is why it was used only to support the data

acquired from the visual image quality assessment. In addition, Martin (2007) who successfully measured CNR conducted the study using film/screen and therefore caution must be taken when translating his findings to current practice which is now predominantly digital systems.

CNR was calculated by placing a region of interest (ROI) on two contrasted homogeneous structures within the anthropomorphic pelvic phantom images in order to sample the mean and standard deviation of the pixel value. The ROI was placed in the same position for all acquired images in accordance with Bloomfield et al. (2014) to allow a consistent value for comparison. In order to maintain a consistent ROI, magnification was considered and ROI adjusted to ensure the same anatomy was sampled for all images. This meant that femoral head diameter and thus magnification calculations (as discussed in the next section 5.7) had to be performed prior to calculating CNR in order to inform the ROI adjustment. This was done because using the same size ROI for all images would induce a level of inaccuracy to the CNR measurements since the anatomy sampled within that ROI would vary depending on the magnification level of the images.

Image J software (National Institutes of Health, Bethesda,MD) was used to calculated CNR; a software tool used regularly in literature for similar calculations (Lanca et al., 2014; Desai et al., 2010; Jang et al., 2011). ImageJ is an open source image processing tool that is widely available and portable (Desai et al., 2010). It establishes the mean pixel values (signal) and the standard deviation (noise) for the ROI (Sun et al., 2012).The following equation was then used to determine CNR:

$$C = \frac{|S_A - S_B|}{\sigma_o}$$

Where S_A and S_B are signal intensities for signal producing structures *A*(*ROI1)* and *B (ROI2)*and σ_o is the standard deviation (blue ROI) of the pure image noise (see figure 21)

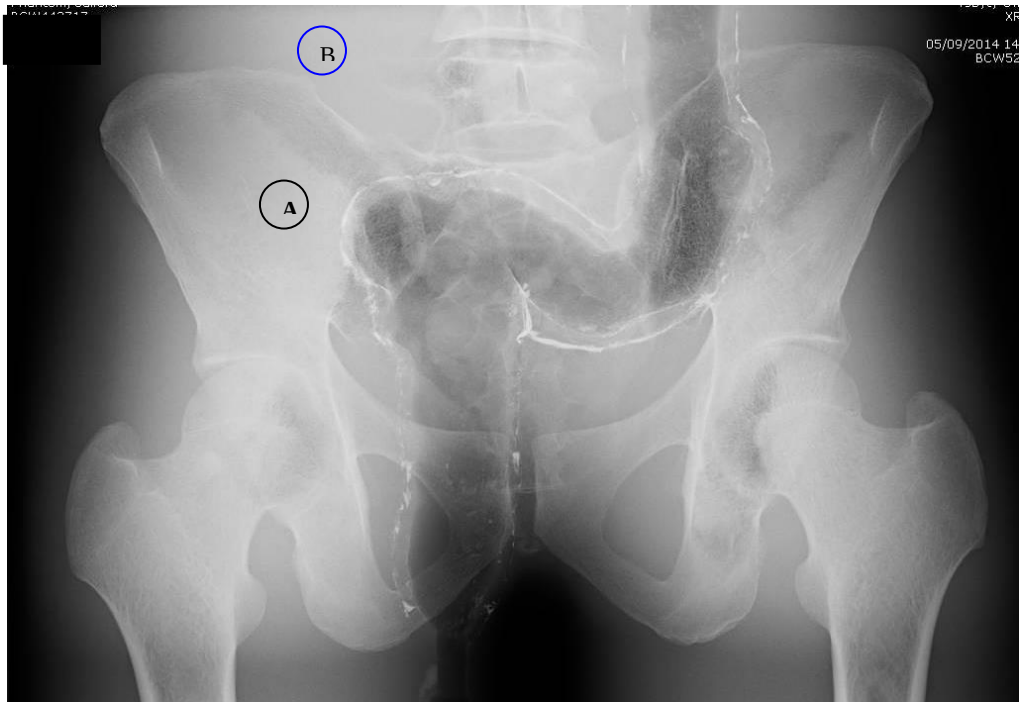

Figure 21 – image demonstrating the two different ROI (circle) locations used to calculate CNR with the blue circle situated in the background and black circle situated within the right iliac crest.

4.7 Magnification

Magnification factor was derived for all images as displayed in PACS to compliment the data on visual image quality. The right femoral head diameter (FHD) was measured in millimetres by one radiographer with experience in pre-operative hip arthroplasty templating. The femoral head of each image was measured eight times and the average, standard deviation, minimum and maximum values were then calculated (see figure 22). These measurements were made eight times, since according to Taylor (1997), the effects of random uncertainties can be reduced by repeated measurements. The measurements were carried out using the ruler (callipers) tool in the Synapse PACS system (Fujifilm, Japan) using the same monitors (5 megapixels) as for the visual image quality assessment task (see section 4.2.6 on page 86). Measurements were performed on all images despite the fact that some images where acquired by changing only the mAs (all other acquisition parameters remained then same) which means magnification level should not differ between these images. Nevertheless, since dose, mAs and image noise are related (lower mAs = increase image noise) the sharpness and visualisation of the femoral head

boundaries may differ between mAs values which would consequently influence the measurements (Woodward, 2011). These measurements made to calculate the displayed magnification are not scaled to 'real size' and therefore cannot be used to predict and plan internal fixations prior to orthopaedic surgeries. These measurements are an indication of the displayed magnification when observers visualise the images. No cropping was permitted post processing and therefore the displayed magnification would only be influence by acquisition parameters used to acquire the images.

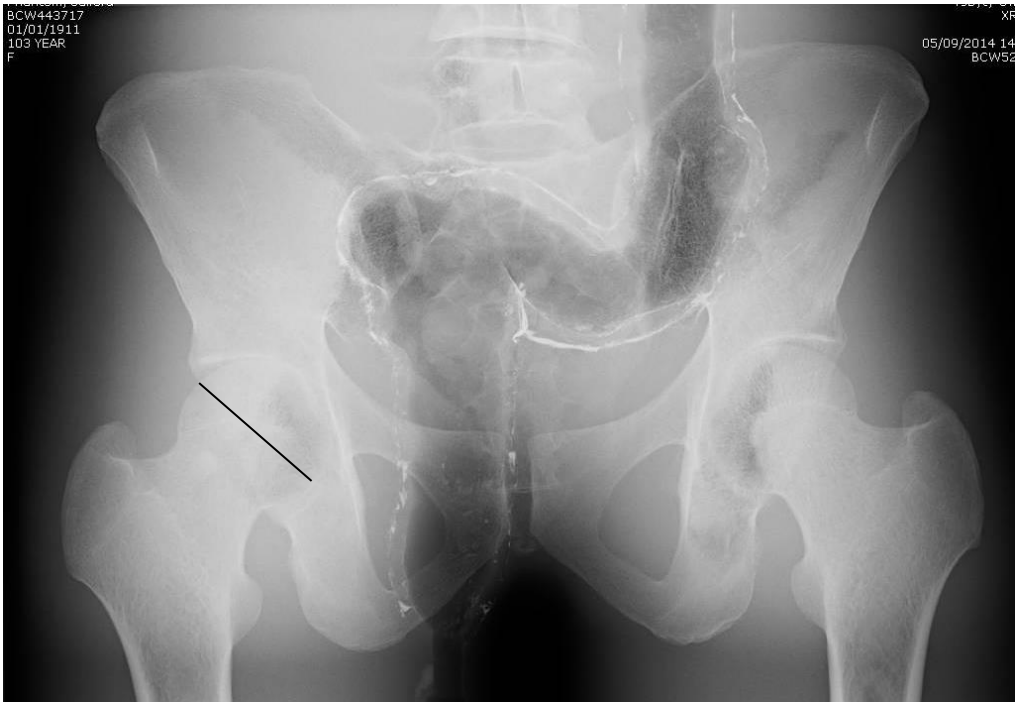

Figure 22 - right femoral head diameter measurement

4.8 Radiation Dose calculations

4.8.1 Entrance Surface Dose (ESD)

ESD was measured at the surface of the phantom at the centre of the collimation field using the UnforsMult-O-Meter 407L ionising chamber (Unfors Equipments, Billdal, Sweden). TLD's were considered for this thesis however they can be time-consuming to read whereas ionising chambers give quick and direct instant measures. Although TLD's are more sensitive to small amounts of radiation such as scatter, this was not an issue for this thesis as the dose measurement was taken from within the primary beam for an AP pelvis exposure. Ionising chambers are criticised due to their bulky nature and thus having

the potential to obscure anatomical details; however, this study used an anthropomorphic phantom which meant that two exposures could be made in equal conditions, one for image quality and the other to calculate ESD. This ensured the field of view was clear of any artefact/objects when image quality was evaluated (Massoud & Diab, 2014); they also have high accuracy and reproducibility with the necessary correction factors well understood (Table 6) (Attix,1986). To enhance the precision of dose measurements and to reduce error, the ESD was measured eight times with the average value and standard deviation calculated. ESD was useful for this project as it took into account the variation in SIDs and OIDs and therefore reflected upon the difference in dose for these imaging conditions. It has also been used successfully in similar projects (Heath et al., 2011; Sun et al., 2012).

kVp RAD	Range (auto)	50-150kVp
Minimum exposure:		7mA at 70kVp, 50cm
Dose R/F Wide	Range (auto)	100nGy-9999GY
Rate R/F Wide	Range (auto)	100 nGy/s -500 mGy/s
Time	Range (auto)	1 ms – 9999s measured with the trigger detector
	Inaccuracy:	0.5%

Table 6 - specification of the Unfors Mult-O-Meter 407L

4.8.2 Effective dose

Effective dose was calculated using Monte Carlo dosimetry simulation software (PCXMC 2.0)(STUK, Helsinki, Finland). This software uses tissue weighting factors of ICRP Publication 103 (2007) to estimate effective dose in milliseverts (mSv). DAP was also used in this estimation along with the acquisition parameters. Collimation size remained constant at the entrance surface of the phantom to ensure the same area of interest was covered and therefore '*beam width'* and *'beam height'* was inputted and remained the same for all experimental imaging conditions (see figure 23). The reliability and accuracy of the PCXMC software in calculating effective dose is supported by literature demonstrating results in close agreement with dose measurements and calculations of other phantom

models (Reis et al., 2014; Schmidt et al., 2000; Helmrot et al., 2007; Poletti & Mclean, 2005) and previously validated against the NRPB.

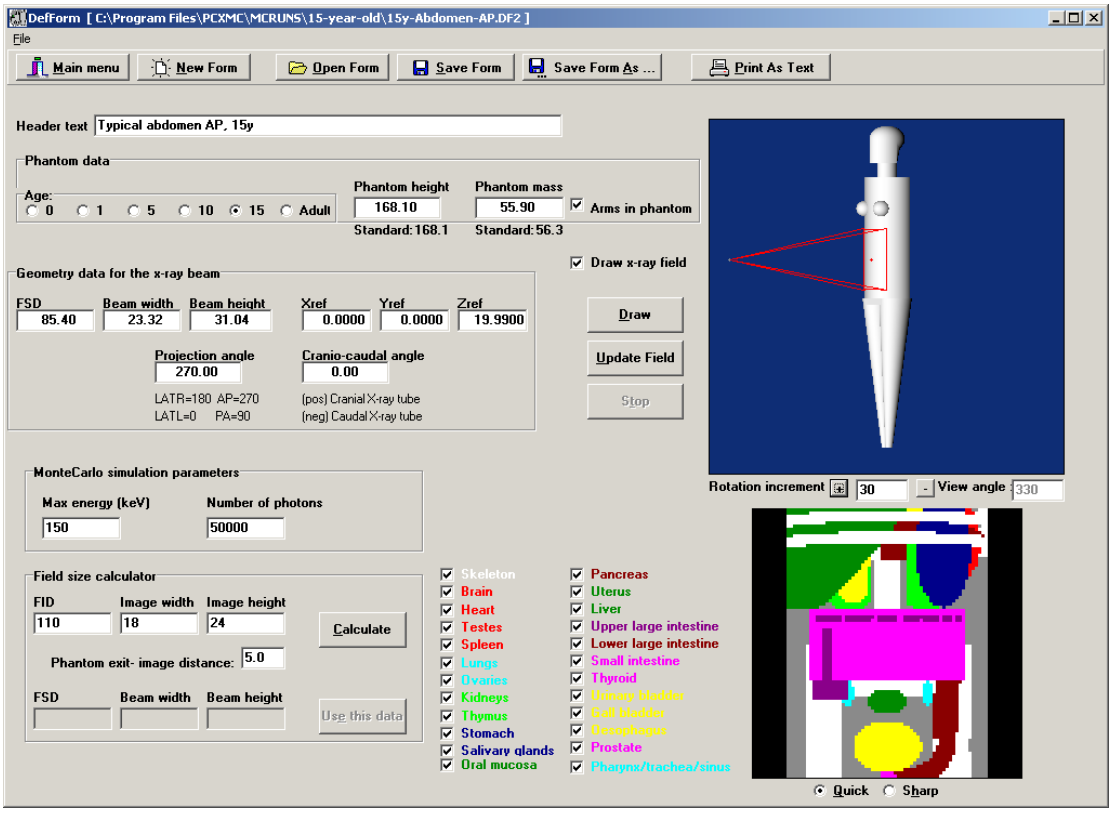

Figure 23 - an example of the x-ray examination data input required for PCXMC (STUK, Helsinki)

4.9 – Optimisation score (figure of merit)

Given the adverse effects associated with ionising radiation, it is important to reduce it where necessary and adhere to the ALARP principle at all times (RCR, 2015). Reducing radiation dose may however compromise image quality since radiation dose controls the amount of image forming photons that are incident and collected by the image receptor. Radiation dose should therefore be optimised in order to maintain adequate image quality for diagnostic purpose but without the radiation dose to the patient being significantly higher than necessary (Allen et al., 2013). Most optimisation studies, for example Tugwell et al. (2014), Lanca et al. (2014) and Ma et al. (2014) consider radiation dose and image quality data separately; however Williams, Hackney, Hogg and Szczepura (2014) proposed a method to combine image quality and radiation dose data where the image quality score is divided by radiation dose to give a figure of merit. This figure of merit would signify an

optimisation score (OS) where a high score would indicate better image quality at lower dose whereas a low score would indicate poorer image quality at higher radiation dose. This method (Image Quality/Effective dose) has been developed from studies that have used similar calculations but using SNR rather than visual image quality scores (Samei, Dobbins, Lo & Tornai, 2005b). As this figure of merit seems a beneficial indicator of the optimal acquisition parameters to be used, the optimisation score of all imaging condition was calculated for this thesis.

4.10 Statistical analysis

All data were inputted into Excel 2007 and transferred to SPSS software package (PASW Statistics 18: version 18.0.2, SPSS Inc., Chicago, IL) for analysis. For the visual image quality data, intra- and inter-observer variability was evaluated by Intra-Class Correlation Coefficient (ICC). A 2-way random effect model for absolute agreement was used for inter-observer agreement whereas a 2-way mixed effect method was used for intra-observer agreement. ICC is used for this thesis because it takes into consideration the differences in scores for individual sections along with the correlation between the observers. In addition, due to the continuous nature of the data, ICC is unaffected by any deviations in mean on retest (Everitt, 1996). The interpretation of inter and intra-observer agreement values can be complex as there are several interpretations available. For this thesis ICC was interpreted using the most commonly used interpretation from Fleiss (1986) and Rosner's (2006, 2010), both who indicate >0.75 as excellent, 0.40-0.75 as fair to good and <0.40 poor (Oremus, Oremus, Hall & McKinnon, 2012; Manning-Stanley et al., 2012; Davey & England, 2014).

Image quality data and radiation dose data (ESD and effective dose) were interpreted in various groupings (e.g. different mattress, different tray position) and subsequently analysed using an independent t-test with a probability level of $p<0.05$ (95%) regarded as significant. Averages, standard deviations and percentage reductions were also used for simple comparisons between and within groups. Pearson's *r* and scatter plots were also used to measure the linear relationship/correlation between visual image quality, CNR and radiation dose whereby a value of 1 indictes a perfect positive relationship, 0 indicating no relationship and -1 indicating a perfect negative relationship. These parametric tests were

chosen as all statistical assumptions were met. The Shaprio-Wilk test in SPSS proved that all the collected data were normally distributed (Ghasemi and Zahediasl, 2012).

4.11Pilot study

Prior to undertaking the main experiment, a pilot study was performed to assess, evaluate, and if required, improve aspects of the proposed method but also to highlight any problems which might have been encountered e.g. the imaging equipment used. van Teijlingen and Hundley (2002) commented that piloting a research method is essential; it provides guidance and information on how to improve and enhance the experiments by pre testing the study instruments and gives advanced warnings regarding an area where the research is likely to fail.

The main method was informed and amended after the conduction of this pilot study with one major change made to the main method. Initially, the plan was to use two different SID setting, one identical to SID used for the reference image (110cm) and another were the OID of each imaging condition was added onto the 110cm SID to compensate for magnification. This latter SID method was ineffective during the pilot study and therefore three SID values were used for the main experiment that were independent of the OID of the imaging conditions. The results and reasons for the above change is highlighted in the following sections:

4.11.1 Exclusion of the mobile x-ray unit

For the pilot study, both the mobile unit and the x-ray room unit were used to acquire images. The mobile unit has a 12.5kW single phase generator, a total filtration of 2.5mmAl, 1.2mm focal spot and an anode angle of 16° (Shimadzu Corporation, Japan). This mobile unit is a state of the art system that has been designed according to radiology requirements including easy manoeuvrability and rapid examination in a variety of situations. The differences between the ceiling suspended x-ray tube and the mobile unit x-ray tube is reflected in table 7. Although the differences in the characteristics of both these units are small, these differences may still cause variation in image quality and radiation dose. For example, a generator controls radiation output and the high frequency generator as seen for the Philips Diagnost x-ray tube will have a more efficient output compared to

the Shimadzu mobile unit and therefore would require lower exposure factors (Johnston & Fauber, 2015). In addition, the difference in total filtration between both units should have minimal impact on image quality however 3.2mmAl filtration would absorb more low energy photons than 2.5mmAl resulting in less absorbed dose by the patient (Trapp & Kron, 2008; Johnston & Fauber, 2015).

	Philips Diagnost	Shimadzu mobile Unit
Generator	50kW high frequency	12.5kW single phase
Broad focal Spot	1mm	1.2mm
Total Filtration	3.2mm Al	2.5mm Al
Anode angle	17°	16°

Table 7 - table demonstrating the difference between the x-ray tube characteristics of the x-ray room and mobile unit

When conducting the pilot study, it was difficult to acquire the images consecutively using the mobile unit due to the high clinical demand of this machine. This study was carried out within a busy district hospital therefore it seemed impossible during the pilot study to acquire all images uninterruptedly and successively without the mobile unit being needed for emergencies. This had major time implications on the pilot study but it also had the potential to cause inconsistency in the imaging conditions as the room and experimental requirements had to be set up repeatedly instead of the images being acquired in one undisrupted session. For this reason the mobile unit was effectively excluded from the main study.

In addition to the above problem, a further rationale for excluding the mobile unit from the main study was because of an additional implication on resources. From a radiation protection requirement the experiments using this mobile unit would need to be conducted within an x-ray room because they are lead lined. This means that two pieces of equipment would be put out of action for the conduction of this study (both the x-ray room and the mobile unit) which would be unreasonable due to their high demand.

Lastly, another reason for excluding the mobile unit was the lack of control over important variables, which may result in error. When undertaking trolley imaging, SID has to be set manually using a tape measure at the side of the trolley (see figure 8). This means the

radiographer has to measure SID at the side of the trolley and then move both the x-ray tube and image receptor in alignment with the patient's area of interest. This was proven difficult with the Shimadzu mobile unit as the button that releases the transverse movement of the tube also realised the up and down movement. This meant that the accuracy and consistency of maintain identical SID for all imaging conditions was difficult as the up and down movement may alter the SID when the tube is re-positioned over the phantom. At this point there is no method available to re-check and determine the SID since the image receptor is in the image receptor holder.

In order to provide evidence for the above problem, a small experiment was conducted following the pilot study to explore the error in achieving a constant SID using the mobile unit and to justify the exclusion of this unit from the main study. Three radiographers were asked to measure an SID of 130cm at the side of the trolley (as they would in clinical practice), and subsequently move the x-ray tube to the desired location over the phantom (centring point). The accuracy of the SID would then be determined by moving the trolley and re-measuring the SID without moving the tube (see figure 24 for results). Carlton and Adler (2013) suggested that radiographers who estimate SID must be within 15 percent to avoid producing a significant exposure difference emphasising the importance of being able to produce consistent acquisition parameters for comparison to be made between the imaging conditions.

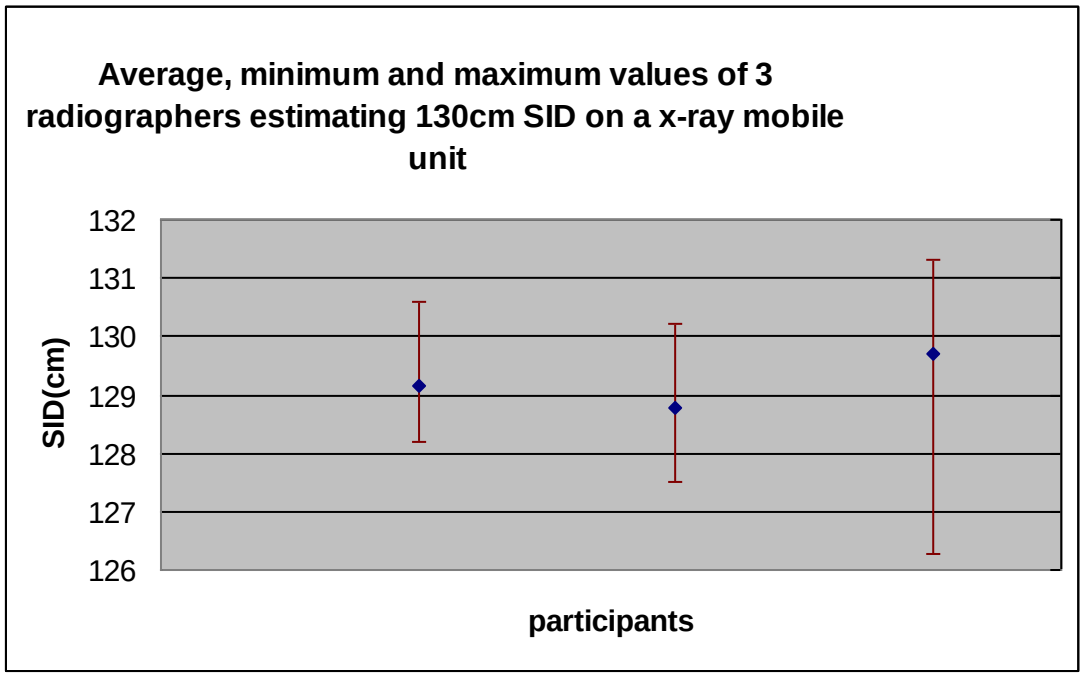

Figure 24 - figure demonstrating the 10 attempt of 3 radiographers to measure 130cm using the Shimadzu mobile unit

Figure 24 highlights the error in achieving an accurate SID using a mobile unit that has a multi release function (button that releases both the transverse and the up and down movement of the tube). Due to the inconsistency seen in figure 24, this was deemed another reasonable factor to exclude the mobile unit from the main study and justify using only the ceiling suspended x-ray tube to acquire all images.

4.11.2 SID changes

For the pilot study, two SID settings were used to acquire images, one using the standard 110cm as used for the reference image and another using an SID that compensated for the OID in each imaging condition (see table 8 for calculations). Chang and Fung (2014) suggested when an air gap is introduced between the patient and image receptor, subsequent increase in SID needs adjusting in order to keep the magnification of the resultant image at a relatively constant and minimal value. For the pilot study this was attempted by adding the OID of the imaging condition to the 110cm e.g. condition using the Bi-flex mattress and platform elevated has a OID of 19cm therefore a SID of 130cm was used (rounded to the nearest 5cm)

Imaging condition					
Tray position	**Mattress**	**OID(cm)**	**SID(cm) (1)**	**OID + SID (1) = SID (2)**	**SID (2) rounded to nearest 5**
Elevated	standard	12.5	110	122.5	125
Not elevated	standard	18.5	110	128.5	130
Elevated	Bi-Flex	19	110	129	130
Not elevated	Bi-Flex	25	110	135	135

Table 8 - method used to calculate the second increased value of SID that compensates for OID.

The proposed method above did not however ensure that all images had identical magnification (varying FHD) and therefore this had to be reconsidered for the main method (see figure 25).

The mathematical equation for magnification factor is:

$$\text{Magnification} = \frac{\text{SOD*+OID}}{\text{SOD*}}$$

*SOD = source to object distance

Using this equation, the magnification level of the reference image is 1.12. If this level was to be achieved for all imaging conditions it would necessitate an SID of 245cm for a magnification factor of 1.29 (when tray is not elevated and Bi-Flex mattress is used), which is unfeasible (see table 9). For the purpose of this demonstration on magnification factor and to emphasise upon the magnification factor of different imaging conditions, the OID was measured from the posterior aspect of the phantom in order for the direct exposure's magnification factor to be zero. Educational textbooks including Whitely et al. (2015), Bushong (2013) and Carver and Carver (2012) show OID measurements being made to an object that is flat (a line). This does not simulate a patient of varying thicknesses. They all however demonstrate the same equation which is SOD +OID = SID and therefore as long as the method of calculating magnification factor uses the measurements of OID and SOD from the same location, it will be valid and consistent.

Condition	SOD(cm)	OID(cm)	Magnification	SID (cm) required
Direct exposure	110	0	1	N/A
Image receptor in Bucky/conventional mattress (REFERENCE)	98.5	11.5	1.12	N/A
1. Image receptor in trolley tray (up) 6.5cm deep mattress	97.5	12.5	1.13	123
2. Image receptor in trolley tray (not elevated) 6.5cm deep mattress	91.5	18.5	1.20	170
3. Image receptor in trolley tray (up) Bi-Flex trauma mattress	91	19	1.21	180
4. Image receptor in trolley tray (not elevated) Bi-Flex trauma mattress	85	25	1.29	245

Table 9 - magnification level/factor for different imaging conditions and the SIDs required to achieve the same magnification level as the reference image level of 1.12.

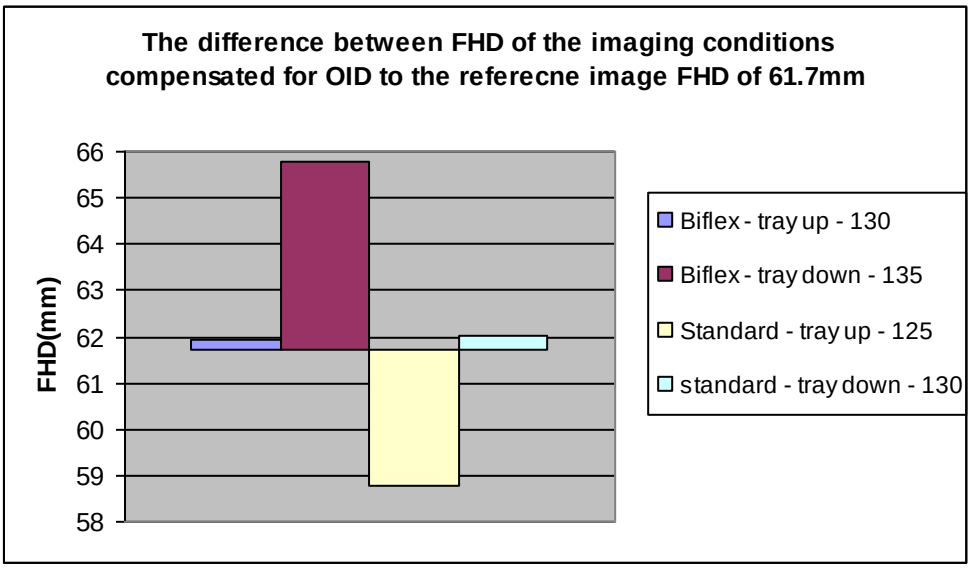

Figure 25 – the influence of the method proposed in the pilot study to calculate the second SID value on femoral head diameter. *FHD (femoral head diameter)

With exception to the two above changes, the pilot study successfully assessed all equipment and software to be used and also confirmed the ease of the visual evaluation task. Two potential observers used the 2AFC software and psychometric scale using eight randomly selected images acquired using different imaging conditions from the main method to assess whether any problems were encountered.

Chapter 5 - Results

5.1 Results Overview

This chapter presents the results. Observer agreement will be considered first (section 5.2) and subsequently the presentation of results will be organised into two main components. The first component (section 5.3) focuses on identifying whether the acquisition parameters used for AP pelvis on the x-ray tabletop (reference image) was appropriate and transferable for imaging AP pelvis on the trolley. As previously discussed, the Lifeguard 50 trolley used for this thesis has two available mattresses and two different image receptor holder position and therefore four images were acquired on the trolley for comparison to the reference image using standard acquisition parameters. The acquisition parameters used for the AP pelvis on the x-ray tabletop and these four trolley images are standard parameters used to acquire AP pelvis in clinical practice and as described in educational textbooks. These included 75kVp, 16mAs, 110cm SID and a broad focal spot size.

The second component of this results section focuses on optimising image quality and radiation dose for AP pelvis on the trolley by identifying the effect and significance of the independent variables (mattresses, image receptor holder position, mAs and SID) on the dependent variables (image quality and radiation dose). This component will be divided into sub sections in order to analyse the effect of the mattress, platform position, SID and mAs separately on image quality (section 5.4), radiation dose (section 5.5), relationship between visual image quality, CNR and effective dose (section 5.6), optimisation score (section 5.7) and magnification (section 5.8). These sections will be presented in the form of tables and graphs to allow a greater understanding on how the independent variables influenced each of these dependent variables.

5.2 Inter and intra-observer agreement for the assessment of visual image quality

Inter and intra-observer agreement was measured using ICC in order to assess the variability between the five observers when evaluating image quality but also between one observer undertaking the task on more than one occasion. For this thesis, observers were

required to set their level of agreement/confidence on how clearly anatomical structures were seen within the images. This approach uses observer judgment and therefore it is highly susceptible to inter-and intra-observer variation (Krupinski, 2010). Intra-observer variation relates to the degree of agreement for one observer when undertaking repeated measurements whereas inter-observer variation is the degree of agreement amongst more than one observer for the same task/measurements (Cheong et al., 2010).

With '1' being perfect agreement, the ICC value for all five observers was 0.8419 (95% confidence interval 0.8137-0.884) implying a high level of agreement (Rosner, 2006). Intra-observer reproducibility was also measured to ensure internal consistency. One observer was randomly selected to repeat the 2AFC task a week following their initial visual evaluation to determine their consistency when evaluating image quality. The ICC value for this one observer was 0.92 indicating an excellent, near perfect reproducibility.

ICC was also calculated for the last image quality criterion (item 16) for this thesis which brought about binary data. The five observers had to decide whether the images being evaluated were diagnostic or non diagnostic (yes/no). The ICC for this criterion was 0.49 (95% confidence interval 0.22-0.69) which indicates fair to good agreement amongst observers when deciding upon whether or not an image is suitable for diagnostic purpose. If observer two and three were excluded from this analysis, the ICC for observer one, four and five was much higher at 0.62 (95% confidence interval 0.40-0.77)

5.3 Data to compare the reference image (x-ray tabletop) and four experimental images (trolley) acquired using identical acquisition parameters

As demonstrated in table 10, when comparing the reference image (x-ray table top) to the experimental images (trolley) acquired using the same acquisition parameters (16mAs and 110cm SID), image quality for both 2AFC and CNR decreased by 13% and 3% respectively; however only the 2AFC results (13%) had a statistically significant decrease ($p<0.05$), (CNR; $p=.012$). In addition, effective dose on average more than doubled (56% average increase) for trolley imaging in comparison to x-ray tabletop using the same

acquisition parameters, again demonstrating a significant difference in patient dose ($p<0.05$). Effective dose calculations should however be carefully considered due to the possibility of error occurring in the method of calculating it and the sample size was fairy small which may have influenced the data. This is further emphasised by the fact that ESD on average was only 22% higher than the reference image ESD yet this was still deemed significant ($p<0.05$). Lastly, magnification increased by 9% from the reference image to the experimental images but with no significant statistical difference ($p=0.93$)

Image condition	mAs	SOD (cm)	SID (cm)	CNR	Effective dose (mSv)	2AFC	Magnification Factor
Reference	16	98.5	110	8.2	0.09	45	60.50
Standard/Elevated	16	97.5	110	7.64	0.12	36.8	60.90
Standard/Down	16	91.5	110	7.99	0.14	38.2	65.67
Bi-Flex/Elevated	16	91	110	8.23	0.15	37.2	65.88
Bi-Flex/Down	16	85	110	7.91	0.16	44	71.27
Average				7.94	0.14	39.05	65.97
Standard deviation				0.24	0.02	3.35	4.24
p-value				p= 0.12	p<0.05	p<0.05	P=0.93
% difference				-3%	56%	-13%	9%

Table 10 - table showing the difference between the results of the reference image and the experimental images acquired with identical acquisition parameters.

5.4 Image quality data for the trolley (experimental) images

For this section, image quality will be considered for all trolley images where forty nine images were obtained, including a reference image and 48 experimental images in various imaging conditions. Four variables were altered in the experiment; these included the type of mattress, SID, mAs and platform position. All other conditions and acquisition parameters were kept constant throughout the experiment.

5.4.1 Data for visual image quality (2AFC)

Visual image quality was assessed by exploring the effect of four independent variables on observer visualisation of anatomical structures within an AP pelvis anthropomorphic phantom. This visual evaluation was undertaken by five observers using a 2AFC method.

Fifteen image quality items were included in the image quality assessment criteria where the visualisation of various anatomical structures was graded on a 5 point Likert scale. In comparison to the reference image, a score of '1' indicated much worse, '3' equal and '5' much better image quality. If all fifteen items on the image quality scale was scored as '3' (equal to) then a total score of 45 for an image was considered equal to that of the reference image. Hence a score of > 45 was considered an improvement in image quality and anything lower than 45 considered a decrease in image quality (see table 12 for mean and standard deviation of image quality scores for all experimental images). Three of the 48 images had a score of ≥ 45 and are highlighted (**underlined**) in table 12. These three images were all acquired using the Bi-Flex mattress with platform not elevated using an SID of a 110cm.

Standard Mattress						
SID(cm)	110		120		130	
mAs	Elevated	Not elevated	Elevated	Not elevated	Elevated	Not elevated
16	36.8 (1.7)	38.2 (0.4)	36.2 (3.5)	37.2 (3)	33.8 (2.5)	35 (3.7)
20	39.8 (1.9)	35.6 (2.3)	38.6 (2.5)	37 (2.6)	34.2 (3.8)	38.2 (2.1)
25	37.6 (4.1)	39.4 (2.6)	34.8 (2.3)	40.6 (1.1)	38.2 (1.9)	35.6 (4.1)
32	41.6 (1.6)	42.2 (2.5)	40 (1.7)	37.4 (2.1)	34.2 (3.9)	37.8 (4.4)
Bi-Flex Mattress						
SID(cm)	110		120		130	
mAs	Elevated	Not elevated	Elevated	Not elevated	Elevated	Not elevated
16	*37.2 (0.9)*	*44 (2.1)*	*36.6 (3.5)*	*40.2 (1.9)*	*33.2 (1.6)*	*35.4 (4.1)*
20	38.8 (2.1)	**45.6 (2.8)**	33.4 (1.1)	42 (2.6)	35.2 (3.2)	36.8 (3.8)
25	41 (2.1)	**45 (3.4)**	35.6 (2.3)	42 (2.6)	35.6 (3.8)	39 (2.3)
32	40 (2.9)	**47.4 (2.3)**	39.6 (1.4)	43 (2.1)	37.2 (1.9)	39.2 (3.2)

Table 11 - the mean and standard deviation values of image quality scores for all imaging conditions which includes the two different mattress (standard and Bi-Flex) and the image receptor holder position (elevated or not elevated), *note that 45 was the reference image's score

As seen above, only three of the experimental images have the mean image quality score equal to or more than reference image (see table 11). Interestingly, of all acquired images, these three images have the highest level of magnification with their femoral head diameter

increased by 10.78mm (18%) compared to the reference image (see table 15 for magnification results).

Image quality scores (Y axis) for the two different mattresses are shown in figures 26 and 27 using a box and whiskers plot where the blue line represents the reference image quality score. These box and whiskers graphs represent the mean (orange triangle), median, maximum and minimum value plus the upper and lower quartile values. The median image quality scores are represented by the line in the centre of the box, while the upper quartile represents the 75thpercentile above the median, whereas the lower quartile signifies the 25th percentile below the median. The maximum and minimum values (whiskers) demonstrate image quality at farthest values for each imaging condition. The mean image quality values scored above the reference image (reference image represented by the horizontal blue line) suggests improved image quality; whereas values below this line indicate a decrease in image quality. The acquisition parameters used for the images on the X axis is summarised in table 12.

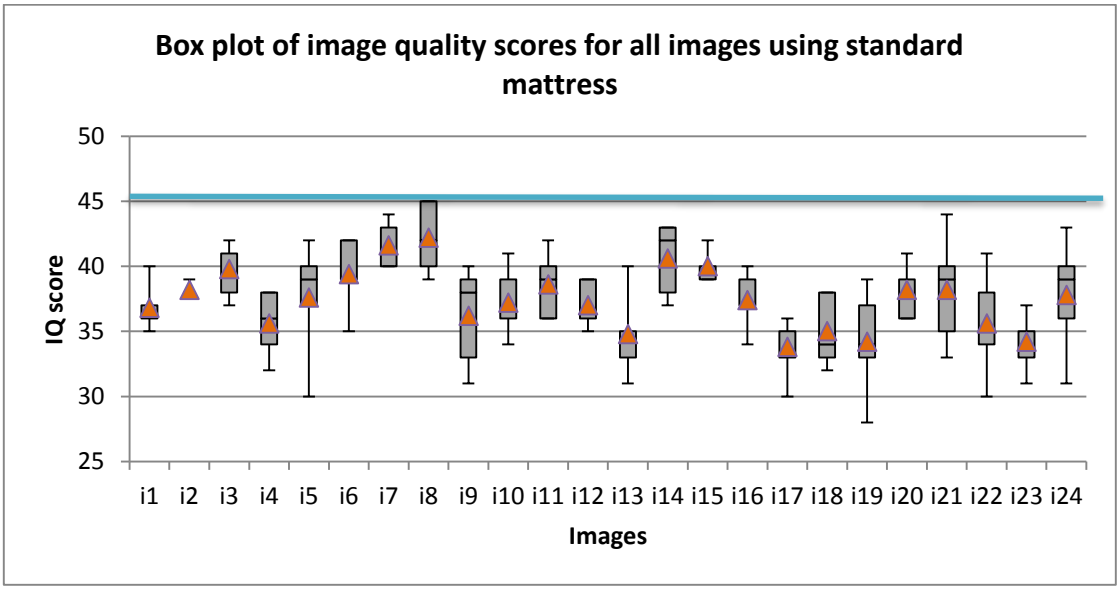

Figure 26 – figure demonstrating the 2AFC image quality scores for all experimental images using the standard mattress in comparison to the reference image (blue line).

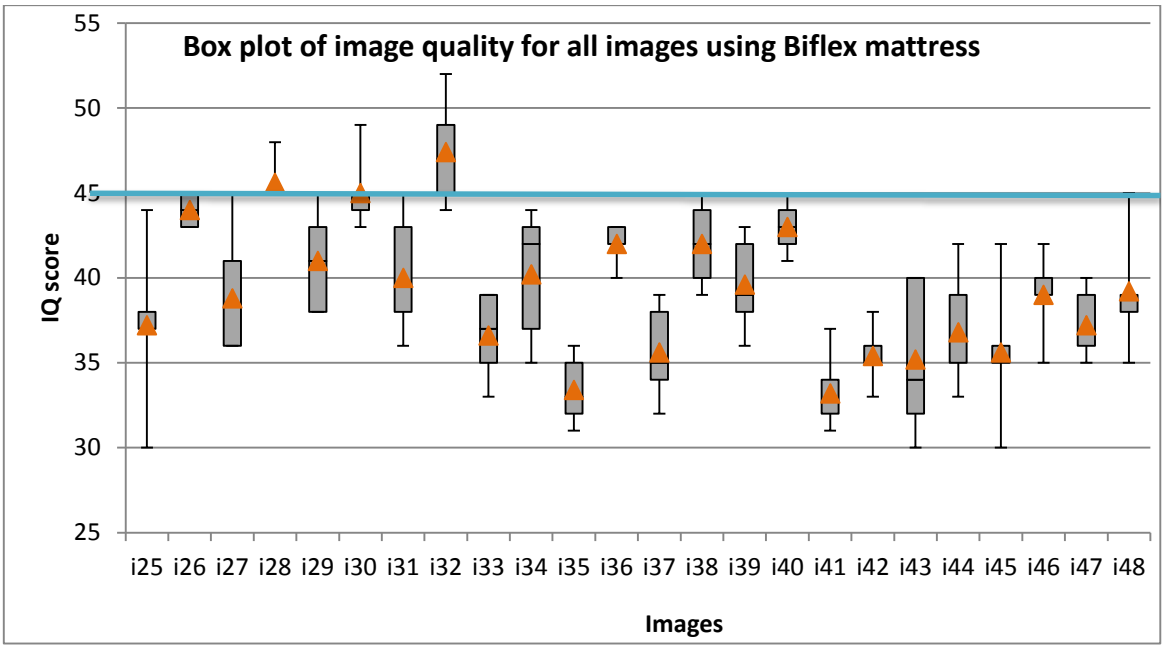

Figure 27 – figure demonstrating the 2AFC image quality scores for all experimental images using the Bi-Flex mattress in comparison to the reference image (blue line)

Imaging conditions coding [platform position/mAs/SID(cm)]							
Standard mattress					Bi-Flex mattress		
i1	elevated/16/110	i13	elevated/25/120	i25	elevated/16/110	i37	elevated/25/120
i2	down/16/110	i14	down/25/120	i26	down/16/110	i38	down/25/120
i3	elevated/20/110	i15	elevated/32/120	i27	elevated/20/110	i39	elevated/32/120
i4	down/20/110	i16	down/32/120	i28	down/20/110	i40	down/32/120
i5	elevated/25/110	i17	elevated/16/130	i29	elevated/25/110	i41	elevated/16/130
i6	down/25/110	i18	down/16/130	i30	down/25/110	i42	down/16/130
i7	elevated/32/110	i19	elevated/20/130	i31	elevated/32/110	i43	elevated/20/130
i8	down/32/110	i20	down/20/130	i32	down/32/110	i44	down/20/130
i9	elevated/16/120	i21	elevated/25/130	i33	elevated/16/120	i45	elevated/25/130
i10	down/16/120	i22	down/25/130	i34	down/16/120	i46	down/25/130
i11	elevated/20/120	i23	elevated/32/130	i35	elevated/20/120	i47	elevated/32/130
i12	down/20/120	i24	down/32/130	i36	down/20/120	i48	down/32/130

Table 12 - this table is a key to the acquisition parameters of each experimental image from image 1 to 48

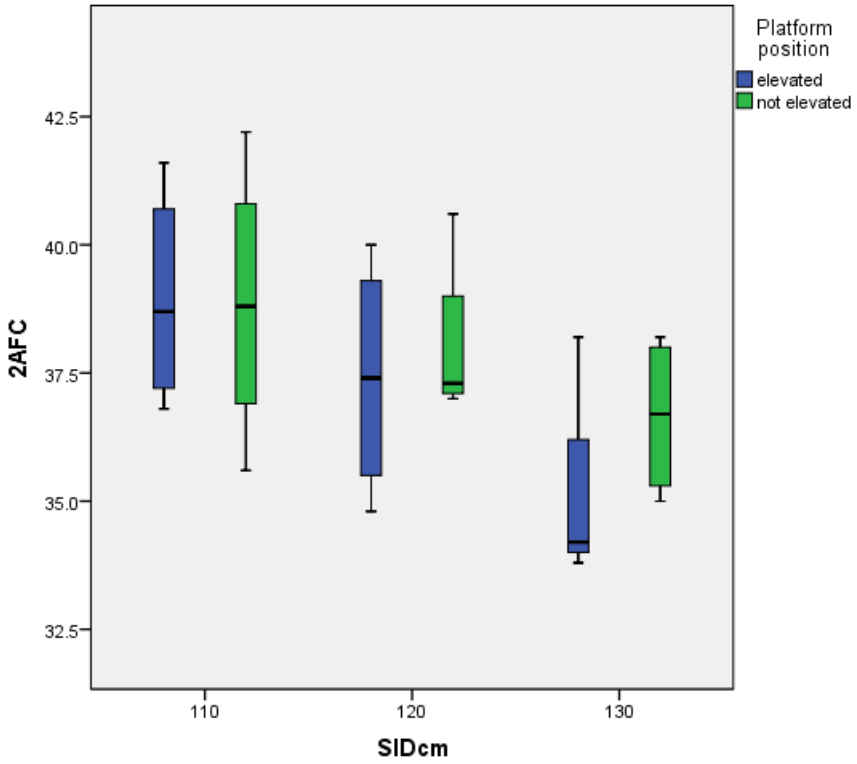

Figure 28 – 2AFC scores in different imaging conditions using the standard mattress.

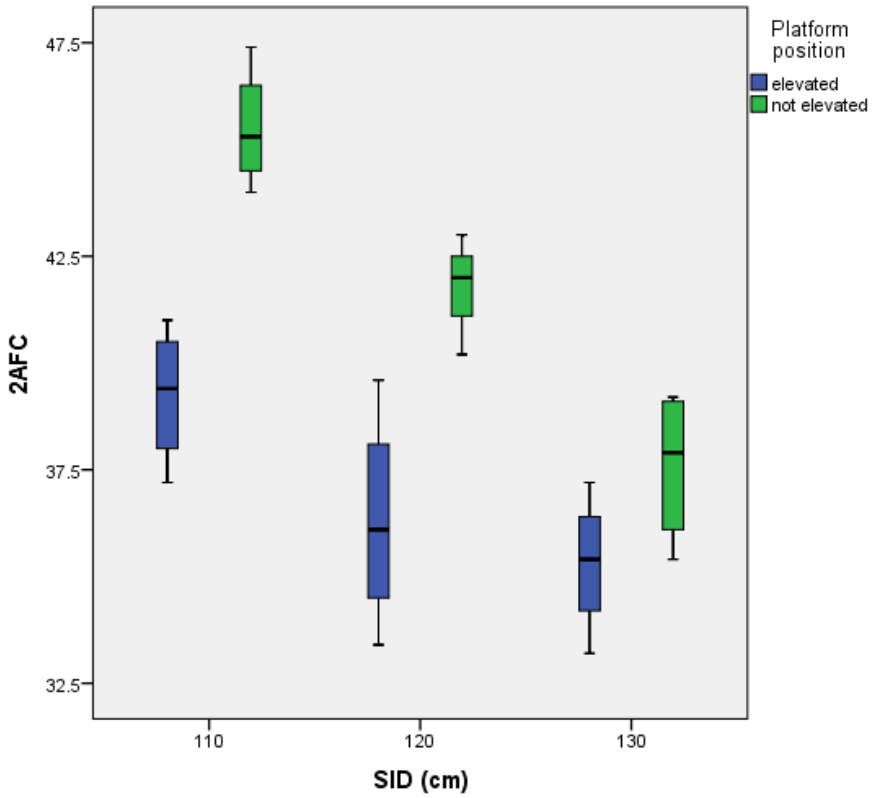

Figure 29 – 2AFC scores in different imaging conditions using Bi-Flex mattress

Upper QUARTILE (12)	mattress	mAs	Tray	SID	IQ score
32	Bi-Flex	32	not elevated	110	47.4
28	Bi-Flex	20	not elevated	110	45.6
30	Bi-Flex	25	not elevated	110	45
26	Bi-Flex	16	not elevated	110	44
8	standard	32	not elevated	110	42.2
36	Bi-Flex	20	not elevated	120	42
38	Bi-Flex	25	not elevated	120	42
7	standard	32	Elevated	110	41.6
29	Bi-Flex	25	Elevated	110	41
14	standard	25	not elevated	120	40.6
34	Bi-Flex	16	not elevated	120	40.2
15	standard	32	Elevated	120	40
Lower QUARTILE (12)					
41	Bi-Flex	16	Elevated	130	33.2
35	Bi-Flex	20	Elevated	120	33.4
17	standard	16	Elevated	130	33.8
19	standard	20	Elevated	130	34.2
23	standard	32	Elevated	130	34.2
13	standard	25	Elevated	120	34.8
18	standard	16	not elevated	130	35
43	Bi-Flex	20	Elevated	130	35.2
42	Bi-Flex	16	not elevated	130	35.4
22	standard	25	not elevated	130	35.6
37	Bi-Flex	25	Elevated	120	35.6
45	Bi-Flex	25	Elevated	130	35.6

Table 13 - table demonstrating the upper and lower quartile results of the 2AFC task (upper 12 being highest scoring images and lower 12 the worst images)

From table 13 and figures 28 and 29, it is clear that the images with the lowest image quality scores are the images acquired at higher SIDs at lower mAs values, whereas the higher scoring images are acquired with lower SIDs at higher mAs. Visual image quality was found to be significantly better when the platform was not elevated ($p<0.05$) whereas no significant difference was found between image quality and the two different mattresses ($p=0.06$). A statistical significant difference was found between image quality acquired at 110cm SID in comparison to 130cm SID ($p<0.05$).

The visual image quality assessment also included a sixteenth item on the criteria scale. Observers were asked whether they felt that the image in question in the right monitor (comparison image) was of diagnostic quality. This item considered the diagnostic quality of the images and therefore was a binary decision (acceptable or unacceptable). As there were five observers, this item was analysed using majority rule decision making. According to Taylor et al. (2013), majority rule outperforms consensus rule and it is also quick, more practical and of better quality. Majority rule meant that the decision on the quality of the images were down to a majority decision of more than 50% which in this case was three or more observers. Of the 48 images, only two were deemed unacceptable by a majority rule (see table 15). Nevertheless, on an individual basis, uncertainty existed amongst observers regarding the quality of various images. Some images were deemed unacceptable by observers but not by a majority (see table 14 and 15). The number of images where an observer was in doubt regarding the diagnostic quality of an image is reflected in table 15, where the images deemed non diagnostic by one or more of the observers are considered in their image quality quartiles. Table 16 demonstrates that the majority of images deemed unacceptable by an observer are within the lower quartile of image quality whereas none of the images from the upper quartile of image quality was considered unacceptable.

	Observer 1	Observer 2	Observer 3	Observer 4	Observer 5	Total
REF	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**
1	YES	NO	YES	YES	YES	YES
2	YES	YES	YES	YES	YES	YES
3	YES	YES	NO	YES	YES	YES
4	YES	YES	YES	YES	YES	YES
5	YES	NO	YES	YES	YES	YES
6	YES	YES	YES	YES	YES	YES
7	YES	YES	YES	YES	YES	YES
8	YES	YES	YES	YES	YES	YES
9	YES	YES	NO	YES	YES	YES
10	YES	YES	YES	YES	YES	YES
11	YES	NO	YES	YES	YES	YES
12	YES	YES	YES	YES	YES	YES
13	YES	NO	YES	YES	YES	YES
14	YES	YES	YES	YES	YES	YES
15	YES	YES	YES	YES	YES	YES
16	YES	YES	YES	YES	YES	YES
17	NO	NO	YES	YES	NO	NO
18	YES	YES	YES	YES	YES	YES
19	NO	NO	YES	YES	YES	YES
20	YES	YES	YES	YES	YES	YES
21	YES	NO	YES	YES	NO	YES
22	YES	NO	YES	YES	YES	YES
23	YES	No	YES	YES	YES	YES
24	YES	NO	YES	YES	YES	YES
25	YES	YES	YES	YES	YES	YES
26	YES	YES	YES	YES	YES	YES
27	YES	NO	YES	YES	YES	YES
28	YES	YES	YES	YES	YES	YES
29	YES	YES	Yes	YES	YES	YES
30	YES	YES	YES	YES	YES	YES
31	YES	YES	YES	YES	YES	YES
32	YES	YES	YES	YES	YES	YES
33	YES	NO	YES	YES	YES	YES
34	YES	YES	YES	YES	YES	YES
35	YES	YES	YES	YES	YES	YES
36	YES	YES	YES	YES	YES	YES
37	YES	NO	YES	YES	NO	YES
38	YES	YES	YES	YES	YES	YES
39	YES	YES	YES	YES	YES	YES
40	YES	YES	YES	YES	YES	YES
41	NO	NO	NO	YES	YES	NO
42	YES	YES	YES	YES	YES	YES
43	NO	YES	YES	YES	YES	YES
44	YES	YES	YES	YES	YES	YES
45	YES	NO	YES	YES	YES	YES
46	YES	Yes	YES	YES	YES	YES
47	YES	NO	YES	YES	YES	YES
48	YES	YES	NO	YES	YES	YES

Table 14 - table above demonstrating observer's opinion as to the diagnostic quality of the acquired images with 'YES' indicating images of diagnostic quality whilst 'NO' indicates unacceptable image quality that would require a repeat exposure.

Quartile (Image quality)	Observer with doubt (n=19)
Upper(1)	0
Second(2)	5
Third(3)	5
Lower(4)	9

Table 15 - table demonstrating the number of images that one or more observer regarded as non diagnostic in their image quality score quartiles.

5.4.2 Data on contrast to noise (CNR)

CNR was calculated for all images using ImageJ software. No statistical significant different in CNR was discovered between platform position (elevated and not elevated) (p=0.29) nor when using two different mattresses (standard and Bi-Flex) (p=0.80). Figure 30 and 31 demonstrates the relationship between CNR of the reference image (orange horizontal line) and the experimental images (trolley). For details on the acquisition parameters used for each image on X axis, see table 12 above. Figures 32 and 33 also demonstrate the relationship between CNR and the impendent variables.

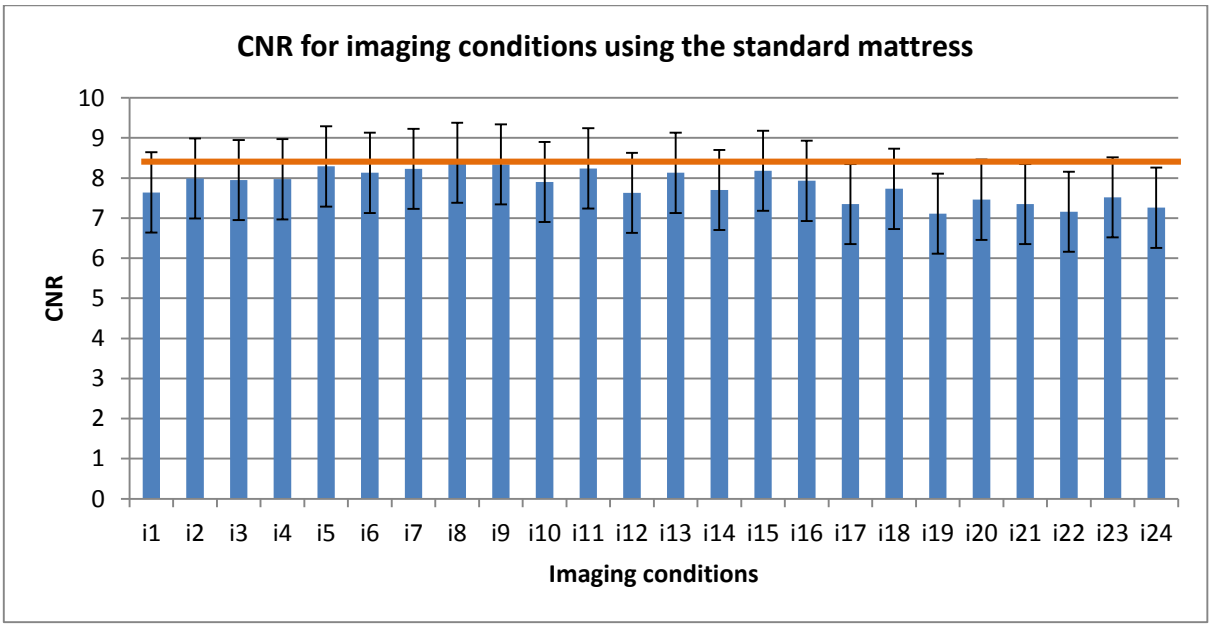

Figure 30 – figure demonstrating CNR calculations (error bars representing the standard deviation) for all experimental imaging condition using the standard mattress with the line indicating the reference image's CNR value.

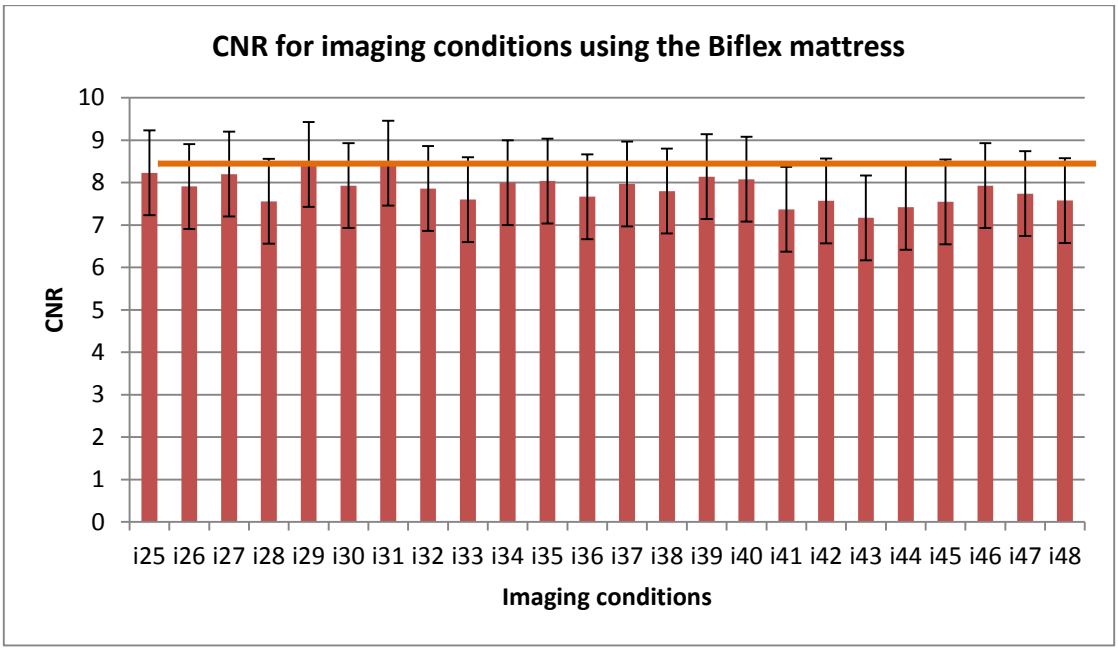

Figure 31 – figure demonstrating CNR calculations (error bars representing the SD) for all experimental imaging condition using the Bi-Flex mattress with the orange line indicating the reference image's CNR value.

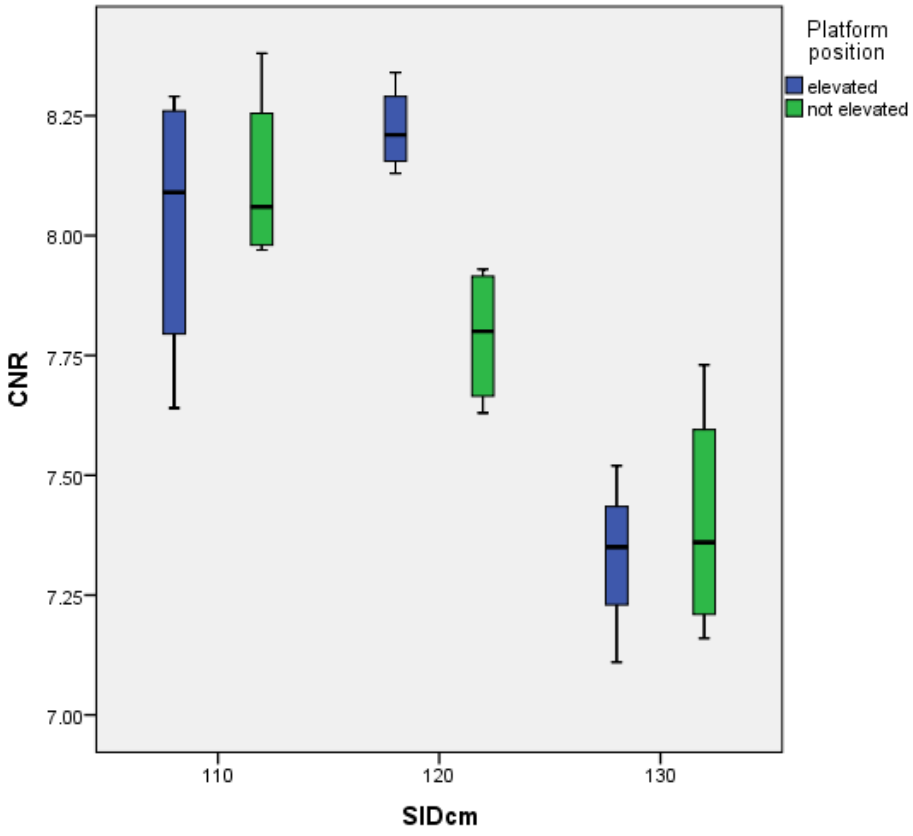

Figure 32 – CNR results in various imaging conditions using the standard mattress

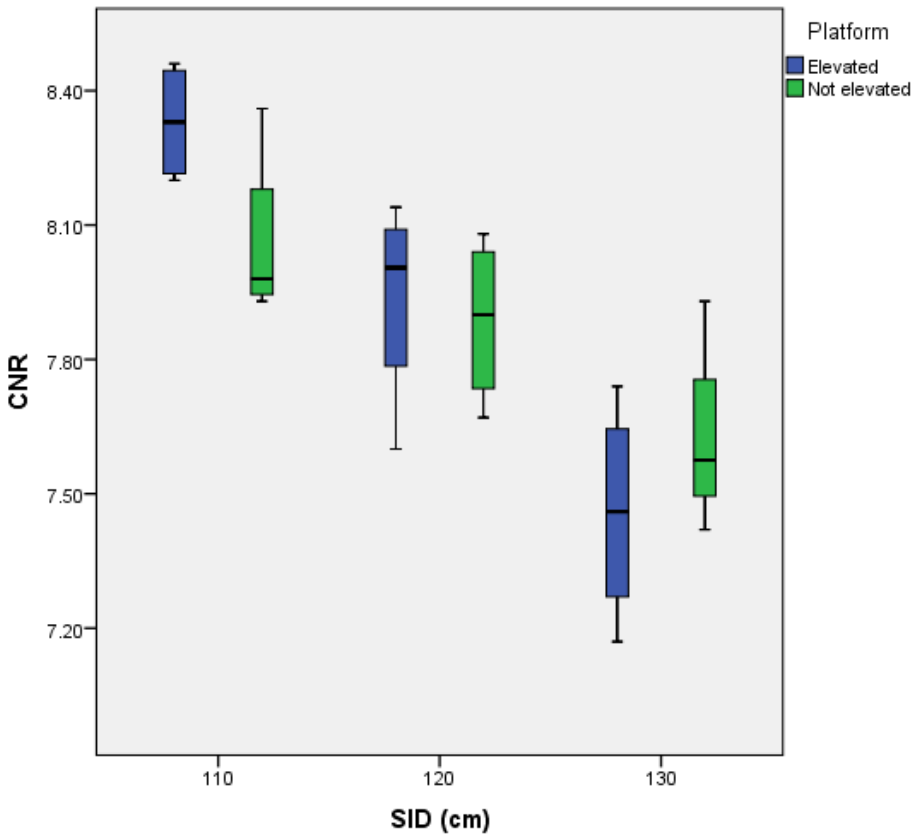

Figure 33 – CNR results in various imaging conditions using the Bi-Flex mattress

5.5 Radiation dose for the (experimental) trolley images

Effective dose and ESD were derived using two different method/calculations. The scatter plot with line of best fit seen in figure 34 demonstrates a near perfect relationship exists between them with R^2=0.99. Both dose measurements were measured multiple times to reduce potential error however no inconsistencies were found between measurements and therefore standard deviation was negligible.

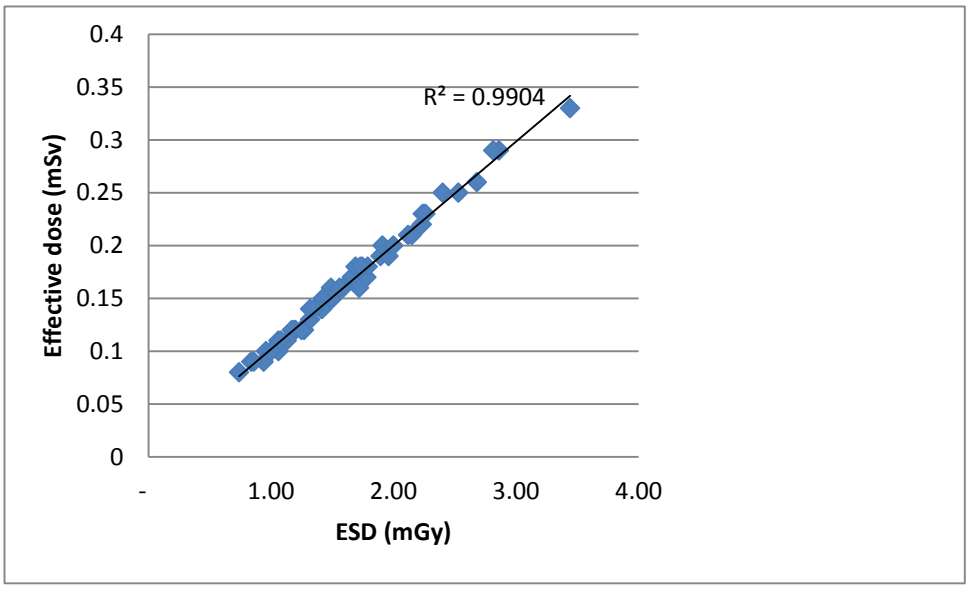

Figure 34 – figure demonstrating the relationship between E and ESD for all trolley (experimental) imaging conditions.

For 92% (n=44) of the experimental images, effective dose was higher than the reference image acquired on the x-ray tabletop (see table 17), with ESD higher for 77% (n=39) on imaging conditions.

When considering the mattress type, average ESD and effective dose for the standard mattress at 110cm SID were 1.91mGycm^2 and 0.19mSv respectively whereas the average ESD and effective dose for the Bi-Flex mattress at 110cm SID were 2.28 mGy and 0.23mSv respectively. This shows a decrease in ESD and effective dose by 37% and 4% when utilising the standard mattress. However, no statistically significant difference was found between effective dose and ESD for the two different mattresses (p=0.14) and (p=0.10) respectively.

When the platform was elevated, the average ESD and effective dose were 1.91mGy and 0.20mSv respectively at a 110cm SID. Whereas with the platform not elevated, the average ESD and effective dose were 2.3 mGy and 0.22mSv respectively. This demonstrates an increase in both ESD and effective dose when the platform was not elevated. Yet again, no statistically significant difference was found between effective dose (p=0.27) and ESD (p=0.16) for platform position. ESD and effective dose were reduced by 37% and 2%

respectively when the platform was elevated and the SID was increased to a 130cm (see figure 35).

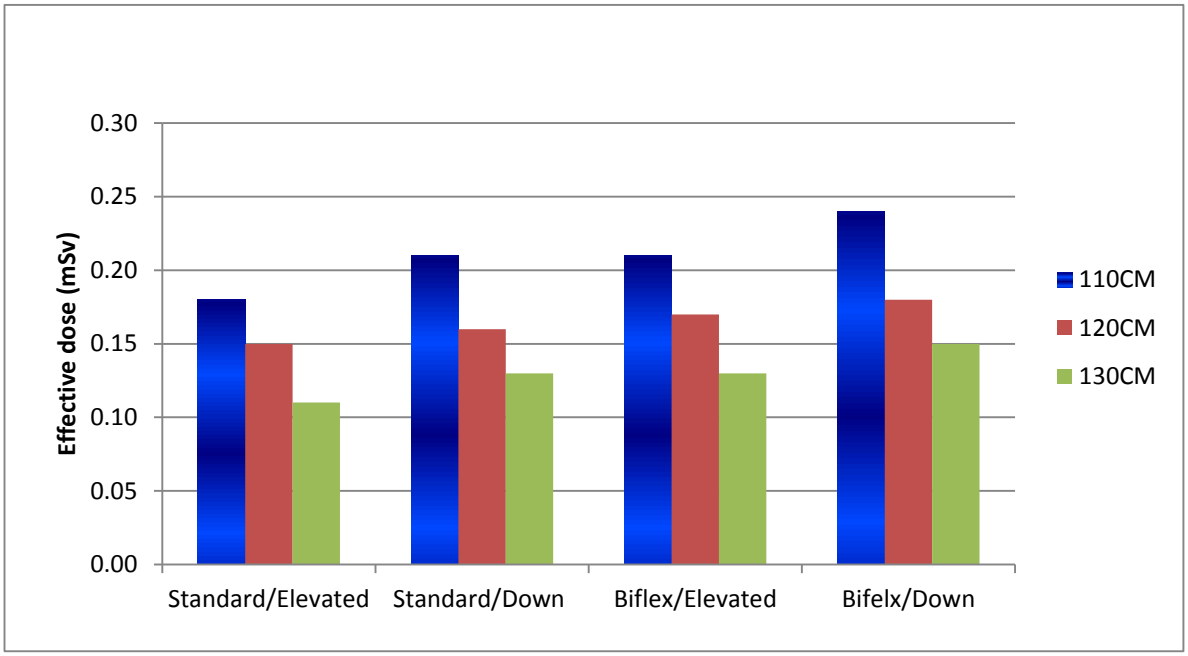

Figure 35 – figure demonstrating average and standard deviation of effective dose for different SID increments using different imaging conditions on the trolley for all mAs values.

A significant statistical difference was found in effective dose between the lowest (110cm) and highest (130cm) SID value ($p<0.05$) and for the lowest (16) and highest (32) mAs value ($p<0.05$). Table 16 demonstrates that the images with the lowest effective dose are the images acquired with higher SID at lower mAs, whereas the higher effective dose values were those acquired with lower SID at higher mAs (see also figure 36 and 37).

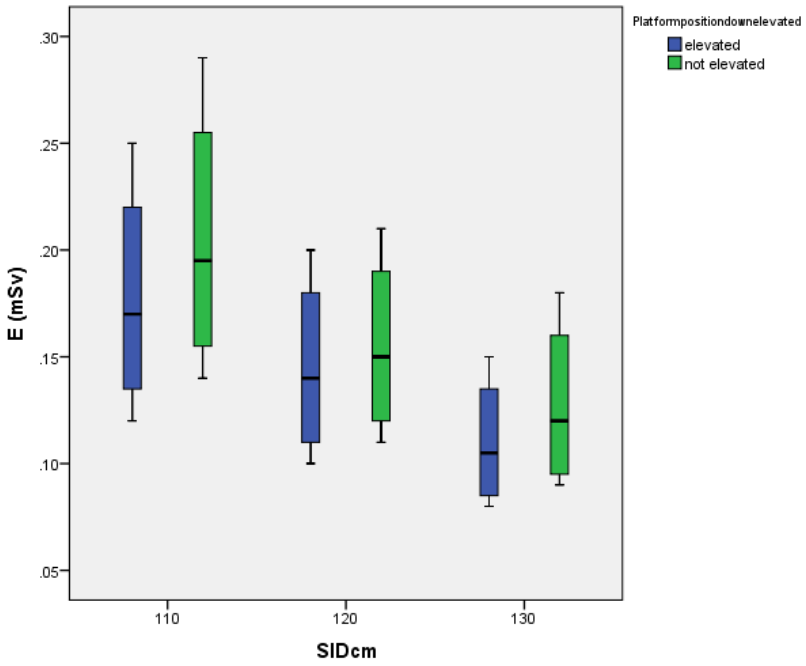

Figure 36 – Effective dose (E) for various imaging conditions using standard mattress across all mAs values

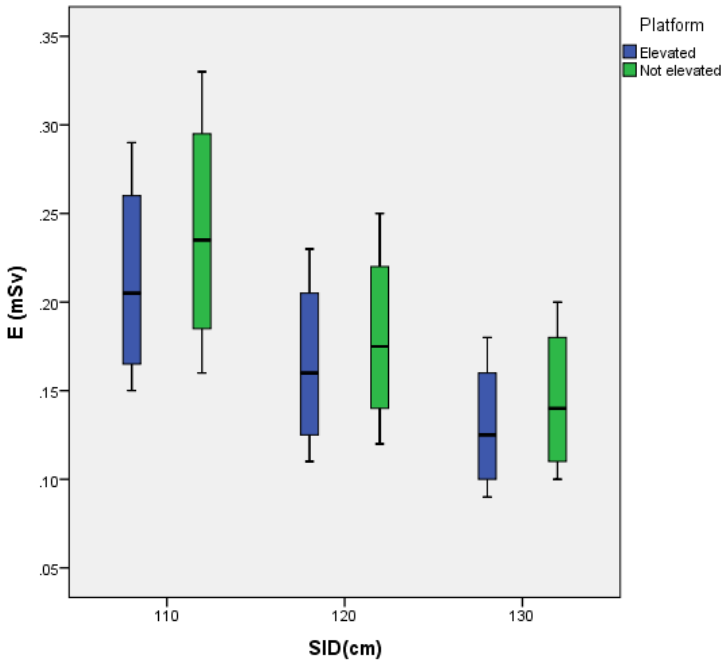

Figure 37 – Effective dose (E) for various imaging conditions using the Bi-Flex mattress across all mAs values.

Upper QUARTILE images (12)	mattress	mAs	tray	SID	E(mSv)
32	Bi-Flex	32	not elevated	110	0.33
8	st	32	not elevated	110	0.29
31	Bi-Flex	32	elevated	110	0.29
30	Bi-Flex	25	not elevated	110	0.26
7	st	32	elevated	110	0.25
40	Bi-Flex	32	not elevated	120	0.25
29	Bi-Flex	25	elevated	110	0.23
39	Bi-Flex	32	elevated	120	0.23
6	st	25	not elevated	110	0.22
16	st	32	not elevated	120	0.21
28	Bi-Flex	20	not elevated	110	0.21
15	st	32	elevated	120	0.2
48	Bi-Flex	32	not elevated	130	0.2
Lower QUARTILE images (12)					
17	st	16	elevated	130	0.08
Reference			n/a	110	0.09
18	st	16	not elevated	130	0.09
19	st	20	elevated	130	0.09
41	Bi-Flex	16	elevated	130	0.09
9	st	16	elevated	120	0.1
20	st	20	not elevated	130	0.1
42	Bi-Flex	16	not elevated	130	0.1
10	st	16	not elevated	120	0.11
33	Bi-Flex	16	elevated	120	0.11
43	Bi-Flex	20	elevated	130	0.11
1	st	16	elevated	110	0.12
11	st	20	elevated	120	0.12
21	st	25	elevated	130	0.12
34	Bi-Flex	16	not elevated	120	0.12
44	Bi-Flex	20	not elevated	130	0.12

Table 16 - demonstrating the upper and lower quartile results of effective dose. Upper 12 representing highest dose and lower 12 being lowest dose images. **Use table 12 above in section 5.4.1 as a key to the imaging conditions for the numbered images**

Table 17 demonstrates change in effective dose between all experimental imaging conditions in order to demonstrate how each imaging condition varies from the reference image. This also highlights the imaging conditions where effective dose was much higher than the reference dose.

STANDARD						
SID(cm)	110		120		130	
mAs	Elevated	Down	Elevated	Down	Elevated	Down
16	0.03(33%)	0.05(56%)	0.01(11%)	0.02(22%)	-0.01(-11%)	0(0%)
20	0.06(67%)	0.08(89%)	0.03(33%)	0.04(44%)	0(0%)	0.01(11%)
25	0.1(111%)	0.13(144%)	0.07(78%)	0.08(89%)	0.03(33%)	0.05(56%)
32	0.16(178%)	0.2(222%)	0.11(122%)	0.12(133%)	0.06(67%)	0.09(100%)
BIFLEX						
SID(cm)	110		120		130	
mAs	Elevated	Down	Elevated	Down	Elevated	Down
16	0.06(67%)	0.07(78%)	0.02(22%)	0.03(33%)	0(0%)	0.01(11%)
20	0.09(100%)	0.12(133%)	0.05(56%)	0.07(78%)	0.02(22%)	0.03(33%)
25	0.14(156%)	0.17(189%)	0.09(100%)	0.1(111%)	0.05(56%)	0.07(78%)
32	0.2(222%)	0.24(267%)	0.14(156%)	0.16(178%)	0.09(100%)	0.11(122%)

Table 17 - table demonstrating change in effective dose (mSv) with percentage change demonstrated in brackets between the images acquired on the trolley in comparison to the reference image.

5.6 The relationship between effective dose, visual image quality and CNR

In order to assess the correlation between effective dose, 2AFC and CNR, a Pearson's r correlation coefficient was calculated to identify if any linear relationship existed between these continuous variables (see table 18). The significance of these values in table 18 are summarised in table 19 were a value of 1 indicates a perfect positive relationship (as one variable increases so does another); a value of 0 indicates no relationship whereas a value of -1 indicates a negative relationship (as one increases the other decreases). To compliment the Pearson's r calculations, scatter plots were also generated to summarise these relationships between the variables (see figures 38, 39 and 40).

	E	*2AFC*	*CNR*
E	1		
2AFC	0.72174332	1	
CNR	0.52916516	0.3470775	1

Table 18 - Pearson's r correlation coefficient between effective dose (E), visual image quality (2AFC) and physical image quality (CNR).

Size of Correlation	Interpretation
.90 to 1.00 (−.90 to −1.00)	Very high positive (negative) correlation
.70 to .90 (−.70 to −.90)	High positive (negative) correlation
.50 to .70 (−.50 to −.70)	Moderate positive (negative) correlation
.30 to .50 (−.30 to −.50)	Low positive (negative) correlation
.00 to .30 (.00 to −.30)	negligible correlation

Table 19 - Interpretations of the Pearson's r values (Hinkle, Jurs & Wiersma, 2003)

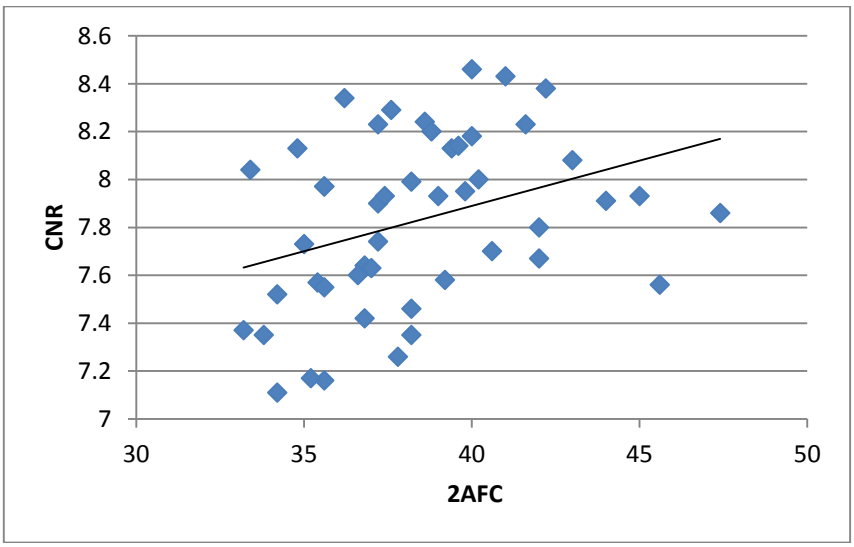

Figure 38 – figure demonstrating the relationship between CNR and average visual image scores (2AFC)

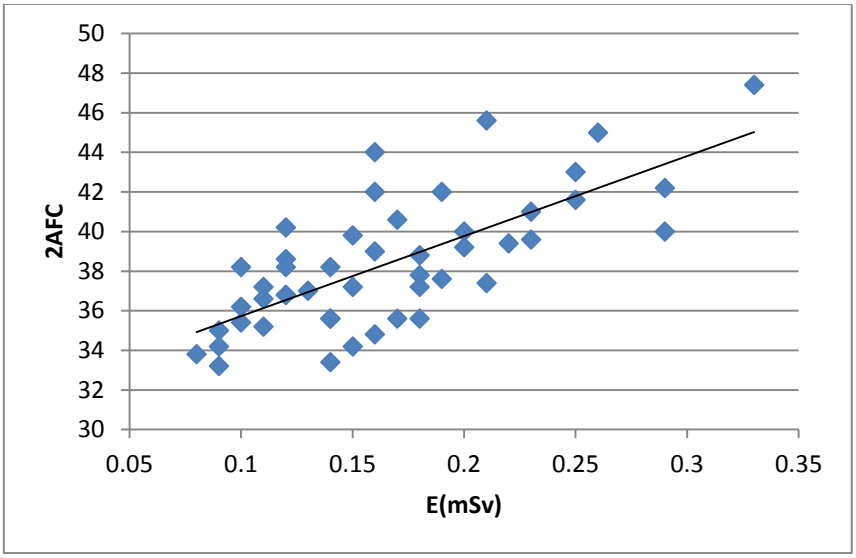

Figure 39 – figure demonstrating the relationship between effective dose (E) and average visual image quality scores (2AFC)

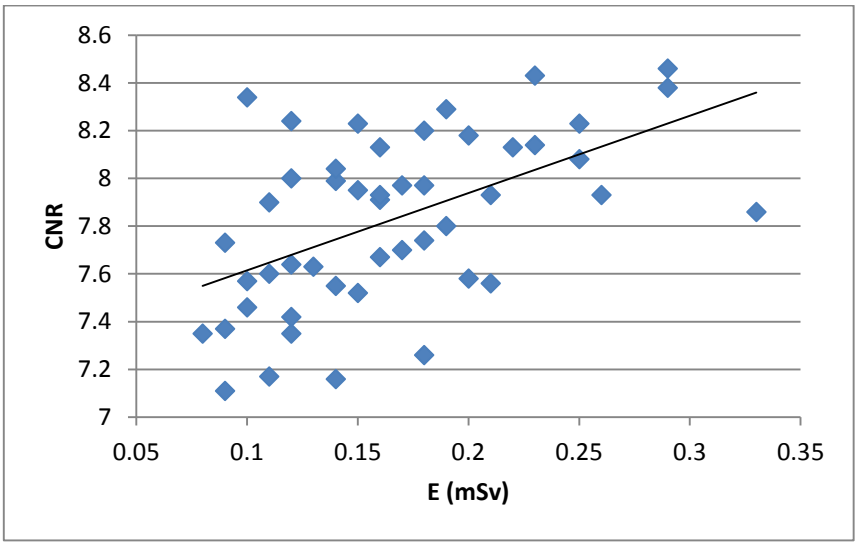

Figure 40 – figure demonstrating the relationship between effective dose (E) and average CNR values

From the above results, a low positive relationship exists between the average 2AFC scores and CNR values. CNR and effective dose had a moderate positive relationship, whereas visual image quality (2AFC) and effective dose had a high positive relationship (Hinkle, Jurs & Wiersma, 2003).

The high positive relationship between visual image quality and effective dose means that lower mAs values results in lower image quality scores at lower dose and vice versa. This can cause problems in optimisation studies since the highest image quality may not be the optimum acquisition parameters to utilise due to the dose implications. In order to evaluate optimisation, a figure of merit in terms of 'optimisation score' was used whereby image quality is divided by effective dose to give an optimisation score (see next section 5.6)

5.7 Optimisation score

When visual image quality scores is divided by effective dose, it intends to reveal the highest image quality at the lowest possible dose. Table 20 highlights the optimisation scores for all images acquired for this thesis with the four highest optimisation scores underlined. The optimisation score for the reference image was 500; none of the experimental images achieved this score with a significant difference observed between the experimental images and the reference image ($p<0.05$) (see figure 41). In addition, no statistically significant difference was found for optimisation score between platform position ($p=0.60$) and both mattresses ($p=0.18$)

Standard mattress

SID(cm)	110		120		130	
mAs	Platform Elevated	Platform Down	Platform Elevated	Platform Down	Platform Elevated	Platform Down
16	306.67	272.86	362	338.18	**422.5**	**388.89**
20	265.33	209.41	321.67	284.62	**380**	**382**
25	197.89	179.09	217.5	238.82	318.33	254.29
32	166.4	145.52	200	178.10	228	210

Bi-flex mattress

SID(cm)	110		120		130	
mAs	Platform Elevated	Platform Down	Platform Elevated	Platform Down	Platform Elevated	Platform Down
16	248	275	332.73	335	368.89	354
20	215.56	217.14	238.57	262.5	320	306.67
25	178.26	173.08	197.78	221.05	254.28	243.75
32	137.93	143.64	172.17	172	206.67	196

Table 20 - tables demonstrating optimisation scores (IQ/E) for all imaging conditions

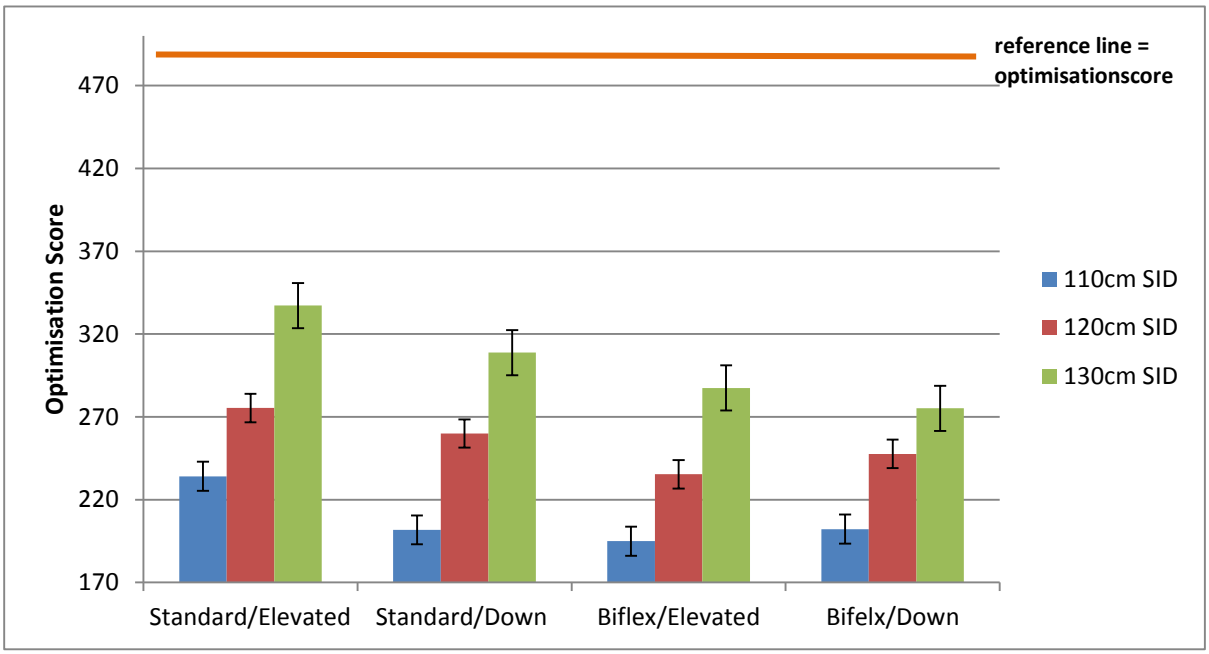

Figure 41– figure demonstrating optimisation scores and standard deviation for various imaging conditions for all mAs values on the trolley in compassion to the reference optimisation score (orange horizontal line)

5.8 Magnification of femoral head diameter for the trolley (experimental) images

Due to the differences in OID between the various imaging conditions on the trolley (e.g. platform not elevated and mattress thicknesses), SID was increased incrementally by 10cm from 110cm to 130cm in order to compensate for this increased OID thus magnification. The right femoral head diameter was measured for all images in order to evaluate these differences in the displayed magnification level. Both platform position and mattress thickness had a statistically significant impact on femoral head diameter hence magnification of the images ($p<0.05$). As expected, when the platform was not elevated, magnification increased by 7% and when the Bi-Flex mattress was used in comparison to the standard mattress, magnification increased by 8% (see table 21 and figure 42).

Trolley images		110		120		130	
Mattress	Tray	Mean diameter and SD (mm)	% change from reference	Mean diameter and SD (mm)	% change from reference	Mean diameter and SD (mm)	% change from reference
Standard	Elevated	60.7(0.3)	0	59.8 (0.1)	-1	58.5 (0.3)	-3
Standard	Not elevated	65.8(0.1)	9	63.6 (0.1)	5	61.8(0.2)	2
Bi-Flex	Elevated	66 (0.2)	9	64.5 (0.2)	7	62.9 (0.3)	4
Bi-Flex	Not elevated	71.3(0.2)	18	68.9 (0.3)	14	67(0.2)	11

Table 21 - table demonstrating differences in magnification including standard deviation in brackets and percentage change from reference image of femoral heads diameter for the experimental images.

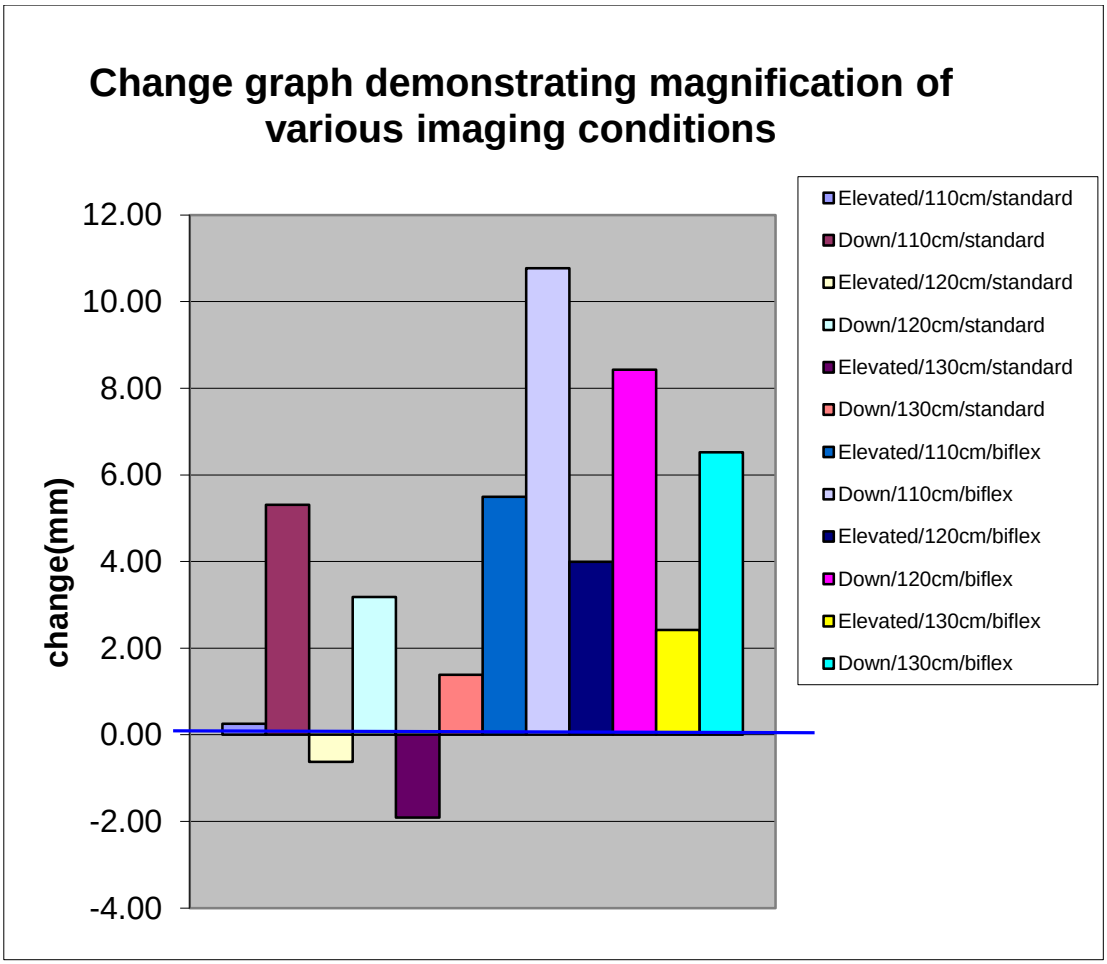

Figure 42 – Bar graph demonstrating change in magnification levels per mm for the experimental imaging conditions in comparison to the reference image (blue line through 0 on the x axis

Chapter 6 - Discussion

This chapter discusses the results and makes critical comparisons to published studies. It includes detailed discussions of the research findings and relates the findings to the thesis aims and objectives. The discussion has the same structure as the results chapter. The primary aim of this thesis is to explore whether acquisition parameters used for AP pelvis on the x-ray tabletop can be successfully utilised and transferred for the same projection on a trolley.

6.1. – Intraclass Correlation Coefficient to measure observer agreement for the visual image quality assessment (2AFC)

When performing a visual evaluation task the method needs to be repeatable and valid with observers' rating images similarly using visual evaluation criteria. Therefore prior to discussing the visual image quality assessment results, it is important to consider the level of inter-and intra-observer variation that occurred for this current thesis.

The ICC results for the 2AFC visual evaluation showed excellent inter and intra observer agreement of 0.84 and 0.92 respectively. The level of inter-observer agreement is comparable to other optimisation studies including Davey and England (2014) and Heath et al. (2011) who had ICC values of 0.85 and 0.83 respectively. Other studies have reported lower values of ICC including Ma et al. (2014) where good to fair observer agreement of 0.62 was identified. Various statistical methods exist to aid in the interpretation of ICC results. For the current thesis, the ICC results have been interpreted using Rosner (2006, 2010) and Fleiss's (1986) recommendations where>0.75 indicates excellent reproducibility, between 0.75 to 0.4 considered fair to good and 1 being perfect agreement. This interpretation of ICC has been used by numerous optimisation studies in medical imaging including Haneline (2006), Oremus, Oremus, Hall and McKinnon(2012), Manning-Stanley et al. (2012), Davey and England (2014).

The purpose of calculating inter-observer variation is to examine the degree of agreement between observers measuring the same event/item. It gives an indication of how much homogeneity, or consensus, there is in the scores given by different observers (Watkins & Pacheco, 2000). The ICC ranges recommended by Rosner (2010) and Fleiss (1986) are general interpretations based on philosophical assumptions and have not been specifically calculated with medical image interpretation in mind. A threshold should perhaps be set for inter-observer agreement amongst medical professionals who interpret images for diagnostic purposes in order to reduce discrepancies and error. The RCR (2014) together with authors including Mucci, Murray, Downie, and Osborne (2013) recognises that clinical image interpretation involves decision making and observations and is therefore susceptible to errors/variation however they do also identify the lack of defined standards for inter-observer agreement in radiology to evaluate and monitor this discrepancy problem. According to Bender, Linnau, Meier, Anzai and Gunn (2012) there is however work in progress in developing national levels/ranges for diagnostic accuracy. A national benchmark for diagnostic accuracy would give a more precise meaning to the inter-observer agreement found in radiology optimisation studies and whether the statistical values (kappa, Pearson's, ICC) meet diagnostic standards. This national level should also include a standard stringent statistical method to interpret observer-agreement because optimisation studies in radiology use different method to calculate the agreement scores (kappa, Pearson's, ICC) which makes it difficult to compare values especially since certain methods overestimating agreement.

Another point to consider is that the steps taken to ensure consistency within the visual image assessment in order to reduce variability between observers may not reflect that of clinical practice. This means that variability between observers in clinical practice may be higher than that reflected within optimisation studies. For this current thesis, these steps to reduce variability were replicated from other optimisation studies such as from Ma et al. 2013a and Mantiuk et al. (2012) which included the provision of instructions to observers prior to the visual evaluation, a training session, ambient lighting and restriction on the manipulation of images such as changing contrast and zooming. Restricting manipulation of images does not reflect what happens in practice and also some of the other steps can only be reduced rather than fully controlled. Krupinski (2010) commented that eye strain and fatigue is common amongst radiology observers when viewing images over long periods of time. The observers for this current study were permitted to take a break after

assessing half of the images but this was optional and not compulsory. Therefore, this could have impacted on the visual evaluation and observer agreement since some observers may have had a break whilst others did not. Perhaps for future work a set amount of images should be observer and an automatic compulsory break is provided for the observers before the last data set is available to them. This would ensure consistency in the break time (rest) for all observers.

Lastly, ICC was also calculated for the last visual image quality criterion to examine the agreement between observers when deciding on whether the images were diagnostic or non diagnostic (yes/no). The ICC values for this was much lower than the remaining visual image quality data at 0.49. This is considered a fair to good agreement by Rosner's (2011) interpretation however as already discussed; these interpretations are not based in the context of human behaviour and therefore specific interpretations should be derived for observers in medical imaging assessment. The ICC value may also be lower than expected because this last criterion (item 16) has not been validated, whereas the remaining fifteen items were part of a validated psychometric scale by Mraity (2015). In addition, the last criterion asked observers to decide whether they would accept the image for diagnostic purpose without knowing the clinical indication for the image. This downfall will be further discussed within this chapter.

6.2 Comparing the reference image (x-ray tabletop) with four experimental images (trolley) acquired using identical acquisition parameters

The main aim of this thesis was to evaluate whether acquisition parameters used for AP pelvis on the x-ray tabletop could be transferable to trolley imaging. When considering the different variables that exist between these two scenarios including the unavailability of the AEC when imaging on the trolley, grid selection, mattresses and so on, it could be assumed that acquisition parameters would require modification for trolley imaging.

The results demonstrate that the visual quality (2AFC) of the image acquired on the x-ray tabletop (reference image) was significantly better to the images acquired on the trolley when using the same acquisition parameters (110cm SID and 16mAs), ($p<0.05$). On the other hand, no significant difference was found between CNR of the reference image in

comparison to the CNR of the trolley images (experimental images) acquired using the same acquisition parameters (p=0.12). This was surprising when considering evidence from previous studies including Tang et al. (2012), Abbey and Barrett (2001) and Sandborg and Onnerth (2004) where physical measures of image quality have been found to be more sensitive to changes in image quality compared to visual evaluation since the human eyes are not as sensitive to subtle changes in image quality in comparison to a computer program calculation. It has been suggested that human observer's visual system can adapt to the noise levels within an image (Sund, Båth, Kheddache, & Månsson, 2004; Abbey, 2013). This means observers may not visually notice small differences in noise levels between images in comparison to physical measures. Uffman and Schaefer-Prokop (2009) emphasised this by suggesting that observers start complaining of noise within an image only when exposure is reduced by 50%.

This statement however does not necessarily mean that noise levels for exposures above 50% are not perceptually noticeable; it might be that the observers only complain of noise levels when they feel that images are visually unacceptable for diagnostic purposes. This is where the correlation between CNR and 2AFC is limited as noise may not be the main concern for observers. Sandborg and Önnerth (2004) indirectly support this, as they found that the detection of lesions may not be limited by noise but by the anatomical background structures and the homogeneity of the area imaged. It must be remembered that visualisation of anatomical detail is an important factor in deciding upon the optimal exposure technique but CNR does not take this into consideration (Moore, Wood, Beavis & Saunderson, 2013). In addition, CNR does not include the display and observational steps of the imaging process and therefore may not have a strong correlation to visual image quality.

There is limited work exploring the link between physical and visual measures of image quality. The studies that do however demonstrate good correlation have been undertaken in simulated scenarios or controlled non-clinical environments. Samei (2009) and Samei et al. (2008) acknowledged this by stating that physical measures of image quality do not reflect the true clinical conditions especially when using physical phantoms. De Crop et al. (2012) recently established a correlation between a contrast detail phantom and clinical chest image quality however a commercially available contrast detail phantom was used with no anatomical detail. With specific regards to CNR, again there are limited studies that have been conducted to establish its relationship to visual image quality. Moore et al. (2013) did

demonstrate a statistically significant correlation between visual image quality and CNR however they did accept that there were limitations to this study. These downfalls included the limited simulated patient details within the phantom for the visual grading which meant that the amount of change one would expect to observe in clinical images, for a given change in the physical image quality, might not be actually seen in reality. Bloomfield et al. (2014) also measured CNR and visual image quality in their study and although a positive correlation is stated and can be seen from the figures, the study does not indicate or use statistics to determine the strength of this correlation.

Other studies have found a positive correlation between SNR of specific structures and visual image quality (Sandborg et al., 2001a, 2001b; Tingberg et al., 2004; Mraity, 2015). SNR is however very different from CNR as it does not consider the effect of noise on our ability to visualise objects within an image since visibility depends on contrast (the difference between signals). An overexposed image may contain a high SNR but demonstrates no valuable information on the structure of interest (Vldimirov, 2010; Lyra, Kordolaimi & Salvara, 2010). Therefore the discovery of a good correlation between SNR and visual image quality is not transferable to CNR and visual image quality. This is emphasises by the findings of the current thesis where poor but positive correlation was found between CNR and 2AFC. Further work is required to understand the relevance of CNR measurements in situations other than on physical phantoms and also it is important to compare the many means of calculating CNR in imaging especially if magnification levels vary between images.

A decrease in visual image quality (2AFC) was found between the reference image and trolley images acquired using the same acquisition parameters. This could be due to a variety of reasons including the unavailability of the AEC on trolleys and geometric factors such as increased OID due to the mattress or image receptor holder. The type of grid may also have potentially influenced image quality since the oscillating grid had a ratio of 12:1 whereas the stationary grid had a ratio of 10:1 and according to Whitley et al. (2015) lower grid ratios reduce image quality since more scatter radiation is able to reach the image receptor. It is therefore important that the radiographer undertaking the examinations is aware of the specification of the stationary grid used for trolley imaging as it may influence the acquisition parameters used including mAs (higher mAs required for higher ratios) and SID (focused grids have set SID) (Allisy-Roberts & Williams, 2008). It is

however important to consider the p value finding with care as a finding of ‘no difference’ is based on the sample size and the use of a single phantom. In addition, a finding of ‘no difference’ may be statistically significant but not necessarily clinically significant. It is therefore important to visually inspect the data using descriptive statistics not just rely on inferential statistics. This above statement applies to all inferential statistical findings within this thesis.

It is recommended by the ICRP (2005) and numerous educational textbooks including Carver and Carver (2012) that the AEC system should be used when acquiring an AP pelvis projection which means the mAs used is determined automatically. However, there are situations that require mAs to be set manually especially if the AEC system is unavailable as seen for this current thesis when acquiring images on a trolley. Since the AEC is unavailable for imaging the pelvis on the trolley, deciding on an appropriate mAs setting for the reference image of this thesis was difficult. Most AP pelvis optimisation studies, including Manning-Stanley et al. (2012) and Heath et al. (2012), do not state the mAs value used for different imaging conditions in their experiments as they have used the AEC system and consequently analysed the resultant given radiation dose. The use of 16mAs as a baseline acquisition parameter for this thesis was derived from the AEC system when acquiring the reference image in accordance with other optimisation studies including Lanca et al. (2014) and Tugwell et al. (2014). In other words, the reference image was acquired using the AEC (outer chambers) and gave 16mAs before terminating hence why 16 was used as the baseline mAs. Nevertheless, this method to determine mAs may not have been as accurate for trolley imaging in comparison to studies undertaken on the x-ray tabletop due to the differences in these imaging conditions as already discussed. It is unknown and unfeasible to determine exactly how much mAs the AEC would deliver for the different imaging conditions within this thesis since the system is unavailable on the trolley. It is therefore unsurprisingly that the results showed a significant decrease in visual image quality between the trolley images and the tabletop image (reference). Nevertheless, none of the observers deemed the images acquired using identical acquisition parameters to the reference image to be nondiagnostic indicating that 16mAs may not have provided the same images quality as the reference image but they were still acceptable for diagnostic purposes.

This thesis also found a significant difference ($p<0.05$) in radiation dose between the reference image and the images acquired on the trolley using the same acquisition parameters. The average effective dose more than doubled when imaging on the trolley. This was expected since the OID hence FOD (when SID is unchanged) was much more for the images acquired on the trolley in comparison to the reference image on the x-ray tabletop. This is because the mattresses on the trolley are thicker and the image receptor holder is lower than that of the tabletop Bucky thus increasing OID. Sprawls (n.d) emphasised this point by suggesting that reducing the distance between the x-ray tube and the patient's skin whilst maintaining the other acquisition parameters increases the intensity of radiation to that patient (see figure 43). This is why increasing SID has been explored several times as a simple and cost effective method to reduce patient dose (England et al., 2015; Tugwell et al., 2014). When SID is increased, the reduction in radiation dose has been found in these studies to be statistically significant for both entrance surface dose and effective dose (England et al., 2015; Tugwell et al., 2014; Heath et al., 2011). It must be remembered however that in comparison to this current thesis Heath et al. and England et al. used the AEC for their experimental design which would influence the radiation dose reduction outcome.

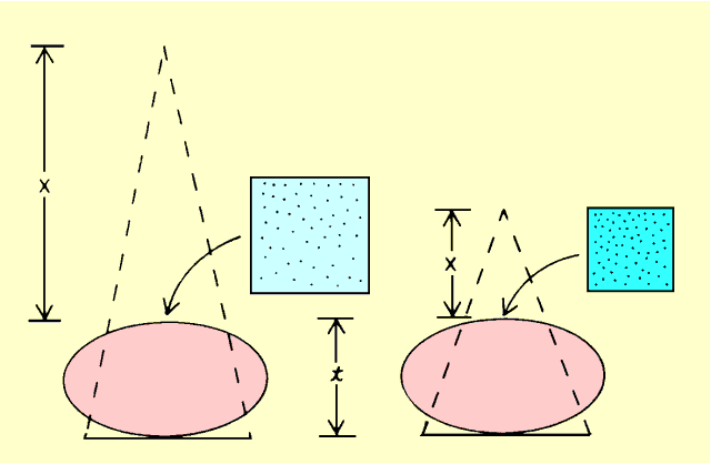

Figure 43– figure taken from Sprawls (n.d) demonstrating that decreasing the distance between the x-ray tube and patient surface increases the concentration of radiation or surface exposure.

In addition, when undertaking the preliminary experiment as discussed in section 4.2.4 on page 80, the mattress on the x-ray tabletop was thinner and absorbed less of the primary

beam resulting in a higher detector dose. This meant that patient radiation dose was reduced for this mattress in comparison to the mattresses used on a trolley. Everton et al (2014b) emphasised on this point by suggesting that imaging surfaces are designed by manufacturers to be radiolucent and anything added to the table such as mattresses or overlays would increase dose to the patient.

On average, no significant difference with regards to magnification level was found between the reference image and the images acquired on the trolley using the same acquisition parameters ($p=0.93$). The image with the greatest magnification level was acquired using the thickest Bi-Flex mattress, at a 110cm SID with the platform not elevated. For this image, the femoral head diameter was 71.3cm in comparison to 60.5mm for the reference image (10.8mm increase) demonstrating a statically significant difference in magnification level ($p<0.05$). This difference could impact upon measurements when planning and sizing surgical fixation devices especially if no calibration device such as a calibration ball were not used. In addition, when imaging the AP pelvis, it is important to ensure that the entire areas of interest are within the borders of collimation including the soft tissue margins of the greater trochanters (Bontrager & Lampignano, 2014). Interestingly, the image acquired on the thickest Bi-Flex mattress, at a 110cm SID with the platform not elevated had both greater trochanters within contact with the lateral borders of the image receptor (see figure 44). Figure 44 demonstrates the omission of the lateral edges of the greater trochaters because the magnification level of the image causes the anatomy to fall outside the lateral borders of the image receptor. This is worrying especially when considering the challenges of accurate centring for trolley imaging. The image receptor that is placed in the image recpetro holder needs to coincide with the median sagittal place (MSP), the anatomy to be imaged and the central ray with this being achieved by the radiographers visual judgment (Carver & Carver, 2012). Radiographers must kneel to see through the gap between the trolley top and the platform to assess alignment of the image receptor to the patient; unfortunately this is not an entirely accurate method of assessing alignment as discussed in the literature review (see section 3.1.3). This problem was also identified in the study by Mutch and Wentworth (2007) where radiographers commented on the difficultly of lining up the image receptor and the neonate when using the tray in the incubator. For the experiment used in this current thesis, the problem of image receptor/patient alignment was addressed by marking the image receptor position with tape in order to improve consistency of image receptor and phantom alignment. The tape

position was determined by trial and error when positioning the phantom and image receptor. In clinical practice, this scenario would be impractical as the radiographer has to ensure proper alignment on first attempt in order to reduce the likelihood of repeating exposure (radiation dose implications) from the misalignment or anatomy cut-off.

Another interesting point to note with regards to image 26 (figure 44) which had significant magnification and hence omitted the lateral soft tissue borders of the greater trochanters is that all observers considered this image to be of diagnostic quality when responding to item sixteen on the image quality criteria scale (figure 44). This is surprising because in a trauma situation, an avulsion fracture of the greater trochanters could potentially be missed suggesting the image would not be suitable for diagnostic purpose. A repeat exposure would be required with an increased SID or elevated platform to ensure the inclusion of the lateral soft tissue borders of the greater trochanters (Carver & Carver, 2012). To reduce bias, observers were blinded to the acquisitions parameters used to acquire the images, and therefore were unaware that the experimental images were undertaken on a trolley. If observers had been aware of the imaging conditions, their judgment with regards to the diagnostic quality of image 26 may have been different as pelvic imaging on a trolley is indicative of trauma since most pelvic imaging on a trolley are acquired in trauma situations (Whitley et al., 2015). Image quality should always be related to the clinical indication therefore it would have been interesting to see whether the observers would still have deemed the image acquired using the Bi-Flex mattress at 110cm SID with the tray not elevated to be of diagnostic quality for a trauma situation (Ullman et al., 2004).

The above paragraph highlights problems associated with visual evaluation of image quality in optimisation studies because at present they limit the observer's response when evaluating image quality. Numerous optimisation studies have strict criteria to evaluate visual image quality using closed questions and Likert scales (Ma et al., 2013a; Mekis et al., 2010; Allen et al. 2013; Davey & England, 2015). The observer's perception of an image is determined by their own expectations and preferences but image quality criteria help the observers to focus on the visibility of pre-defined anatomic structures which minimises bias and observer variability by focusing their attention upon certain features within the image (Martin, 2007).

Closed questions are useful for obtaining factual information however they do limit a participant's response. Open ended questions on the other hand are useful to seek opinion and perceptions (Kumar, 2014). Open ended questions allow participants (or observers in this current thesis) to express their views freely yet again no visual image quality task at present allows for this. When radiologists write imaging reports, the reporting system isn't a 'closed' process where they have to state a 'yes' or 'no' answer with regards to detecting a fracture or lesion as an example. The Royal College of Radiologists (2006) define a radiology report as 'a clinically relevant opinion' meaning that it is highly subjective. Closed questions and Likert scales force observers in visual image quality assessments to make a decision but does not allow them to elaborate on that decision unlike a radiology report (Kumar, 2014). It would therefore be interesting to consider adapting the 2AFC software and incorporate a qualitative aspect into it which would allow observers if required to make additional comments to their decisions. Thematic analysis could then be performed on the qualitative data i.e. the comment boxes under each image to see whether themes emerge with regards to the quality of specific images. This could be done using qualitative software such as Computer Assisted Qualitative Data AnalysiS (CAQDAS) or NVIVO to code and analyse the qualitative data. Observers may decide that an image is of diagnostic quality for most clinical indications but not for example an initial trauma investigation. This method of evaluating visual image quality would reflect more accurately the reality of medical image interpretation as the level of image quality required is dependent upon the given clinical indication (Harding et al., 2014; Uffman & Schaefer-Prokop, 2009).

The reliability and validity of the sixteenth item on the image quality scale for this current thesis could also be questioned as this criterion required the observers to make a decision regarding the diagnostic quality of the image in question without knowing its clinical indication. Although this item represents what radiographers do everyday in working practice which is to accept or repeat an image based on professional clinical judgment, this item was not part of the validated psychometric scale developed by Mraity et al. (2013, 2015). If this current experiment was to be repeated, it would be interesting to see whether the opinion of radiographers with regards to the diagnostic quality of an image would change with different clinical indications i.e. AP pelvis following trauma verses AP pelvis to evaluate a healing fracture. Providing the observers with a clinical indication may also increase the ICC for observer agreement on the last visual image quality item. Kupinski

(2012) believes that in medical imaging, images are acquired for specific purposes and it is important to consider the clinical indication in order to evaluate the level of image quality required. Chan and Fung (2014) suggested that the level of image quality required between these two indications would differ, with trauma investigations requiring a higher image quality than follow up imaging. In addition, the qualitative aspect of the assessment may reduce the likelihood of image quality conflation because Joyce, McEntee, Brennan and O'Leary (2013) found that practitioners tend to unify aesthetic quality with diagnostic quality which can become an issue especially if the observers do not find the image aesthetically pleasing but yet again anatomical landmarks can be clearly visualised making image quality acceptable for diagnostic purposes. This issue would be highlighted and reflected by the qualitative nature of the assessment via the comment box after each image.

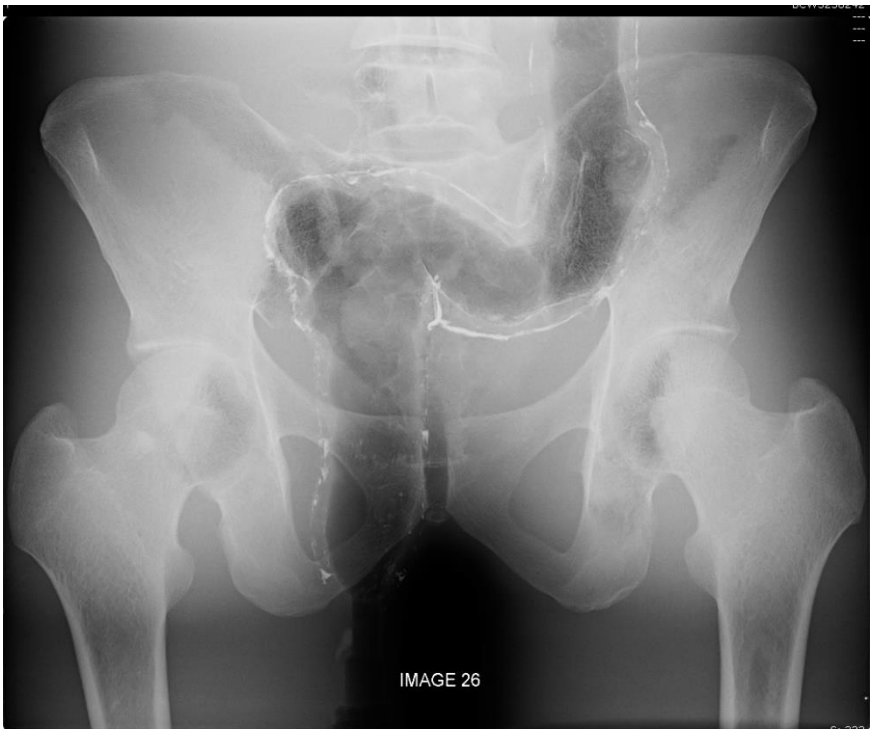

Figure 44- image acquired using Bi-Flex mattress, 110cm SID, 16mAs and platform not elevated.

When considering the outcomes of this section i.e. the trolley images acquired with identical acquisition parameters to the reference image were of lower image quality and higher radiation dose, the decision to transferring the patient onto the x-ray tabletop for imaging becomes even more critical. Even though the x-ray tabletop image (reference) was significantly better at lower radiation dose, the decision of moving/transferring patients' needs major consideration as the risks associated with this may outweigh the benefits.

Several articles including Beebe and Myers (2012), Carlton and Adler (2013) and Lee and Porter (2007) all stressed the importance of the patient being moved as little as possible when there are concerns regarding injures and when severity and type of injuries are unknown. According to the RCR (2011) *'Standards of Practice and Guidance for Trauma Radiology in Severely Injured Patients'*, moving a severely injured patient can cause delays due to the resources required when transferring and the risk of exacerbating blood loss which would be detrimental to patients wellbeing. For certain types of injury, the less the patient is moved and the shorter the distance, the greater the chance of survival and the less the chance of complications due to moving. There are also benefits to the healthcare team too in not moving patients as according to Stryker Prime X, many nursing injuries occur during transferring, repositioning, lifting or moving patients. These injuries are expensive for healthcare organisations and can shorten careers. It therefore might be a case of making a joint clinical decision whether the patient is stable and well enough to be moved onto the x-ray tabletop for imaging.

This above section (section 6.2 starting on page 142) explores whether acquisition parameters used to acquire an AP pelvis on the x-ray tabletop (reference image) can also be used to successfully acquire images on the trolley (experimental images) using the same acquisition parameters. The conclusion to this section is that acquisition parameters for AP pelvis on the x-ray tabletop are not directly transferable to AP pelvis examination on a trolley since there is a significant difference between both the visual image quality of these images and the radiation dose received by the patient (phantom in this case). This consequently presents the imaging department with two options when imaging the AP pelvis on a trolley. One is to develop a separate exposure chart for trolley imaging to ensure optimum image quality at the lowest possible dose or secondly a decision must be made to transfer patients for AP pelvis during trauma onto the x-ray tabletop for imaging. The first option seems to be favourable because in most situations, patients present on the trolley for a reason, this reason being that the emergency department is concerned about the patient's condition (Whitley et al., 2015). In addition, the AP pelvis still plays a major part in the ATLS imaging protocol and therefore the radiographer has to acquire the image in the resuscitation room rather than in the x-ray room on the tabletop (The National Clinical Guideline Centre, 2011). This demonstrates the need for a separate exposure chart for trolley imaging in this situation as the option of transferring a patient onto the x-ray tabletop isn't always feasible.

Another reason why the first option which is to develop a dedicated exposure chart is favourable is that transferring a patient onto the x-ray tabletop requires several members of staff which can be an issue during night shifts where there is limited numbers of staff. Also Obaid et al. (2006), Chmelová et al. (2006) and Guillamondegui et al. (2002) demonstrated their concern regarding transferring or pat-sliding a traumatised patient when major fractures have not been excluded. This reiterates the statement made earlier that patients present to the imaging department on a trolley for a reason.

Consideration is therefore required as to the optimum acquisition parameters required when imaging trolley bound patients in order to reduce the radiation dose to the patient, maintain an image of diagnostic quality and reduce the need of transferring patients from the trolley onto the x-ray tabletop. The optimisation scores of the experimental images in comparison to the reference image emphasises on this point and highlights the need for further work to be done on finding the optimum acquisition parameters required for trolley imaging. The optimisation score for the reference image was 500 which was significantly higher (nearly double) than the average sores for the experimental images (trolley) which was 254.9 (70SD). The image with the highest optimisation score (422.5) of the trolley images was one of the two images that was deemed unacceptable by a majority for diagnostic purposes. The implications of increased magnification in the resultant images also require major consideration if previous and future images are to be comparable. At present there are no published guidelines or exposure charts specifically designed for trolley imaging and according to Tugwell (2014), acquisition parameters are selected based on judgment rather than on empirical evidence. This current thesis highlights the need for a specific protocol when imaging trolley bound patients taking into consideration the type of grid utilised, the thickness and construction of the mattress, and the design of the trolley and image receptor holder as they all influence OID/magnification.

Considering the above observations from the current experiment regarding the need for modification in acquisition parameters for trolley imaging, the aim of the next section is to explore how modifying different acquisition parameters influence image quality and radiation dose for AP pelvis trolley imaging in order to optimise this imaging situation.

6.3 Comparison of image quality and radiation dose for the experimental images (trolley)

This section discusses and analyses the remaining results of the thesis by exploring how modifying the four variables influenced image quality and radiation dose for all the experimental images. The aim of this section is to assess and evaluate how the mattresses, platform position, SID and mAs influenced image quality and radiation dose when imaging a trolley bound patient and to establish how and when the acquisition parameters require manipulation in order to optimise image quality and patient dose.

6.3.1 Comparison of image quality and radiation dose for the two different mattresses (standard verses Bi-Flex)

Two different mattresses are available with the Lifeguard 50 trolley (standard and Bi-Flex) and both were explored for this thesis. Due to the limited manufacturer information regarding the specific materials and density of these two mattresses, a preliminary experiment was conducted prior to the main experiment in order to discover their attenuating properties (see section 4.2.4 on page 80). From the results of this preliminary experiment, the Bi-Flex mattress resulted in the lowest detector dose indicating it had absorbed more of the x-ray photons than the standard mattress. This preliminary experiment did not indicate specifically the source of this reduction in detector dose and therefore the difference seen between the absorbing characteristic of the two mattresses could be due to the thickness, density, design or scatter produced. The Bi-Flex mattress however had the lowest detector dose and therefore it would be reasonable to assume that this mattress would result in increased dose to the patient (increased OID) and poorer image quality. According to Uffman and Schaefer-Prokop (2009) image noise is inversely related to the amount of detector radiation dose hence an indication of image quality. Nevertheless, for the main experiment no statistical significant difference in visual and physical image quality was found between the standard mattress and the Bi-Flex mattress. Even though this was unexpected, it was not surprising since no p-value was derived for the difference found in the preliminary experiment and therefore even though the Bi-Flex mattress had lower detector dose, this decrease may have not been statistically significant.

Although authors including Hess and Neitzel (2012) and Whitley et al. (2015) comment that an absorbing material such as a mattress in the path between the patient and the detector would absorb photons, reduce image forming radiation and cause more scatter, the opposite should also be considered. The Bi-Flex mattress is thicker and has been proven to absorb more photons than the standard mattress, but yet again this mattress might have absorbed the low energy photons and therefore increase the quality of the beam similar to a grid or a filter. This is another reasonable explanation why there was no significant difference found between image quality when using these two mattresses. Mutch and Wentworth (2007) found similar results in their study when investigating incubator trays on SCBU. They found that the incubator with the largest mattress support thickness of 10 cm had the lowest attenuation factor of 40% and produced similar image quality to the other mattresses and incubator designs. This emphasises the importance of considering various factors associated with a piece of equipment/object in the primary beam's path including its thickness, the density of the absorbing material between the x-ray tube and the patient plus its design. These factors should all be considered when purchasing imaging equipment however manufactures including ArjoHuntleighs, Seers Medical Limited, Wardray Premise and Stryker Prime X advertise their mattresses as suitable for imaging but with no empirical evidence or statistics to support their statements. Perhaps each manufacturer should quote the aluminium equivalent of their mattresses similar to NICE (2011) in order to highlight the potential absorbing characterising of the mattresses. This would allow the customer to decide whether the transmission of x-ray was acceptable or similar to other mattresses used in the department.

There was also no significant difference found in radiation doses between the two different mattresses for this thesis. With this in mind and the fact that there was also no significant difference found in visual and physical image quality between the mattresses, the thicker Bi-Flex mattress should perhaps become the typical mattress purchased with a Lifeguard trolley. This is because the Bi-Flex mattress offers more benefits to the patient from a comfort and safety perspective since it is designed to reduce the likelihood of developing pressure ulcers (ArjoHuntleighs, 2010). Reducing this likelihood is very important since pressure ulcers remain a familiar problem in health care and are one of the most costly and physically debilitating medical complications in twentieth century care (Agrawal & Chauhan, 2012). They most commonly develop in patients who remain in one bodily position for an extended period of time (Shoker, 2010). This is worrying when

considering that patients requiring imaging examinations on trolleys need to lie still in the same position to acquire the images but also they may have been on the same trolley in the emergency room for a long period of time. This is a common problem in emergency departments across the UK where the number of patients waiting on trolleys for beds has tripled in four years (Donnelly & Sawer, 2014; Wales News Service, 2015). This demonstrates that these prolonged waiting times in the emergency department results in patients remaining on trolleys for long periods of time, increasing their risks of developing pressure ulcers. This is why the Lifeguard trolleys in the emergency department are purchased with Bi-Flex mattresses since they are pressure redistributing foam mattress, designed to reduce the likelihood of developing pressure ulcers. According to the ArjoHuntleigh (2014), this mattress has been constructed using two layers of foam, the base layer is a higher density foam providing support for the patient in the sitting position and the top layer is of lower density foam for comfort and easy manipulation of the mattress angulation. This has resulted in a comfortable and stable mattress design, which maximises pressure redistribution, thereby aiding the prevention of pressure ulcers. Purchasing this Bi-Flex mattress therefore results in no significant implications from an imaging perspective and it decreases the likelihood of patients taking legal action when pressure ulcers developed due to clinical negligence.

Currently, the imaging department where this experiment was undertaken uses the standard mattress on the Lifeguard trolley as oppose to the Bi-Flex mattress used in the emergency department. This is because patients do not remain on these trolleys for as long, e.g. ward patients who are transferred onto the trolley for imaging and are subsequently returned to the ward and transferred immediately back to their beds. Nevertheless, Dharmarajan and Ugalino (2006) demonstrated the potential for tissue breakdown after only 20 minutes of prolonged interface pressure. This is worrying because from clinical experience, the wards patients which use the Lifeguard trolley with the standard mattresses remain on them for longer than 20 minutes depending on where they are transported to and from, how busy the department is and what and how many body parts are being imaged. Everton et al. (2014 a/b) recognised this potential for patients to develop pressure ulcers whilst in the imaging department and went on to explore this concept further. Everton et al. (2014b) measured the pressure interface from two radiological surfaces (with and without a mattress) in order to estimate their potential to contribute to the development of pressure ulcers after lying on them for 20 minutes. This study however used healthy volunteers aged 18-51 which did

not reflect the true problems encountered in clinical practice. If Everton et al. would have used patients, especially high risk individuals such as the elderly or the immobile (Cullum, McInnes, Bell-Syer & Legood, 2004; Haleem, Heinert & Parker, 2008) the results may have been exacerbated in terms of the, pressure interface, time implications and comfort. This is interesting considering that trauma patients requiring AP pelvis imaging would be lying supine in the same position because of immobility and also neck of femur fractures are predominantly seen in the elderly (high risk population) (Almazedi et al., 2011). Another point to consider with regards to the study by Everton et al. (2014b) was the discomfort experience by the individuals having to lie still on a radiological surface. Discomfort might cause patient movement and hence degrade image quality or necessitate a repeat exposure. Therefore by providing patient with a comfortable mattress such as the Bi-Flex mattress, it may reduce the likelihood of developing pressure ulcer but it may also increase patient comfort and cooperation whilst imaging.

Another factor that was explored for this thesis was magnification when imaging trolley bound patients. The two mattresses available on the Lifeguard trolley are of different thickness (standard 6.5mm and Bi-Flex 13mm) and therefore not surprisingly a significant difference in magnification level on the resultant images was found between them. The average difference in magnification between the two mattresses was 5mm. The RANDO pelvis anthropomorphic phantom used for this thesis simulates an average adult weighing 73kg. However, with the prevalence of obesity increasing and thus having major effects on the imaging department, it would have been interesting to explore the effect of varying patient sizes on magnification level (Uppot, Sahani, Hahn, Gervais & Mueller, 2007; Le, Robinson & Lewis, 2015).It is reasonable to assume that magnification level would differ for larger/heavier patient as they may sink more into the mattresses than a smaller patient resulting in compression of the mattress. This observation is beyond the scope of this thesis plus obese patients present with other imaging difficulties that would need to be further explored in conjunctions with this (e.g. exceeding the weight limits of imaging equipment, motion artefacts due to increased exposure factors requiring elongated exposure time, insufficient coverage of the image receptor, difficulty in palpating anatomical landmarks).

6.3.2 Comparison of image quality and radiation dose for the two different image receptor holder position (platform elevated verse not elevated)

Another objective set out in this thesis was to assess and evaluate how trolley platform position (elevated or not elevated) affect image quality and radiation dose. The platform for the Lifeguard 50 used for this thesis should always be elevated prior to an exposure as per manufacturer operating instructions in order to reduce OID and hence magnification. The only reason images were acquired with the platform not elevated was because Tugwell's (2014) study showed that some radiographers did not always ensure the elevation of the platform due to reasons such as time impactions, damage or it being used for storage. Surprisingly, the results demonstrated that visual image quality was significantly better when the platform was not elevated. There is an OID difference of 60mm when the tray is not elevated which significantly increases magnification on the resultant images by an average of 4.5mm (0.7 standard deviation).

One reasonable explanation for the increased visual image quality when platform was not elevated could be the naturally occurring air gap between the image receptor and the patient which reduced scatter. Numerous studies including Sorenson and Floch (1985) Gleeson et al. (2001) and Neitzel (1992) have explored the benefits of an air gap between the patient and the image receptor suggesting it reduces the scatter reaching the image receptor. Nevertheless, most studies on air gap technique e.g. Sorenson and Floch (1985) and Persliden and Carlsson (1997) have used computer modelling via Monte Carlo simulation which has the disadvantage of being able to create imaging situations that are not practical or clinically possible such as that shown by Poletti and McLean (2005). In addition, there is reliance on the researchers when using computer modelling to test and validate the program in comparison to measurements performed on an actual x-ray system (Morrell, 2006). These studies on air gap were also conducted on film/screen and therefore the effect and outcome identified on image quality and radiation dose for these studies might be different for digital systems. There has been a lack of studies on air gap technique using anthropomorphic phantoms where image quality has been visually evaluated. The two more recent studies found on air gap where by Chan and Fung (2014, 2015). They used a similar method to the current thesis where they acquired various images using different air gap thickness and these images were subsequently evaluated by experienced observers comparing the image quality of the experimental images (air gap) to a reference

image acquired under *'standard imaging conditions'* using a grid. They found on both occasions that visual image quality was reduced when using air gap method compared to using a grid and therefore questions the explanation that visual image quality increased due to air gap for this thesis. They also interestingly concluded that although the air gap technique demonstrated a significant reduction in dose, this technique should only be considered when high image quality is not required such as for follow up imaging or post operatively.

In addition, when considering the evidence from previous studies on air gap technique, it is difficult to apply it directly to the current thesis's scenario on the trolley since firstly the trolley images with platform not elevated were acquired with a grid therefore both an air gap and a grid were present. This has not been explored in previous studies since the main purpose of introducing an air gap is to eliminate the necessity of the grid in order to reduce dose. Using an air gap whilst removing the grid was considered for this thesis however during the preliminary stages of the experiment, images were acquired on the trolley without a grid but image quality was visually poor and unacceptable and therefore excluded.

Keating and Grange (2011) studied the use of stationary and moving grids in comparison to a non-grid technique for AP cervical spine. This study did not consider the difference in OID between these three techniques which would have been approximately 8-10cm when considering the average OID difference between direct and Bucky exposure (Bontrager & Lampignano, 2014). In addition, Keating and Grange did not consider the implications of the AP cervical spine in a trauma situation where the image receptor would have to be placed in a image receptor holder under the trolley. They did however observe an increase in scatter (noise) on the image acquired without a grid. It would have been interesting to see whether the noise level on this image would have been reduced if the image receptor was placed in the trolley holder as the increased OID may have removed some scatter which would have reinforced the findings of this thesis. But yet again, this study by Keating and Grange did not consider their imaging conditions on a trolley.

These arguments and explanations above on why visual image quality was better when platform was not elevated are based on physical theories such as the inverse square law and geometric unsharpness which is influenced by OID and SID. Gorham and Brennan

(2010) however argued that the link between these facotrs and visual image quality is not well understood. Gorham and Brennan's (2010) and Ma et al. (2014) explored the effect of small and large focal spot sizes on visual image quality and whether a small focal spot is actually required for smaller body parts in order to demonstrate fine detail. As discussed previously, geometric unsharpness is a key component of degradation of spatial resolution in CR systems and is influenced by three parameters: focal spot size, OID, and SID (Ma et al., 2014). Although physically it is suggests that a small focal spot may improve image quality, they found that focal spot size has an insignificant effect on visual image quality which might therefore be true for an increase in OID. According to Whitley et al. (2015) increased OID results in greater geometric unsharpeness which reduces image detail; however for this thesis the decrease in image detail due to geometric unsharpness caused by the increased OID was not visually noticeable to observers. This means that the physical factor here associated with an increased OID may not be visible to the human eye.

Another point to consider for this current thesis is although visual image quality was better when the trolley platform was not elevated, it does not necessarily mean that these images were of high quality. As was seen in section 6.2 on page 142, the visual quality of the images acquired on the trolley (with and without the elevation of the platform) was significantly worse in comparison to the image acquired on the x-ray tabletop. It is important to remember that high image quality is necessary when searching and evaluating fractures and considering that most pelvis imaging on a trolley is undertaken following trauma, this further emphasises the need to produce high quality images of the pelvis on trolley (Uffman & Schaefer-Prokop, 2009; Busch & Faulkner, 2005). There are some instances where the pelvis may be imaged with the patient remaining on the trolley other than for trauma situation for example post operatively in order to reduce the movements of the patient onto the x-ray tabletop (Whitley et al., 2015). Image quality for this situation differs considerably from a trauma situation according to various authors including Chan and Fung (2014) and Uffman and Schaefer-Prokop (2009) since high image quality is not compulsory when evaluating the position of metallic implant. This needs to be considered in the conclusion of this thesis as certain acquisition parameters used to acquire some images may be sufficient for the latter scenario but not for trauma imaging

Another reasonable explanation as to why visual image quality was better with an un-elevated platform may be due to magnification. When the platform is not elevated, it

significantly increases magnification ($p<0.05$) especially when the SID is maintained at 110cm. Manning, Ethell and Donovan (2004) suggests that visual image quality is influenced by more than just the sharpness of anatomical outlines and the image noise; the size and complexity of structures can impact upon observer interpretation too. Could this mean that the increase in magnification may have influenced the observer assessment of various structures? Visual acuity is strongly linked to image interpretation in radiology (Alexander, 2010; Marchiori, 2014; Quaghebeur, Bhattacharya & Murfitt, 1997) and the method of examining visual acuity is by using the common Snellen chart. The principle of this chart is that it assesses visual acuity by presenting individuals with random letter that reduce in size per line (Colenbrander, 2013). This chart assumes that vision is influences by the size of the letters hence strengthens the assumption made for this current thesis that visual perception in radiology may be influence by magnification. The increased magnification seen in some of the experimental images (increased OID with platform not elevated) enlarges pelvic structures by up to 10mm making them more prominent in comparison to both the reference image and the images were the platform is elevated. This assumption is also supported by work conducted by Vladimirov (2010) when performing visual evaluation on test phantoms. Vladimirov suggests that the largest circles within the phantom are easier to see in comparison to the smallest circle which is virtually invisible because our perception performs a local averaging of intensities. The visibility of an object is proportional to its area with contrast, noise object size and shape all affecting our ability to extract visual information from an image.

In addition, there was no significant difference found between CNR and platform position which means the difference was only witnessed for visual image quality. This strengthens the argument that magnification influences the perception of observers as objects of greater size is perceived to be better visualised.

The above argument regarding magnification influencing perception of visualised structures may be more apparent due to the fact that image manipulation was not permitted for the visual evaluation which meant that the magnification level of each displayed image was the only scaling seen by the observers. It would have been interesting to see how visual evaluation was influenced if observers were permitted to zoom and magnify the image. One of the advantages of digital radiography is its ability to manipulate the images post-processing. RCR (2012b) and Korner et al. (2007) both suggested that the

magnification and zooming facility in PACS can improve image interpretation. Nevertheless there is inconsistency in optimisation studies as to whether observers are permitted to manipulate the images in visual evaluation tasks. Davey and England (2015), Woods and Messer (2009), Ma et al. (2014) prohibited zooming or any manipulation in their visual image assessment in order to keep the images seen by the observer consistent. If optimum acquisition parameters are being explored then this method prevents the post processing capabilities of digital systems influencing the results but on the other hand it does not reflect what really happens in clinical practice. De Crop et al. (2012) and Lorusso et al. (2015) were two studies found that allowed observers to manipulate the image including zooming on various structures when assessing image quality. Other studies including Allen et al.(2013) and Lanca et al.(2014) do not state whether manipulation was permitted or not. This inconsistency within optimisation studies makes it difficult to compare findings which is further emphasised by the fact that zooming as seen for this current thesis has the potential to change the outcome of the visual evaluation especially if experimental images have varied magnification levels. Further studies need to be conducted in the psychology of perception, cognition, and human influence that would contribute to the understanding of the human eye-brain system and factors controlling medical interpretation (Krupinski, 2010).

The argument regarding magnification level influencing visual perception could be one of the reasons why visual image quality scores was also slightly better when using the Bi-Flex mattress (although this was not considered significant p=0.07). The Bi-Flex mattress was double the thickness of the standard mattress and therefore produced greater magnification of the structures within the pelvis. The fact that there was no statistical difference identified between CNR and the two variables discussed (mattresses and platform position) also suggests that observer assessment may be influenced by something other than noise level. The main clinical indications for imaging the AP pelvis are trauma, arthritis, multiple myloma, perthes and slipped upper femoral epiphysis (Carver & Carver, 2012). These indications all relate to the bony pelvis rather than low-contrast objects within the pelvis such as lesions and therefore the AP pelvis needs to be of high contrast to enable visualisation of the bony trabeculae and the margins of the cortex clearly (Mckinnis, 2013). Verdun et al. (2002) and Sprawls (1995) indicate that good CNR is more important when visualising low-contrast objects, however this is not the case for AP pelvis imaging and as seen in this current thesis CNR does not correlate well with visual image quality.

Increased OID, resulting in increased magnification, can cause image blurring; this is caused by the penumbra. Penumbra is the blurring at the edges of a structure on a radiograph influenced by the SID, focal spot size and OID. When the distance between the object (patient) and the image receptor is increased (increased OID), penumbra also increases causing increased burring and reduced image sharpness on the resultant image (Carlton & Adler, 2013). Nevertheless, for this current thesis, the images with greatest magnification have the highest visual image quality score which means the effect of penumbra did not influenced visual image quality for AP pelvis. This finding is not however unexpected when considering the observation made by Sprawls (n.d.) that the effect of blur has limited effect on the visibility of larger objects, it only affects smaller low contrast objects. In addition, Sprawls went on to suggest that viewing distance may have an affect on the visibility of structures since small objects will have the same detectability at close viewing distances as a larger object viewed at a greater distance. The detectability of an object is associated with the angle it creates in the visual field with this angle being the ratio of object diameter to the distance between image and observer. This therefore suggests that the visualisation of structures is indirectly related to magnification because when the viewing distance is reduced the object creates a larger angle and is normally easier to visualise. If the experiment in this thesis was to be repeated in the future, it might be worth restricting the viewing distance of the observers but allow for zooming and scaling of the images to see whether it has a different impact on visual image quality.

No statistical significant difference was found between radiation dose and the platform position but also there was no statistical difference found between the figure of merit (‘optimisation score’) and the platform positions either. Considering that there was a significant difference found in visual image quality between platform position (platform not elevated was significantly better), the radiation doses must have a slight difference in this scenario (platform not elevated has higher radiation dose) in order for the ‘optimisation score’ to have no significant difference either. This means that although no significance difference was found between radiation dose and platform position, there must have been enough of a difference to make the optimisation scores similar (no significant difference) since optimisation score is derived from dividing image quality scores with radiation dose.

6.3.3 Comparison of image quality and radiation dose for the source to image distances (SID)

Predictably, radiation dose significantly decreased with increasing SID ($p<0.05$) with also a decrease in visual image quality found with increasing SID ($p<0.05$). This was slightly surprising considering the studies conducted in this area from Tugwell et al. (2014), Heath et al. (2011), Woods and Messer (2009) where they found increasing SID to significantly reduce dose but with no significant difference in visual image quality. Nevertheless, these studies were carried out using conventional imaging on an x-ray tabletop and therefore may not be directly comparable to trolley imaging when considering the differences between these two scenarios as discussed in section 3.1.4 on page 20. These previous studies on SID did not have an increased OID as for trolley imaging; there was less variables to consider. This thesis demonstrates a decrease in image quality with increasing SID which is not surprising when considering that image quality should theoretically decrease when SID is increased according to the inverse square law due to reduced beam intensity (Reid-Paul, 2011).

Another reasonable explanation for the decrease in visual image quality with increasing SID may possibly be related to the method used to assess image quality. The visual image quality assessment for this thesis used bespoke software and a newly developed validated psychometric scale. This scale may be more sensitive to changes in image quality than the scales used in previous literature such as that of the CEC quality criteria which are based on film/screen imaging (Heath et al., 2012; Woods & Messer, 2009; Brennan, McDonnell & O'Leary, 2004; Grondin et al., 2004). As previously stated, the CEC guidelines were developed in 1996 for film/screen imaging and therefore many of the benchmarks do not apply in the digital environment, plus other important aspects of image quality relating to digital imaging are missing (Knight, 2014). In comparison to the CEC image quality criteria, the psychometric scale used for this thesis has gone through robust systematic testing and has validation data to support it. This newly developed psychometric scale may therefore be more sensitive to changes in visual image quality.

The last item on the 2AFC task brought about interesting results as it required the observers to decide whether the experimental image in question was acceptable or

unacceptable for diagnostic purposes. This item was included in the image quality scale since an image with a lower score than the reference image does not necessarily signify that it is not acceptable for diagnostic purpose thus requiring a repeat. There were 48 experimental images acquired for this thesis and five observers evaluating image quality. Twenty images where deemed to be of unacceptable image quality by one or more observers, however, only two of these twenty images were deemed unacceptable by a unanimous decision (i.e. three or more observers). This demonstrates a large variation in opinion amongst the observers as to the diagnostic quality of the images. Even though this type of decision (deeming images acceptable or unacceptable for diagnostic purposes) is an important and everyday responsibility of radiographers, in clinical practice the clinical indication for the examination is known to the radiographer. As previously mentioned, this demonstrates a major downfall to the last item on the visual image quality criteria because observers were asked to decide whether image quality was acceptable or not without any indication as to why the examination was undertaken. This is important because the clinical indication determines the required quality of an image (Chan & Fung, 2014; Harding et al., 2014). The AP pelvis examination is predominantly performed on a trolley in trauma situations (Whitley et al., 2015; Carver & Carver, 2012) and therefore image quality needs to be high when searching for fractures (Chan & Fung, 2014; Uffman & Schaefer-Prokop, 2009).

On the other hand, if observer number two was eliminated from the experiment, only seven images would have been deemed diagnostic by more than one observer instead of twenty. This means that observer number two was much more critical of image quality in comparison to the other observers. Allen and Triantaphillidou (2011) commented that the experience of the observer may cause variation in the assessment of image quality which is interesting since observer number two was more senior in comparison to the other four. Perhaps stricter observer inclusion criteria should be made for visual evaluation rather than it being a radiographer with more than 5 years experience as this could be a radiographer with 6 years experience or a radiographer with 30 years experience.

On reflection to the above limitation regarding the last item on the visual image quality scale, it would have benefited from some validation work to determine whether the item achieved its aims and discriminated between good, adequate and unacceptable images rather than it being binary. In addition, this item may have achieved its goal if a more

specific question such as *"is this image of diagnostic quality to detect fractures for trauma AP pelvis?'* would have been asked. Perhaps observers would have been more critical of image quality since according to Mraity et al. (2014a), it is commonly accepted that image quality can be described with regards to its acceptability for achieving the main clinical question. Uffman and Schaefer-Prokop (2009) and Busch and Faulkner (2005) also stated that the interpretation of image quality should be considered in groups/class where fracture detection requires the highest possible image quality in comparison to an image post hip replacement which requires lower image quality.

For this thesis, three (platform position, mattress thickness and SID) of the four independent variables caused inconsistency in magnification level. This was because the OID varied for the different imaging conditions which meant that magnification level increased for all experimental images compared with the reference image. This can be worrying from a clinical perspective since the AP radiograph, even after trauma, can be used for surgical planning where the measurements of the patient's prosthesis are determined. Femoral offset is a common measurement taken from the AP pelvis, were surgeons measure the distance from the centre of rotation of the femoral head to a line bisecting the long axis of the femur (Lecerf et al., 2009). According to Merle et al. (2013), femoral offset is frequently underestimated on AP pelvis radiographs as a result of imprecise magnification. Paul, Docquier, Cartiaux and Banse (2008) went on to state that magnification on radiographs is a well known predicament in preoperative planning of orthopaedic surgery where software are used to presume magnification of approx 110% due to buttocks. When magnification levels vary, it can impact upon the correct selection of prosthesis size; this is why the use of a calibration ball is regularly used in clinical practice (Conn, Clarke & Hallett, 2002). To overcome these issues, Clohisy et al. (2008) stated that when evaluating a radiograph, whether it is AP pelvis or other projections, diagnostic accuracy and disease classification is improved when there are standardised imaging protocols in place where the same acquisitions parameters are used for every projection. This would not only improve surgical planning but also improve the interpretation of images as they would be more comparable to previous and future images of the same area in the same patient.

6.3.4 Comparison of image quality and radiation dose for various mAs increments

As expected, both image quality and radiation dose increased with increasing mAs. There is a direct relationship between dose and mAs since an increase in mAs causes a proportional increase in dose (Chan & Fung, 2013). Higher mAs increases beam intensity consequently reducing image noise and improving radiographic contrast (Allen et al., 2013).

This is why optimisation is very important in radiographic imaging to ensure that image quality and radiation dose are considered collectively, otherwise due to the relationship between mAs and image quality radiographers may increase mAs unnecessarily in order to guarantee an image of high diagnostic quality on first attempt. This is where the phenomenon 'dose creep' has originated from since radiographers increase mAs to ensure image of diagnostic quality allowing for too high a dose than needed (Uffman & Schaefer-Prokop, 2009). Unlike film/screen, digital radiography does not provide the radiographer with direct feedback on whether appropriate exposure factors are used. Digital imaging systems have wide exposure latitude and a linear response to x-ray energies and therefore can compensate and correct for inappropriate exposure factors. Ma et al. (2013a) witnessed higher doses given to patients for chest x-ray imaging without image degradation and that the largest over-exposure factor for a chest was 139 before the image was visually deemed unacceptable.

With the above paragraph in mind, dose creep could be a worrying phenomenon when imaging the AP pelvis on a trolley especially considering that it occurs often in examinations where the AEC is unavailable. When the AEC is unavailable, radiographers may use higher mAs to ensure the correct exposure on the initial attempt (Ma et al., 2013a). This may be the case for trolley imaging since the AEC is not feasible and therefore mAs was set manually for the experiment in this thesis. It would be interesting to discover how much mAs each imaging condition would actually receive if the AEC was made available on a trolley however currently this is impossible. An AEC system on the trolley would reflect more clearly the differences in attenuation of each imaging condition since the AEC terminates the exposure once the image receptor has received enough x-ray photons. Unfortunately this scenario is not possible and could not be reliably replicated on the x-ray tabletop due to much differences existing between these two satiations (air gap,

trolley top, mattresses). Seeram, Bushong, Davidson and Swan (2014) recognised that manual techniques (this including mAs when AEC is unavailable) are missing from the recommended parameters set out by CEC quality criteria (1996) and therefore during trolley examinations and portable radiography the radiographer depend on exposure charts and judgment. Herrmann et al. (2012) expresses concerns in this area by commenting that if a imaging department does not develop exposure technique charts or make them accessible to radiographers, it is challenging for radiographers to manually set acquisition parameters such as mAs, kVp and SID (Herman et al., 2012).

For the current thesis a predictable inverse correlation between SID and mAs was also noted. Images acquired at 110cm SID using 32mAs produced the highest visual image quality scores but at the cost of highest effective dose whereas images acquired at a 130cm SID using 16mAs had the lowest visual image quality scores at the lowest effective dose too. This correlation causes difficultly when deciding upon the optimum technique to use, there needs to be a compromise between both image quality and radiation dose. Williams et al. (2014) proposed a method in which visual image quality scores are divided by effective dose to give a figure of merit. This figure of merit would signify an optimisation score where a high score would indicate better image quality at lower dose whereas a low score would indicate poorer image quality at higher radiation dose. This optimisation score (image quality divided by effective dose) provides useful information on exposure levels and helps identify the optimum technique that produces suitable image quality with low dose. For this thesis, the experimental image with the highest optimisation score was the image using the standard mattress, elevated platform, 16mAs and an SID of 130cm. Nevertheless, this image was considered unacceptable by three or more observers. Although issues have been raised with regards to the validity of this image quality item, it cannot be a coincidence that the majority of observers deemed this image to be of low quality. For the remaining images which were regarded as diagnostic by the observers, the optimum acquisition parameters identified from the optimisation score was the image acquired with an SID of 130cm at 20mAs with platform not elevated using the standard mattress. This image was of diagnostic quality and fell within the middle quartiles of the image quality scores. The effective dose for this image was 0.01mSv higher than the reference image dose and was within the lower quartile of radiation dose.

Even though the above image (SID of 130cm, 20mAs, platform not elevated, standard mattress) had the greatest optimisation score, the optimisation score for the reference image is significantly higher than all experimental images ($p<0.05$). On average, the optimisation score for the experimental images dropped by 49% which further highlights the need for trolley imaging to be explored and optimised appropriately.

In summary to this discussion section, the following points need to be considered when imaging the AP pelvis on a trolley:

1. The acquisition parameters used to acquire the AP pelvis on the x-ray tabletop need to be considered carefully when transferring these to trolley imaging. Radiation dose significantly increased and visual image quality significantly decreased for trolley imaging using the same acquisition parameters as the reference image. Yet again none of these trolley images were deemed non diagnostic by the observers. The limitation witnessed with item 16 on the image criteria does however jeopardise the reliability of this observation. A separate exposure chart should be developed for all imaging examinations on the trolley that uses the trolley platform.

2. No significant difference was found for visual image quality or effective dose when comparing the standard and Bi-Flex mattresses. This Bi-Flex mattress should therefore be considered gold standard when purchasing a Lifeguard 50 trolley as it offer more benefits to the patients since it is designed to reduce pressure ulcers and it does not significantly impact on the imaging examination.

3. Magnification variation is an issue that needs attention when imaging the AP pelvis on a trolley especially if images are to be used for planning orthopaedic surgery without the use of a calibration device. To overcoming these issues, specific guidelines need to be set when imaging trolley patients (e.g. maintain constant SID and platform position) in order to minimise variations between different patients and obtain consistent measurements in an individual over time. Another option is to use a calibration ball or an object of know size on every image to allow for calibration and scaling to occur.

4. The clinical indication of every examination needs consideration before an exposure is made because this may influence the acquisition parameters which are set. Some clinical indications require a higher quality image e.g. to detect an occult fractures as oppose to images that do not require a high quality images such as those that confirm the positions of pins and nails or to monitor bone alignment (Chan and Fung, 2014)

5. If the 'optimisation score' (figure of merit) is considered for this current thesis, the optimum acquisition parameters for imaging the AP pelvis on a trolley are, 20mAs, 130cm SID, standard mattress and platform not elevated. These parameters resulted in an image with the highest optimisation score but also not one observer deemed this image to be non diagnostic. However as mentioned above, guidelines need to be set to standardise practice in order to reduce inconsistencies in magnification and image quality because a significant difference in magnification level exists between the platform being elevated and not elevated.

Chapter 7 - Conclusion

This thesis was conducted using an experimental design with the aim of optimising the AP pelvis examination on a trolley using a CR system with an anthropomorphic phantom. The main objective was to investigate whether acquisition parameters used for AP pelvis on an x-ray tabletop can be successfully transferred for this projection on a trolley. It was found

that visual image quality for the trolley images (experimental) using the same acquisition parameters as for the x-ray tabletop image (reference) significantly decreased ($p<0.05$) with effective dose significantly increasing ($p<0.05$). Although visual image quality did decrease for the four images acquired on the trolley using identical acquisition parameters as to the reference image, the last item on the image quality criteria scale (item 16) revealed that the observers unanimously found them to be of diagnostic quality. This last item in the image quality task was not however part of the validated psychometric scale developed by Mraity (2015) and therefore its results should be dealt with cautiously. It requires the observers to make a decision on the diagnostic quality of the experimental images using a binary response (yes/no) without any information as to the clinical indication for that examination.

The secondary aim of this thesis was to optimise image quality and radiation dose for AP pelvis imaging on a trolley. This was achieved by exploring different variables on the trolley including two different mattresses, platform position, mAs and SID, and to identify their influence on visual image quality, CNR, effective dose and magnification. From the four variables, SID and mAs had the main impact on image quality and effective dose with increased SID significantly reducing both visual image quality and radiation dose whilst an increase in mAs significantly increased both image quality and dose. It is therefore not surprising that the only two images that were deemed non diagnostic by three or more of the observers were the images acquired using the highest SID of 130cm, lowest mAs of 16, an elevated platform using both the mattresses.

The most surprising finding from this thesis was that visual image quality was significantly better with the platform not elevated. There is an increased OID by 6cm when the platform is not elevated in comparison to the platform being elevated. The discussion section has covered reasonable explanations for this finding however further work needs to be conducted to prove some of these theories. One of the arguments for this finding was that increased magnification caused by the platform not being elevated resulted in structures appearing larger than those when the platform was elevated, plus, observers were restricted to use zooming and scaling facilities during the visual image quality assessment. It is worth remembering that no significant difference was identified between platform position and CNR with the CNR calculated using a method that compensated for the differences in magnification.

In the results section, visual image quality scores and effective dose have been grouped into quartiles, with the upper quartile indicating images of highest quality (table 13) and highest radiation dose (table 16). There are four quartiles and 48 experimental images therefore twelve images fall into each quartile. Of the twelve images that fall within the upper quartile of image quality, only one of these images appear in the lower quartile of effective dose (lowest radiation dose) which is the image acquired using the Bi-Flex mattress, platform not elevated, 120cm SID at 16mAs. These parameters should therefore be considered to be the optimal parameters as they produced an image of high diagnostic quality at lower dose.

Optimisation plays and important role in determining which acquisition parameters need modifying to enhance image quality whilst keeping dose to the ALARP principle. Optimisation can be complicated in radiography since it requires image quality to be sufficient to provide clinical diagnostic information with the radiation dose not significantly higher than necessary (Mraity, 2015). However, image quality will in general improve with the use of more radiation, therefore careful consideration is important to determine the level of image quality required to make a diagnosis. The level of image quality required will depend upon the clinical indication (Uffmann & Schaefer-Prokop, 2009).The figure of merit proposed by Williams et al. (2014) as an indication of optimisation (optimisation score) seemed to be an effective method and a starting point in determining the optimum technique that produces suitable image quality at low dose. From all experimental images, the images with the highest optimisation scores and considered to be of diagnostic quality were the images acquired with an SID of 130cm, 20mAs, elevated platform whilst using both mattresses. It must be noted however that the optimisation score for all of the experimental images were significantly lower than the optimisation score of the reference image ($p < 0.05$).

Magnification was a sub-section of image quality that was explored for this thesis. Magnification is a misrepresentation of object size as projected onto PACS (Bontrager & Lampignano, 2014). This is caused by the diverging beam as it passes from the object to the image receptor. Therefore the variation in OID between imaging conditions within this thesis had an impact on magnification of the displayed images. Magnification for this

thesis was assessed by measuring the femoral head diameter of each image. From all the images acquired during the thesis's experiment, the difference between the image with greatest magnification in comparison to the image with least magnification was 12.8mm. The image with greatest magnification was acquired with a 110cm SID, platform not elevated using the Bi-flex mattress, whereas the image with the least amount of magnification was acquired with 130cm SID, platform elevated using the standard mattress. This 12.8mm difference between these two images is significant ($p<0.05$) especially when considering a 12.8mm measurement variation on a monitor for visual image quality evaluation. It is important to establish standardised acquisition parameters for imaging examinations to minimise variations between different patients but also to obtain consistent measurements for one patient over time. This is very important especially if orthopaedic surgeons use the images to plan surgery without a calibration device (Crooijmans, Laumen, van Pul & van Mourik, 2009). It is therefore vital for trolley imaging to have its own technique and exposure chart in order to maintain consistency of image quality and radiation dose (Bontrager & Lampignano, 2014; Fauber, 2013).

Reiterating on the latter sentence, the results of this thesis have demonstrated the need for specific exposure charts for trolley imaging as it is noticeably different from general x-ray tabletop imaging. Gleeson et al. (2001) also recognised the need to modify acquisition parameters appropriately when imaging on a trolley due to thicker trolley mattresses and the image receptor holder beneath the trolley increasing the distance between the image receptor and the patient. Gleeson et al. also demonstrated concern for the increased magnification of this scenario whilst emphasising the need to revisit the technique and acquisition parameters used in this situation. The results of this thesis have strengthened this argument. It is understandable that exposure charts take time and effort to develop accurately however they provide consistent radiation dose to the patient and prevent exposure technique errors. They also eliminate some confusion and apprehension concerning appropriate use of acquisition parameters such as kVp, mA, grid use and SID (Herrmann et al., 2012). This highlights and emphasised the importance of having a dedicated exposure chart for trolley imaging.

The results of this thesis have also clarified some misconceptions found in Tugwell's (2014) study where some radiographers believed exposure factors should be doubled for trolley imaging because of the increase thickness of the mattress and the increased OID.

Mutch and Wentowrth (2007) also found misconceptions amongst radiographers in a similar situation where they investigated imaging neonates using a tray underneath the incubator. When radiographers were asked about the principles and procedure involved in imaging the neonate in this situation, Mutch and Wentworth found many misconceptions which were later proven otherwise by the experimental aspect of their study. Some of the misconceptions included the need for increased radiation dose when using the tray, deterioration in image quality as the OID increased; these are similar to some of the misconceptions found by Tugwell (2014).

In summary, this thesis has demonstrated that imaging an AP pelvis on a trolley to be challenging with regards to the associated human and physical factors and that the acquisition parameters used for x-ray tabletop imaging should not be directly transferred to trolley imaging. Consideration should be given to the difference between these two situations especially the increased OID which would benefit from an increase in SID to 130cm in order to reduce both magnification and radiation dose. Radiation dose significantly increased for trolley imaging whilst visual image quality decreased and therefore is important that separate exposure charts are developed for trolley imaging to ensure optimal image quality at the lowest possible dose. Mutch and Wentworth (2007) emphasise this by suggesting that clear protocols are required if optimal imaging techniques are to be developed and maintained in situations that are different from 'standard imaging techniques' and practice. With regards to AP pelvis trolley imaging, exposure charts are even more essential since the AEC is unavailable and radiographers rely on their own clinical judgment. Uffmann and Schaefer-Prokop (2009) commented that exposure charts are critical when mobile radiography is utilised with CR, because manual technique factors are used. This is important when considering that the AP pelvis is often imaged on a trolley portably because it still forms part of the ATLS protocol in the resuscitation room.

7.1 Limitations and Recommendations

When conducting a study in an area that has limited previous published work such as that seen for trolley imaging, there can sometimes be too many variables to explore in one single experiment which results in some variables being kept consistent. For this thesis, imaging the AP pelvis on a trolley was explored for various reasons including the importance of acquiring a diagnostic image of the pelvis in trauma situations on trolleys, the fact that there are obvious differences between imaging on a trolley to x-ray tabletop (e.g. mattresses and image receptor holder) and also to ensure the acquisition parameters used for trolley imaging keep the dose as low as reasonably practical since the gonads which are highly radiosensitive are exposed. The aim of this thesis was to assess and evaluate whether acquisition parameters used to acquire an AP pelvis on the x-ray tabletop was transferable to trolley imaging and also to determine the influence of different variables including mattresses, platform position, mAs and SID had on image quality and radiation dose in this situation. These four variables were deemed the most important variables to explore for this experimental study having conducted the literature review and reflecting upon Tugwell's (2014) study. Nevertheless, many more variables need to be explored for trolley imaging especially kVp and grid selection.

There were a vast amount of variables to consider when imaging a patient on a trolley and not all of them were included within this thesis due to time implications and the resources available. Here are some of the limitations and future recommendations for this thesis:

Spinal immobilisation devices

For this thesis, imaging the pelvis on a trolley with the presence of a spinal board or scoop stretcher was not considered. In major trauma, a number of patients that require AP pelvis imaging could potentially be lying on a spinal board which means the primary beam has to travel through it before reaching the image receptor. According to Linsenmaier et al. (2001) spinal boards can cause artefacts and are very dense. Some spinal boards are not recommended for x-ray purposes as they are not 100% radio-opaque. Vickery (2001) suggested that spinal boards can cause artefactual distortion and noise on images, they can obscure important diagnostic information and also they may produce more scatter. All of these factors can have a detrimental effect on image quality. These issues were also highlighted by Keating and Grange (2011) who suggested the possibility of additional scatter being generated from beam interaction with apparatus such as spinal

boards. Vickers (2001) went on to suggest that early removal of the spinal board would optimise the quality of trauma radiographs and should be considered when requesting radiographs. More recently however, there have been many studies including Conrad et al. (2012), Theodore et al. (2013), Lance et al. (2011) that have questioned the value of spinal immobilisation devices during trauma. They found better neurological outcomes without the use of these devices plus the time taken to safely position a patient onto such devices caused delay in resuscitation. This is very important from an imaging perspective since the exclusion of such devices could also have a positive impact on imaging. Further work needs to be conducted to assess which immobilisation devices are still used in clinical practice, how they impact on image quality and radiation dose to the patient and whether modification of acquisition parameters is required when they are present during trolley imaging. This type of experiment/evidence may support the other studies that have questioned the benefit of these devices, especially if it is found they impact negatively on image quality hence a confident diagnosis.

Mobile/portable x-ray machine

Initially this thesis intended to use both the x-ray room machine and a mobile x-ray machine for comparison since the AP pelvis is sometimes imaged portably in the resuscitation room as part of the ATLS protocol. However during the pilot study, issues arose with the mobile machine and therefore it was excluded. Future work would benefit from repeating the experiment using a mobile machine since there are differences between the specifications of a fixed x-ray tube and a mobile machine as highlighted in section 4.11.1 on page 106. Martin (2007) argued that images acquired using a mobile machine are likely to be of lower quality because image receptors cannot be aligned as accurately as with a fixed unit, and the distance of the image receptor from the x-ray tube will be variable because it is difficult to set accurately. The information from Martin (2007) should however be carefully considered because his study was based on film/screen rather than digital systems and therefore some information ay be outdated by modern newer technology. The output of mobile machines are also lower than fixed ones, so the range of exposures that can be used is limited and longer exposure times may be required which increases the likelihood of movement artefacts. Williams et al. (2007) also commented that manual techniques are used in portable setting and that a separate exposure chart is

required for this type of imaging. This emphasises not only the importance of conducting further experiments on the mobile machine for comparison to the current thesis but it also demonstrates the need for more work surrounding many aspects of this thesis in order to start developing an exposure chart for trolley imaging. The development of an exposure chart is a complex and time consuming process requiring a large amount of preliminary work in order to inform the recommendations on the chart (Hermann et al., 2012)

Trolley manufacturer

This thesis used one commercially available trolley to perform the experiment. However there are several different trolleys available on the market suitable for imaging. This study therefore needs to be extended to include different trolleys, especially since they vary in design and possibly have different mattress thickness and density but also different trolley top materials e.g. carbon or aluminium. Manufacturers do not specify the actual materials used to build trolleys therefore further experiments may be beneficial. Various trolleys may also differ with regards to the image receptor holder design and therefore impact upon the distance between the patient and the image receptor (OID). An example of this variation is seen by the new design by Stryker Prime X where they have developed a platform that has bevelled edges to allow the image receptor to be placed closer to the patient and also visual alignment guides to aid in aligning the image receptor (Stryker, 2012). Unlike the Lifeguard 50 trolley used in this current thesis, the Stryker Prime X does not require elevation of the image receptor holder platform and therefore has only one OID to explore if an experiment was to be conducted.

In addition, when considering the results of this thesis with regards to the trolley design's impact on image quality and radiation dose, x-ray departments should ideally perform a similar experiment on newly purchased trolleys (or current trolleys if not already done) in order to discover their effect on image quality and radiation dose. Whitley et al. (2015) suggested that imaging departments should have close links with the emergency department when purchasing new trolleys to ensure they meet the minimum requirements for imaging. The imaging department should be involved in testing them in the period of evaluation in order to identify weaknesses and whether they are fit for practice. This would not only help to improve image quality and reduce radiation dose to patients but it would

also educate staff on how the design of the trolley requires modification in acquisition parameters or even allow the department to reject a certain trolley design.

AP pelvis

This thesis was limited to one type of axial examination, the AP pelvis projection. It would be beneficial for further research to be conducted on other body parts that are imaged on the trolley using the image receptor holder in order to reveal its effects on image quality and radiation dose for these projections. Images acquired in the image receptor holder are the only examination of interest e.g. spine, abdomen, femur and chest because other examinations such as the lower and upper extremities can be imaged with the image receptor directly beneath the area of interest (direct exposure) and therefore the imaging technique and parameters would not require modification.

Anthropomorphic phantom

As previously discussed in section 3.8 on page 72, anthropomorphic phantoms are commonly used in optimisation studies as they allow unlimited exposures of the same anatomy. Although anthropomorphic phantoms simulate human anatomy and tissue exceptionally well, they are only approximations. The phantom's skeleton and soft-tissue chemical compositions are not exactly the same as human bone and tissue, therefore further observation on human tissue should be performed to verify results. In addition, the use of an anthropomorphic phantom does not account for variations in body sizes and composition. The results of this thesis can only be applied to an average build human since this is what the phantom represents. Tang et al. (2012) suggested that attenuation of the incident x-ray beam depends on the size of the body portion being images i.e. higher exposure is required in larger patients to attain image quality equal to that in thinner patients. The patients size may also influence the amount of compression upon the mattress therefore a heavier patient may compress the mattress much more than the 73kg phantom thus reducing the OID slightly. Further work needs to be conducted on human cadavers and a clinical trial performed with patients of varying body habitus.

X-ray tabletop mattress

Another point to consider is that some x-ray departments as highlighted by Everton et al. (2014b) do not use a mattress when imaging patients on the x-ray tabletop. If this experiment was repeated, it would be interesting to acquire the reference image on the x-ray tabletop without the use of a mattress. Considering visual image quality was significantly lower and radiation dose was significantly higher for the trolley images in comparison to the reference image, it is reasonable to assume that the removal of the mattress on the x-ray tabletop would further exacerbated the differences between these imaging scenarios and also perhaps demonstrate a significant difference in magnification level since the removal of the mattress would reduce OID.

Visual image quality

Some aspects of the visual image quality assessment did not reflect what actually happens in clinical practice. Restrictions were placed on some aspects of the visual image quality assessment in order to improve control, reduce bias and to ensure consistency within the experiment. This included restricting the manipulation of images post-processing. One of the main advantages of digital radiography is the ability to adjust the images after acquisition (Bontrager & Lampignano, 2014). Post-processing allows for the manipulation of raw data just after acquisition in order to enhance the visibility of the details within an image; it has become an importance variable when evaluating and determining image quality (IAEA, 2012). If this experiment was to be repeated, perhaps no restrictions should be placed upon image manipulation in order to simulate more closely clinical practice.

Item sixteen, the last item on the visual image quality criteria, was another limitation to the visual evaluation task because it was not validated unlike the other items developed by Mraity et al. (2013, 2015). After analysing the results it became apparent that item sixteen gave wide ranging results with low but positive observer agreement. This item aimed to evaluate whether each of the experimental images acquired on the trolley were acceptable for diagnostic purpose using a binary decision method. Observers were asked to decide whether the image was acceptable for diagnostic purpose without any clinical indication as to why the images where acquired. The clinical indication is important when justifying and optimising image quality and radiation dose as it may have major implications on how observers evaluate and score image quality. Image quality is based upon the clinical

question which means that an AP pelvis to exclude fractures would need to be of higher quality to an AP pelvis acquired post operatively to establishing the position of a metallic implant (Uffmann & Schaefer-Prokop, 2009). Due to the un-validated nature of item 16 on the image quality assessment, it is important to carefully consider the results of this item because although most images acquired on the trolley were deemed diagnostic by the observers, the context by which they were evaluated is flawed therefore they may not necessarily be diagnostic for certain clinical situations e.g. trauma where higher image quality is necessary to evaluate possible fractures.

A suggestion to improve the visual evaluation of image quality was to add a qualitative aspect to the 2AFC software developed by Hogg and Blindell (2012). Currently the 2AFC software allows the observers to make a decision on the visualisation of structures using a Likert scale. This method forces the observer to make decisions regarding image quality without any opportunity to elaborate on their decision. Therefore, a comment box incorporated into this software after each image would allow observer to clarify and explain their decision if they felt it was necessary. This would improve the visual evaluation of image quality by providing a more in-depth valuable information regarding image quality. It must be remembered that a radiographic report on images is a clinical judgment and opinion (RCR, 2012a).

Lastly, it would be helpful to see more optimisation studies being conducted using the newly developed AP pelvis psychometric scale to assess image quality as it would allow for more reliable comparison of future studies when assessing AP pelvis image quality. Currently, most studies (even recent studies) on AP pelvis optimisation including Chan and Fung (2014) and England et al. (2015) have used the CEC (1996) image quality criteria which are based on film/screen imaging and therefore not as relevant to digital image quality.

Visual image quality verses physical image quality

Another point to consider that has been highlighted within this thesis is the correlation between visual and physical image quality. There is still controversy surrounding this issue especially since the methods for measuring physical and visual image quality is still developing. A moderate positive correlation was found between CNR and visual image

quality within this thesis however this is difficult to fully trust since there are many different methods of calculating both CNR (which do not consider magnification) and visual image quality. As highlighted throughput the thesis, especially in section 6.2, much work is needed to determine whether a true correlation actually exists between these different measures. It is also important to consider that most radiographic optimisation studies including Lanca et al. (2016), Moore et al. (2013), Vladimirov (2010), Choi et al. (2015) measure CNR utilising a physical phantom or a paraffin wax block which means the selected region of interests for signal intensity have come from homogeneous locations such as discs. It is only more recently that some authors (Lanca et al., 2014; Mraity, 2015) have decided to measure CNR in anthropomorphic phantoms and yet again no evidence is present as to whether CNR can be successfully measured in heterogeneous phantoms. This is why a single ROI was used for the current thesis to reduce likely errors occurring within a heterogeneous phantom. Further work is required to explore the correlation between the use of multiple and single ROI to measure CNR.

With the above paragraph in mind, physical measures of image quality are still considered useful for describing the performance of the imaging system in terms of image quality and are vastly used to characterise system performance (Seeram et al., 2014). Nevertheless they do not relate to all components of the imaging chain such as when the image is finally displayed on a monitor for interpretation by an observer. This means that physical measures of image quality do not predict or consider the observational aspect of medical imaging yet this is the most important stage of medical image interpretation. An accurate diagnosis relies on the reporting observers (e.g. radiologists or specialist radiographers) to visualise what is necessary in order to interpret and make a clinical opinion on the acquired image/s (RCR, 2006). Yet again exposure charts, APR systems and quality assurance programs are informed by physical measures of image quality. Tools such as Leeds Test Objects are used that do not resemble patient clinical imaging and according to Tapiovaara (2006) these methods may not always be suitable for evaluating different imaging systems or imaging techniques, since their contrast could behave differently to the contrast of clinically relevant details with a changing radiation quality.

With this in mind perhaps a new model should be developed by manufacturers and physicist when setting APR systems and determining the performance of an imaging system that incorporates the visual/observational aspect of image quality interpretation.

This could include using perceptual methods based on the visualisation and reproduction of defined anatomical structures in images to help consolidate what is known fro the physical measures.

Factorial experiential design

Most optimisation studies in medical imaging manipulate one parameter 'factor' at a time to determine their effect on the outcome variables (which was visual image quality and effective dose for this thesis). One of the disadvantages of manipulating one parameter at a time is that there is no way of determining the effect of the interaction that might occur between the other factors (Norrman & Persliden, 2005).One way to overcome this problem is to carry out a factorial experiment similar to the experimental design of Mraity's (2015) PhD thesis. As briefly mentioned in section 3.3 on page 33, a factorial experiment was considered for this thesis however it was disregarded as an appropriate method to achieve the aims and objectives. A factorial design has to be planned precisely, as an error in one of the levels/equations, or in the general structure, could jeopardize the outcome of the entire study (Geijer, Norrman & Persliden, 2009). The formula for designing a factorial experiment is expressed as n^k whereby k refers to the number of factors (parameters) being explored (e.g. SID, mAs…etc) whereby *n* refers to the number of ranges within each factor (e.g. mAs values used). This method enables more than one acquisition parameters to be tested at the same time in order to investigate their combined effect upon image quality and radiation dose. It is a more truthful simulation of clinical practise and therefore would have been an alternative method to use for this thesis. If the experiment for this thesis was to be repeated, perhaps a factorial design should be considered to evaluate what effect manipulating more than one variable has on visual mage quality and radiation dose.

Direct digital radiography (DDR)

This thesis was conducted using one CR system and therefore it would be advisable to validate the results on different CR and DDR systems especially when considering the different systems available and the technological advancements over the past 20 years (see table 22).

Year	Digital technology availability
1980	Computed radiography (CR), storage phosphors
1987	Amorphous selenium-based image plates
1990	Charge-coupled device (CCD) slot-scan direct radiography (DR
1994	Selenium drum DR
1995	Amorphous silicon–cesium iodide (scintillator) flat-panel detector
1995	Selenium-based flat-panel detector
1997	Gadolinium-based (scintillator) flat-panel detector
2001	Dynamic flat-panel detector fluoroscopy–digital subtraction angiography
2006	Digital tomosynthesiS
2009	Wireless DR (flat-panel detector)

Table 22 - Timetable of developments in digital technology (Lanca & Silva, 2013).

Exposure chart development

The need for a separate exposure chart for trolley imaging has been questioned and evaluated throughout this thesis and further emphasised in the conclusion because the results demonstrate that acquisition parameters used for AP pelvis on an x-ray tabletop are not directly transferable to trolley imaging. Although this thesis is a step in the right direction towards developing such a chart, there are many more experiments and steps to consider which include the limitations and recommendations highlighted in this above section but also the impact of different kVp settings for AP pelvis imaging. Developing an exposure chart is a complicated and time consuming process that has not been thoroughly covered within published literature. Having conducted a search for appropriate literature on exposure charts, limited guidance and direction was found in order to help radiographers develop such charts. The importance of exposure charts are regularly emphasised in numerous textbooks and published studies including Hart, Wall, Shrimpton and Dance (2000), Johnston and Fauber (2015) and Herrmann et al. (2012), however these literature do not specify on a method for developing such charts in a scientific and systematic manner. Johnston and Fauber (2015) vaguely suggest using tissue-equivalent phantoms and raider graphs but did not elaborate on a specific method and how reliable and valid these methods are if translated into clinical practice. Herrmann et al. (2012) was also fairly vague but did specify which acquisition parameters should be included within an exposure chart for digital systems. These were mAs (if set), SID, kVp, focal spot size, use of grid,

grid ratio, AEC detectors(s) and acceptable exposure indicator ranges. Knight (2014) was the only peer reviewed journal found which actually developed an exposure chart and discussed the steps taken. This study by Knight used an evidence based practice approach and reviewed the literature specifically for each acquisition parameters to be used in the chart (kVp, mAs, filtration, grid etc) in order to decide upon the most relevant technique. These literatures used to inform the chart included The European Commission, ICRP and optimisation studies conducted on the various acquisition parameters of interest. Following the introduction of the newly developed exposure chart into practice, pre and post radiation dose (DAP) and image quality (SNR and CNR) measurements were recorded in order to observe improvement in these measurements. Although this study by Knight seemed to be conducted in a rigorous and systematic fashion, many flaws existed in the development of this exposure chart including the fact that some of the guidelines and studies used to inform decisions with regards to technique and acquisition parameters were dated (film/screen) and also contained flaws too. Also, DAP and physical measures of image quality may not be the most appropriate methods in determining the impact of improvement; effective dose gives a better indication of patient risk and visual image quality reflects more closely what happens in clinical practice (Pradhan, Kim & Lee, 2012; Martin 2007).

From what has been discussed regarding exposure charts, perhaps this could be another interesting project to follow on from this thesis - *how to systematically develop a rigours exposure chart in order to optimise radiographic examinations in digital radiography.*

To conclude, whilst there have been many interesting findings from this thesis, it is difficult to determine how they can currently be translated in clinical practice without further investigations and experiments conducted to confirm and consolidate some of the findings. Some of the main recommendations from this thesis for trolley imaging are: the use of a 130cm SID to reduce magnification and patient radiation dose and also to consider the clinical indication for the AP pelvis when selecting mAs as 16mAs would be sufficient for an average patient when imaging post surgical fixation. The limitations and recommendation above should however be carefully considered before the results of this thesis can be fully appreciated in clinical practice. This thesis demonstrated that image quality decreased and radiation dose increased when imaging on a trolley using the image receptor holder in comparison to using a Bucky system on the x-ray tabletop. Further work

is now required to explore different acquisition parameters such as kVp and how they impact image quality and radiation dose for trolley imaging. In conclusion, this thesis has laid down the foundation for developing a trolley imaging exposure chart.

Appendices

Appendix I: Quality Control (QC) test procedures carried out prior to experiment

LBD alignment and Bucky Centring

This teat simultaneously checks x-ray beam alignment, collimation and Bucky centring accuracy with a single exposure and should be carried out monthly.

METHOD

Remove the mattress from the tabletop

Place a 24×30 cm regular IR in Bucky tray. Image receptor aligned with blue edge nearest to you (landscape). Place the light beam diaphragm phantom test tool on the table. Ensure small alignment tool is screwed into centre of Phantom.

Centre tube to table Bucky after setting SID to 100cm precisely (used tape measure).

Adjust the phantom to the exact centre of the beam with the alignments direction the same as the the image receptor and the diamond on the right-hand side

Collimate a square within phantom. Align the left-hand side of LBD with LHS of 24×30 marks and bottom edge (nearest) with bottom edge of 24×30 marks on phantom.

Expose at 55kVp, 2mAs and fine focus

Open cones to cover whole of the phantom and expose again on same image receptor, i. e. prior to processing

Process image receptor

For the ERECT Bucky, repeats points *1-8 for the erect Bucky using the holder to secure test tool*

Post-processing

Image should be viewed on the QA workstation. Using the measurement tools provided, diagonal lines should be drawn from each opposite corner. This will give the actual centre of the image. The centre of the image should be measured to the point where the diagonal lines cross.

AEC Sensitivity check

This test is designed to ensure that the automatic exposure control (AEC) is functioning correctly and consistently. This test needs to be carried out every 2 months

METHOD

Place 1 mm Cu filtration in the x-ray beam at the tube, with the tube facing the erect Bucky
Centre x-ray tube to erect Bucky using SID of 100cm (leave cones open wide to include all three Chambers)
Place a 24×30 cm CR plate in the Bucky tray (landscape)
Select – 60kVp; centre chamber; zero density; broad focus and expose
Note the post exposure mAs reading and time (where available) and record in the table overleaf
Read the plate, processing it at'190/TEST/QC/S Value'. Identify it as "Centre chamber" and room number using the annotation tool
Read and note the S Value
Repeat above sections for the table Bucky
Compare results to previous tests (see below***)***

RESULTS

S Value

Normal - less than +25% or -17% difference from original/previous S Value reading
Remedial - level occurs at greater than +25% or -17% difference (notify QA officer, duty manager or senior radiographer in charge
Suspension - of use of equipment MUST occur if results succeed+100% OR -33% difference (notify QA officer, duty manager or senior radiographer in charge).

Post exposure mAs and time

Normal readings – the mAs should vary no more than 30% from the baseline.
Remedial level – between 31 and 60% variance (notify QA officer, duty manager or senior radiographer in charge)
Suspension level – if variance exceed 60% then use of the equipment must be suspended until further tests or repairs are carried out (notify QA officer, duty manager or senior radiographer in charge).

kV Accuracy, Radiation Output per mAs and Timer Accuracy

METHOD

Place the Mult o Meter on the tabletop. Set focus to top of detector distance of 75 cm precisely (used tape measure)

set the first exposure parameter from the table overleaf, pay careful attention to which focus to use. Make an exposure

record output in µGy and the output per mAs on the table overleaf

NB - all exposures workout is 10 mAs hence output per mAs is easily calculated by dividing the µGy output by 10.

Also from the same exposure, record the actual kVp and the actual time (ms) from the meeting using the 'parameter' key to toggle between measured factors

Radiation Output as per daily check

DIATION Output check*

GIG CYMRU NHS WALES | Bwrdd Iechyd Prifysgol Betsi Cadwaladr University Health Board

Radiology Department, West Division

QUALITY ASSURANCE CHECKS: ROOM

PROCEDURE:

This test is to be performed a **minimum of 3 times per week** at the beginning of the morning session (before any patients are imaged).

The purpose of these checks is to limit unnecessary exposure to patients! They are important.

1. Open Cones Fully.
2. Set Exposure.
3. Zero Diamentor
4. Expose
5. Note Diamentor Reading, Date & Sign
6. Check against reference exposure
7. **Notify QA Team/Senior/Superintendent when ± 12.5% variat Noted (or limits exceeded)**

Exp.	kVp	mA	s	mAs	Focus	Upper/Lower Limit	Date							
							Initial							
a)	66		6·15	4	B	31/22								
b)	66		76.9	50	B	373/265								
c)	102		173	40	F	705/546								
Date														
Initial														
a)														
b)														
c)														

Appendix II: Ethical Approval Letter

University of Salford MANCHESTER

Research, Innovation and Academic Engagement Ethical Approval Panel

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18 March 2015

Dear Jenna,

RE: ETHICS APPLICATION HSCR14/104 – Analysis of human and physical factors which affect image quality and radiation dose on trolley-bound patients

Based on the information you provided, I am pleased to inform you that application HSCR14/104 has been approved.

If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible.

Yours sincerely,

Sarah Starkey

Sarah Starkey
Engagement & Innovation Assistant

Appendix III: Copy of Research Participant Consent Form

Research Participant Consent Form

Title of Project: Impact and analysis of human and physical factors which affect image quality and radiation dose on trolley-bound patients

Ethics Ref No:

Name of Researcher: Jenna Tugwell

(Delete as appropriate)

➢ I confirm that I have read and understood the information sheet for the above study (version 1.3 (20/2/2015) and what my contribution will be	Yes	No
➢ I understand that my participation is voluntary and that I can withdraw from the research at any time without giving any reason	Yes	No
➢ I agree to take part in the above study	Yes	No

Name of participant ……

Signature ……

Date …….

Name of researcher taking consent Jenna Tugwell……

Researcher's e-mail address Jenna.Tugwell@wales.nhs.uk……

References

Abbey, C.K., & Barrett, H.H. (2001). Human- and model-observer performance in ramp-spectrum noise: effects of regularization and object variability. *Journal of Optical Society of America: Optics and Image Science and Vision*, 18(3), 473-488. Retrieved from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2943344/

Abbey, C., & Eickstein, M.P. (2002). Classification image analysis: Estimation and statistical inference for two-alternative forced-choice experiments. *Journal of Vision,* 2, 66-78. doi:10.1167/2.1.5

Abbey, C. (2013). Classification images aid understanding of visual task performance and diagnosis. *Biomedical Optics & Medical Imaging*. SPIE, 8 February. DOI:10.1117/2.1201301.004687

Agrawal, K., & Chauhan, N. (2012). Pressure ulcers: Back to the basics. *Indian Journal of Plastic Surgery*, 45, 244-54

Aird, E.G.A. (1988). *Basic Physics for Medical Imaging*. Oxford: Butterworth-Heinemann Ltd

Al-Khawari, H., Athyal, R.P., Al-Saeed, O., Sada, P.N., Al-Muthairi, S., & Al-Awadhi, A. (2010). Inter- and intraobserver variation between radiologists in the detection of abnormal parenchymal lung changes on high-resolution computed tomography. *Ann Saudi Med,* 30(2), 129–133. doi: 10.4103/0256-4947.60518

Aldrich, J.E., Duran, E., Dunlop, P., & Mayo, J.R. (2006). Optimization of Dose and Image Quality for Computed Radiography and Digital Radiography . *Journal of Digital Imaging*, 19(2), 126–131.

Alers, H., Bos, L., & Heynderickx, I. (2011). How the task of evaluating image quality influences viewing behaviour. Paper presented at the third International Workshop on Quality of Multimedia Experience (QoMEX) (pp 167-172). Mechelen, Belgium: IEEE. Retrieved from: http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6065697&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D6065697

Alexander, K. (2010). Reducing error in radiographic interpretation. *The Canadian Veterinary Journal*, 51(5), 533–536. Retrieved from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2857438/#

Allen, E., & Triantaphillidou, S. (2011). *The Manual of Photography*. Oxford: Elsevier/Focal Press

Allen, E., Hogg, P., Ma, W.K., & Szczepura, K. (2013). Fact or fiction: An analysis of the 10 kVp 'rule' in computed radiography. *Radiography*, 19, 223-227

Allisy-Roberts, P., & Williams, J. (2008). Farr's Physics for Medical Imaging (2nd ed.). Edinburgh: Elsevier

Almen, A., Tingberg, A., Mattsson, S., Besjakov, J., Kheddache, S., Lanhede, B., Mansson, L.G., & Zankle, M. (2000). The influence of different technique factors on image quality of lumbar spine radiographs as evaluated by established CEC image criteria. *British Journal of Radiology*, 73(875), 1192–9.

Alpen, E.L. (1998). *Radiation Biophysics* (2nd ed.). Massachusetts: Academic Press

Almazedi, B., Smith, C.D., Morgan, D., Thomas, G., & Pereira, G. (2011). Another fractured neck of femur: do we need a lateral X-ray? *British Journal of Radiology.* 84(1001), 413-417. doi: 10.1259/bjr/57316056

American Association of Physicists in Medicine (AAPM). (2006). Acceptance Testing and Quality Control of Photostimulable Storage Phosphor Imaging Systems Report of AAPM

Task Group. Report 93, 10 October. California: AAPM. Retrieved from: https://www.aapm.org/pubs/reports/RPT_93.pdf

American College of Radiology. ACR Appropriateness Criteria. Available at: https://acsearch.acr.org/list (Accessed 26 December, 2015)

ArjoHuntleighs. (2010). Bi-flex trolley mattress replacement system. Bedfordshire: ArjoHuntleigh Getinge Group. Retrieved from: http://www.arjolibrary.com

ArjoHuntleigh. (2014). Lifeguard trolley ranges brochure. Sweden: ArjoHuntleigh Getinge Group. Retrieved from: www.arjohuntleighlibrary.com

Attix, F.H. (1986). *Introduction to Radiological Physics and Radiation Dosimetry*. New York: Wiley

Ball, J., Moore, A., & Turner, S. (2012). *Essential Physics for Radiographers* (4th ed.). Oxford: John Wiley and Sons

Balonov, M., & Shrimpton, P. (2012). Effective dose and risk from medical X-ray procedures. *Annals of the ICRP*, 41(3-4),129-41. doi: 10.1016/j.icrp.2012.06.002

Bartholomew, A.L., Denton, E., Shaw, M., & Marshall, T.J. (2004). A randomised controlled trial comparing lateral skull computerised radiographs with or without a grid. *Radiography*, 10(3), 201-204.

Beebe, R., & Myers, J. (2012). *Professional Paramedic, Vol III: Trauma Care and EMS Operations* (1st ed.). New York: Cengage Learning

Behrman, R., & Yasuda, G. (1998). Effective dose in diagnostic radiology as a function of x-ray beam filtration for a constant exit dose and constant film density. *Medical Physics*, 25(5), 780-790

Bell, M. (2006). The UK Human Tissue Act and consent: surrendering a fundamental principle to transplantation needs? *Medical Ethics*, 32(5), 283–286. doi: 10.1136/jme.2005.012666

Bell, N., Erskine, M., & Warren-Forward, H. (2003). Lateral cervical spine examinations: an evaluation of dose for grid and non-grid techniques, *Radiography*, 9(1), 43–52. doi:10.1016/S1078-8174(02)00078-0

Bender, L.C., Linnau, K.F., Meier, E.N., Anzai, Y., & Gunn, M.L. (2012). Interrater Agreement in the Evaluation of Discrepant Imaging Findings With the Radpeer System, *American Journal of Roentgenology*, 199, 1320-132

Bloomfield, C., Boavida, F., Chabloz, D.,Crausaz, E., Huizinga, E., Hustveit, H., Knight, H., Pereira, A., Harsaker,V., Schaake, W., & Visser, R. (2014). Experimental article – Reducing effective dose to a paediatric phantom by using different combinations of kVp, mAs and additional filtration whilst maintaining image quality. In P. Hogg, L. Lança (Eds.), *Radiation dose and image quality optimisation in medical imaging*, Erasmus Intensive Programme OPTIMAX#2014: Lisbon, Portugal.

Boese, C.K., Lechler, P., Rose, L., Dargel, J., Oppermann, J., Eysel, P., Geiges, H., Bredow, J. (2015). Calibration Markers for Digital Templating in Total Hip Arthroplasty. *PLoS ONE*, 10(7), e0128529. doi:10.1371/journal.pone.0128529

Bontrager, K.L. (2010). *Handbook of Radiographic Positioning and Techniques* (7th ed.). St. Louis:Mosby/Elsevier

Bontrager, K.L., & Lampignano, J.P. (2014). *Textbook of radiographic positioning and related anatomy* (8th ed.). Missouri: Mosby

Brennan, P.C., & Nash, M. (1998). Increasing FFD: An effective dose-reducing tool for lateral lumbar spine investigations. *Radiography*, 4(4), 251-259.

Brennan, P.C., & Madigan, E. (2000). Lumbar spine radiology: analysis of the posteroanterior projection. *European Radiology*,10(7), 1197-201.

Brennan, P.C., McDonnell, S., & O'Leary, D. (2004). Increasing film-focus distance (FFD) reduces radiation dose for x-ray examinations. *Radiation Protection Dosimetry,*108, 263-268.

Brenner, D.J. (2008). Effective dose: A flawed concept that could and should be replaced. *British Journal of Radiology*, 81, 521–3.

Brenner, D.J. (2011). *Effective Dose- A Flawed Concept that Could and Should be Replaced*. In *International Commission on Radiological Protection*, Washington DC.

Brenner, D.J. (2012). *We can do better than effective dose for estimating or comparing low-dose radiation risks.* Annals of the ICRP, 41(3-4), 124-128.

Brindhaban, A., Al Khalifah, K., Al Wathiqi, G., & Al Ostath, H. (2005). Effect of x-ray tube potential on image quality and patient dose for lumbar spine computed radiography examinations. *Australasian Physics & Engineering Sciences in Medicine*, 28(4), 216-222

Briody, K., & Walker, P. (2013). Guidelines for the manual handling care of bariatric patients in hospitals. 11th of September. Manchester: Salford Royal National Health Service. Retrieved from: http://www.srft.nhs.uk/EasysiteWeb/getresource.axd?AssetID=32649&type=full&servicetype=Inline&filename=/TWCG20(13)_-_Issue_No_2_-_Guidelines_for_the_manual_handling_care_of_bariatric_patients_in_hospital.pdf

Burgess, A. (2011). Visual Perception Studies and Observer models in Medical Imaging. Seminars of Nuclear Medicine, 41, 419-436. DOI:10.1053/j.semnuclmed.2011.06.005

Burns, R. (2000). *Introduction to Research Methods*. London: Sage

Busch. H.P., & Faulkner, K. (2005). Image quality and dose management in digital radiography: a new paradigm for optimisation. *Radiation Protection Dosimetry*, 117(1-3), 143-147.

Bushberg, J., Seibert, J., Leidholdt, E., Boone, J., & Goldschmidt Jr, E. (2002). *The essential physics of medical imaging.* (2n ed.). Philadelphia: Lipncott Willams & Wilkins.

Bushong, S.C. (2013). *Physics, Biology, and Protection. Radiologic Science for Technologists* (10th ed.). Missouri: Elsevier

Cannon, J., Silvestri, S., & Munro, M.(2009). Imaging Choices in Occult Hip Fracture. *The Journal of Emergency Medicine,* 32(3), 144-152

Carlton, R.R., & Adler, A.M. (2013). *Principles of Radiographic Imaging: An Art and a Science*. (5th ed.). Australia: Cengage Learning

Carroll, Q.B., & Bowman, D. (2013). *Adaptive Radiography with Trauma, Image Critique and Critical Thinking*, (International ed.). New York: Cengage Learning

Carter, P.H., Paterson, A.M., Thornton, L.M., Hyatt, A.P., Milne, A., & Pirrie, J.R. (1994). *Chesneys' Equipment for Student Radiographers* (4th ed.). London: Blackwell Scientific

Carver, E., & Carver, B. (2012). *Medical Imaging: Techniques, Reflection & Evaluation* (2nd ed.). Philadelphia: Churchill Livingstone

Chakraborty, D.P. (2005). Recent advances in observer performance methodology: jackknife free-response ROC (JAFROC). *Radiation Protection Dosimetry*,114(1-3), 26-31

Chan, C.T., & Fung, K.K. (2014). Dose optimization in pelvic radiography by air gap method on CR and DR systems; a phantom study. *Radiography*. In press available online. doi:10.1016/j.radi.2014.11.005

Chan, C.T., &Fung, K.K. (2015). Dose Optimization in Lumbar Spine Radiographic Examination by Air Gap Method at CR and DR Systems: A Phantom Study. *Radiography*, 46(1), 65–77

Chaparian, A., Kanani, A., & Baghbanian, M. (2014). Reduction of radiation risks in patients undergoing some X-ray examinations by using optimal projections: A Monte Carlo program-based mathematical calculation. *Medical Physics*, 39(1), 32–39. doi: 10.4103/0971-6203.125500

Cheong, K.B., Leung, K.Y., Li, T.K.T., Chan, H.Y., Lee, Y.P., & Tang, M.H. (2010). Comparison of inter- and intraobserver agreement and reliability between three different types of placental volume measurement technique (XI VOCALTM, VOCALTM and multiplanar) and validity in the *in-vitro* setting. *Ultrasound Obstetrics Gynaecology*, 36, 210–217. DOI: 10.1002/uog.7609

Cherry, P., & Duxbury, A. (2009). Practical Radiotherapy, Physics and Equipment (2nd ed.). Oxford: Wiley-Blackwell

Ching, W., Robinson, J., & McEntee, M. (2014). Patient-based radiographic exposure factor selection: a systematic review. *Journal of Medical Radiation Sciences*, 61(3), 176-190.

Chmelova, J., Mrazkova, D., Dzupa, V.. Baca, B., Grill, R., & Pleva, L. (2006). The role of plain radiography in pelvic trauma in the era of advanced computed tomography. *Acta Chir Orthop Traumatol Cech*, 73(6), 394-399.

Clancy, C. L., O'Reilly, G., Brennan, P.C., & McEntee, M.F. (2010). The effect of patient shield position on gonad dose during lumbar spine radiography. *Radiography*, 16(2), 131-135.

Clohisy, J.C., Carlisle, J.C., Beaulé, P.E., Kim, Y., Trousdale, R.T., Sierra, R.J., Leunig, M., Schoenecker, P.L., & Millis, M.B. (2008). A Systematic Approach to the Plain Radiographic Evaluation of the Young Adult Hip. *Bone Joint Surg Am*, 90(14), 47-66. doi: 10.2106/JBJS.H.00756

Cohen, G., McDaniel, D.L., & Wagner, L.K. (1984). Analysis of variations in contrast-detail experiments, *Medical Physics*, 11, 469–473

Colenbrander, A. (2013). *Measuring vision and vision loss*. In: W. Tasman, EA. Jaeger (Eds.), *Duane's Ophthalmology*. Philadelphia, PA: Lippincott Williams & Wilkins
Commission of the European Communities (CEC). (1996). European guidelines on quality criteria for diagnostic radiographic images: (EUR 16260 EN). Brussels: CEC. Retrieved from: ftp://ftp.cordis.lu/pub/fp5-euratom/docs/eur16260.pdf

Conn, K.S., Clarke, M.T., & Hallett, J.P. (2002). A simple guide to determine the magnification of radiographs and to improve the accuracy of preoperative templating. *Journal of Bone and Joint Surgery*, 84B, 269-272.

Conrad, B.P., Rossi, G.D., Horodyski, M.B., Prasarn, M.L., Alemi, Y., & Rechtin, G.R. (2012). Eliminating log rolling as a spine trauma order. *Surgical Neurology International*, 3(3), S188–S197.

Cooper, L., Gale, A., Darker, I., Toms, A., & Saada, J. (2009). Radiology image perception and observer performance: how does expertise and clinical information alter interpretation? Stroke detection explored through eye-tracking. In B. Sahiner, DJ. Manning (Eds.), *Medical Imaging: Image Perception, Observer Performance, and Technology Assessment.*(Vol 7263, 12pp). Canadian: SPIE press doi:10.1117/12.811098.

Cronin, P., Ryan. F., & Coughlan, M. (2008). Undertaking a literature review: a step by step approach. *British Journal of Nursing*, 17(1), 38-43.

Crooijmans, H., . Laumen, A., van Pul, C., & van Mourik, J. (2009). A New Digital Preoperative Planning Method for Total Hip Arthroplasties. *Clin Orthop Relat Res*, 467(4), 909–916. doi: 10.1007/s11999-008-0486-y

Cryer, H.M., Miller, F.B., Evers, B.M., Rouben, L.R., & Seligson, D.L. (1988). Pelvic fracture classification: correlation with haemorrhage. J*ournal of Trauma-Injury Infection & Critical Care*, 28(7), 973-80.

Cullum, N., McInnes, E., Bell-Syer, S.E., & Legood, R. (2004). Support surfaces for pressure ulcer prevention. *Cochrane Database Systematic Review*, 13 (4), CD001735. doi: 10.1002/14651858.CD001735.pub4.

Davey, E., & England, A. (2015). AP versus PA positioning in lumbar spine computed radiography: Image quality and individual organ doses, *Radiography*, 21(2), 188-196

Dawkins, S. (2012). Impact Assessment on a Newly Implemented Service Utilising Recovery Nurses as Transfer Nurses, Incorporating a Literature Review of Pressure Ulcer Reduction Strategies, i.e. Mattress and Overlay Types, for Patients on Hospital Trolleys**.** *British Journal of Anaesthetic and Recovery Nursing*, 13(3-4), 58-64

De Crop, A., Bacher, K., Van Hoof, T., Smeets, P.V., Smet, B.S., Vergauwen, M., Kiendys, U., Duyck, P., Verstraete, K., D'Herde, K., & Thierens, H. (2012). Correlation of contrast-detail analysis and clinical image quality assessment in chest radiography with a human cadaver study. *Radiology*, 262, 298–304 10.1148/radiol.11110447

Decoster, R., Mol, H., & Smits, D. (2015). Post-processing, is it a burden or a blessing? Part 1 - evaluation of clinical image quality. *Radiography*, 21, e1-4

Desai, N., Singh, A., & Valentino, D. (2010). Practical Evaluation of Image Quality in Computed Radiographic (CR) Imaging Systems. Proceedings of SPIE, Medical Imaging: Physics of Medical Imaging. San Diego: The International Society for Optical Engineering. DOI: 10.1117/12.844640

Dharmarajan, T.S., & Ugalino, J.T. (2006). Pressure ulcers: clinical features and management. *Journal of American Medical Association*, 296, 974-84.

Dietze, G., Harrison, J.D., & Menzel, H.G. (2009). Effective dose: A flawed concept that could and should be replaced. *British Journal of Radiology*, 82, 348–51. Comments on a paper by Brenner, DJ. (British Journal of Radiology, 2008; 81:521-3)

Dobbins, J.T., Samei, E., Ranger, N.T., & Chen, Y. (2006). Intercomparison of methods for image quality characterization. II. Noise power spectrum. *Medical Physics*, 33(5), 1466-75.

Donnelly, L., & Sawer, P. (2014, 29th November). Number of patients waiting on trolleys in A&E triples. The Telegraph. Retrieved from: http://www.telegraph.co.uk/news/health/news/11262541/Number-of-patients-waiting-on-trolleys-in-AandE-triples.html

Doolan A, Brennan P.C, Rainford, L.A, & Healy, J. (2004). Gonad protection for the antero-posterior projection of the pelvis in diagnostic radiography in Dublin hospitals. *Radiography*, 10(1), 15–21.

Doyle, P., Gentle, D., & Martin, C.J. (2005). Optimising Automatic Exposure Control in Computed Radiography and the impact on patient dose. *Radiation Protection Dosimetry*, 114, 236-239

Dowsett, D.J., Kenny, P.A., & Johnston, R.E. (2006). *The Physics of Diagnostic Imaging* (2nd ed.). London: Hodder Arnold Publishers

Drake, R.L., Vogl, A.W., Mitchell, A.W.M. (2014). *Gray's Anatomy for Students (*3rd ed.). Edinburgh: Churchill Livingstone

Dunn, M., Gwinnutt, C.L., Grey, A.J. (2007). Critical care in the emergency department: patient transfer. *Emergency Medicine Journal*, 24(1), 40–44

Egbe, N.O., Inyang, S.O., Ibeagwa, O.B., & Chiaghanam, N.O. (2008). Pediatric radiography entrance doses for some routine procedures in three hospitals within eastern Nigeria. Journal of Medical Physics, 33(1), 29-34. doi: 10.4103/0971-6203.39422.

Egbe, N.O., Heaton, B., & Sharp P.F. (2010a). A simple phantom study of the effects of dose reduction (by kVp increment) below current dose levels on CR chest image quality. *Radiography*, 16(4), 327-332.

Egbe, N.O., Heaton, B., & Sharp, P.F. (2010b). Application of a simple phantom in assessing the effects of dose reduction on image quality in chest radiography. *Radiography* 16(2), 108-114.

Ekpo, E.U., Hoban, A.C., & McEntee, M.F. (2014). Optimisation of direct digital chest radiography using Cu filtration. *Radiography*, 20, 346-350

England, A., Evans, P., Harding, L., Taylor, E.M., Charnock, P., & Williams, G. (2015). Increasing source-to-image distance to reduce radiation dose from digital radiography pelvic examinations. *Radiologic Technology*, 86(3), 246-56.

Ertan, F., Mackenzie, A., Urbanczyk, H.J., Ranger, N.T., & Samei, E. (2009). Use of effective detective quantum efficiency to optimise radiographic exposures for chest imaging with computed radiography. Proceedings from SPIE, Medical Imaging: Physics of Medical Imaging, vol 7258. doi: 10.1117/12.813650

Everitt, B. (1996). *Making Sense of Statistics in Psychology.* Oxford : Oxford University Press

Everton, C., Bird,S., Brito,W., Collé, P., Franco, A.P., Lutjeber, S., Nodeland, K., Rième, S., Siddika, M., Webb, J., & Angmorterh,, S. (2014a). Review article – The effects of clinical support surfaces on pressure as a risk factor in the development of pressure ulcers, from a radiographical perspective: a narrative literature review. In P. Hogg, L. Lança (Eds.), *Radiation dose and image quality optimisation in medical imaging*, Erasmus Intensive Programme OPTIMAX#2014: Lisbon, Portugal.

Everton, C., Bird, S., Brito, W., Collé, P., Franco, AP., Lutjeber,, S., Nodeland,K., Rième, S., Siddika, M., Webb, J., & Angmorterh, S.. (2014b). Experimental article – An experimental study to compare the interface pressure and experience of healthy participants when lying still for 20 minutes in a supine position on two different imaging surfaces. In P. Hogg, L. Lança (Eds.), *Radiation dose and image quality optimisation in medical imaging*, Erasmus Intensive Programme OPTIMAX#2014: Lisbon, Portugal.

European Council Directive. (2013/59/EU). Directive 2013/59/EU of 5th of December 2014 Euratom on basic safety standards for the protection against the dangers arising from exposure to ionising radiation and repealing directives 89/618/Euratom, 90/641/Euratom, 96/29/ Euratom, 97/43/Euratom and 2003/122 Euratom. Official Journal of the European Union.

Falchi, M., & Rollandi, G.A. (2004). CT of pelvic fractures. European Journal of Radiology, 50:96–105 54

Farrell, K.R.C., Abbott, C., Round, K., Willis, S.J., Yalden, R., & Knapp, K.M. (2008). Pelvic projection radiography: increasing the source to image distance provides diagnostic images at reduced dose. Proceedings of the UK radiological congress, page 16. Manchester: British Institute of Radiology.

Fauber, T. (2013). *Radiographic imaging and exposure* (4th ed.). Missouri: Mosby, Inc

Faulkner, K., Broadhead, D.A., Harrison, & R.M. (1999). Patient dosimetry measurement methods. *Applied Radiations and Isotopes*, 50(1), 113-123

Fletcher, J.G., Hara, A.K., Fidler, J.L., Silva, A.C., Barlow, J.M., Carter, R.E., Bartley, A., Shiung, M., Holmes, D.R., Weber, N.K., Bruining, D.H., Yu, L., & McCollough, C.H. (2015). Observer performance for adaptive, image-based denoising and filtered back projection compared to scanner-based iterative reconstruction for lower dose CT enterography. *Abdominal Imaging*, 40(5), 1050-9. doi: 10.1007/s00261-015-0384-1.

Fleiss, J. (1986). *The Design and Analysis of Clinical Experiments*. New York: John Wiley & Sons

Fosbinder, R., & Orth, D. (2011). *Essentials of Radiologic Science*. Philadelphia: Wolters Kluwer Health/Lippincott Williams and Wilkins

Frantzen, M.J., Robben, S., Postma, A.A., Zoetelief, J., Wildberger, J.E., & Kemerink, G.J. (2012). Gonad shielding in paediatric pelvic radiography: disadvantages prevail over benefit. *Insights Imaging*, 3(1), 23–32. doi: 10.1007/s13244-011-0130-3

Fridrich, P., Krafft, P., Hochleuthner, H., Mauritz, W. (1996). The effects of long-term prone positioning in patients with trauma-induced adult respiratory distress syndrome. *Anaesthesia and Analgesia*, 83(6), 1206-11.

Garg, S. (2010). *Essentials of Orthophysiotherapy for Upper & Lower Limb Fractures.* New Delhi: Jaypee Brothers Medical Publishers

Geijer, H., Norrman, E., Persliden, J. (2009). Optimizing the tube potential for lumbar spine radiography with a flat-panel digital detector. *British Journal of Radiology*, 82, 62–68

George, J., Eatough, J.P., Mountford, P.J., Koller, C.J., Oxtoby, J., & Frain, G. (2004). Patient dose optimization in plain radiography based on standard exposure factors. *The British Journal of Radiology*, 77, 858–863

Ghasemi, A., Zahediasl, S. (2012). Normality tests for statistical analysis: a guide for non-statisticians. *International Journal of Endocrinology and Metabolism*, 10(2):486-9. doi: 10.5812/ijem.3505

Giordano, N. (2009). *College Physics: Reasoning and Relationships*. Belmont: Cengage Learning

Gleeson, C.E., Spedding, R.L., Harding, L.A., & Caplan, M. (2001).The mediastinum—Is it wide? *Emergency Medicine Journal*, 18, 183–185

Gorham, S., & Brennan, P.C. (2010). Impact of focal spot size on radiologic image quality: A visual grading analysis. *Radiography*, 16(4), 304-313.

Green, D., & Swets, J.A. (1966). Signal Detection Theory and Psychophysics. New York: Wiley

Grondin, Y., Matthews, K., McEntee, M., Rainford, L., Casey, M., Tonra, M., Al-Qattan, E., McCrudden, T., Foley, M., & Brennan, P.C. (2004). Dose-reducing strategies in combination offers substantial potential benefits to females requiring X-ray examination. *Radiation Protection Dosimetry*, 108(2), 123-132.

Grotz, M.R.W., Gummerson, N.W., Gansslen, A., Petrowsky, H., Keel, M., Allami, M.K., Tzioupis, C., Trentz, O., Krettek, C., Pape, H.C., & Giannoudis, P.V. (2006). Staged

management and outcome of combined pelvic and liver trauma. An international experience of the deadly duo. *Injury*, 37(7), 642-51. doi:10.1016/j.injury.2005.11.009

Guillamondegui, O.D., Pryor, J.P., Gracias V.H., Gupta R., Reilly P.M., & Schwab, C.W. (2002). Pelvic radiography in blunt trauma resuscitation: a diminishing role. *Journal of Trauma*, 53(6), 1043-1047.

Haleem, S., Heinert, G., & Parker, M.J. (2008). Pressure sores and hip fractures. *Injury*, 39(2), 219-223. doi: 10.1016/j.injury.2007.08.030.

Harding, L., Manning-Stanley, A.S., Evans, P., Taylor, M.E., Charnock, P., England, A. (2014). Optimum patient orientation for pelvic and hip radiography: A randomised trial. *Radiography*, 20, 22-32. http://dx.doi.org/10.1016/j.radi.2013.09.002

Harrison, J., & Lopez, P.O. (2015). Use of effective dose in medicine. *Annals of the ICRP*, 44(1), 221-228. doi: 10.1177/0146645315576096

Hart, D., Wall, B.F., Hillier, M.C., & Shrimpton, P.C. (2008). *Frequency and collective dose for medical and dental X-ray examinations in the UK*. Report HPA-CRCE-012. Health Protection Agency. Available from: http://www.hpa.org.uk/webc/ HPAwebFile/HPAweb_C/1287148001641[accessed 19.04.12].

Hart, D., Wall, B.F., Shrimpton, P.C., & Dance, D. (2000). The establishment of reference doses in paediatric radiology as a function of patient size. Radiation Protection Dosimetry, 90, 235–8.

Health and Social Care Information Centre. (2013). Focus on accident and emergency. NHS England. Retrieved from: http://www.hscic.gov.uk/catalogue/PUB13040/acci-emer-focu-on-2013-rep-V2.pdf

Heath, R., England, A., Ward, A., Charnock, P., Ward, M., Evans, P., & Harding, L. (2011). Digital pelvic radiography: increasing distance to reduce dose. *Radiologic Technology*, 83(1), 20-8.

Heetveld, M.J., Harris, I., Schlaphoff, G., & Sugrue, M. (2004). Guidelines for the management of haemodynamically unstable pelvic fracture patients. *Australian and New Zealand Journal of Surgery*, 74(7), 520-9.

Helmrot, E., Pettersson, H., Sandborg, M., & Altén, J.N. (2007). Estimation of dose to the unborn child at diagnostic x-ray examinations based on data registered in RIS/PACS. *European Radiology*, 17, 205-209

Hendee, W., & Ritenour, E. (2002). *Medical imaging physics* (4th ed.). New York: Wiley-Liss

Herrmann, T.L., Fauber, T.L., Gill, J., Hoffman, C., Orth, D.K., Peterson, P.A., Prouty, R.R., Woodward, A.P., & Odle, T.G. (2012). Best practices in digital radiography. *Radiological Technology*, 84, 83-89

Hess, R., & Neitzel, U. (2012). Optimizing image quality and dose for digital radiography of distal pediatric extremities using the contrast-to-noise ratio. *Rofo*, 184(7), 643-9. doi: 10.1055/s-0032-1312727

Hiles, P., Mackenzie, A., Scally, A., & Wall, B. (2005). Recommended standards for the routine performance testing of diagnostic X-ray imaging systems: Institute of physics and engineering in medicine (IPEM); Report No. 91. York: IPEM

Engel-Hills, P. (2006). Radiation protection in medical imaging. *Radiography*, 12, 153-160

Hinkle, D.E., Wiersma, W., & Jurs, S.G. (2003). *Applied Statistics for the Behavioural Science (*5th ed.). Boston: Houghton Mifflin

Holm, T. (2000). Consumer guide for the purchase of x-ray equipment. Sweden: World Health Organization.

Holmberg, O., Malone, J. , Rehani, M., McLean, D., & Czarwinski, R. (2010). Current issues and actions in radiation protection of patients. *European Journal of Radiology*, 76(1), 15–19

Hogg, P., & Blindell, P. (2012). *Software for image quality evaluation using a forced choice method*. Paper presented at the UKRC, Manchester, UK.

ImageJ. (2014). Image processing and analysis in Java (*Version 1.47*). Retrieved from http://rsb.info.nih.gov/ij/.

International Atomic Energy Agency (IAEA). (2004). Optimization of the radiological protection of patients undergoing radiography, fluoroscopy and computed tomography. Vienna, Austria: IAEA. Available online from: http://www-pub.iaea.org/MTCD/publications/PDF/te_1423_web.pdf

International Atomic Energy Agency. (2009). Justification of Medical Exposure in Diagnostic Imaging. Proceedings of an International Workshop. September. Brussels: IAEA. Retrieved online from: http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1532_web.pdf

International Atomic Energy Agency (IAEA). (2012). *Avoidance of unnecessary dose to patients while transitioning from analogue to digital radiology*. Vienna, Austria: IAEA

International Commission on Radiological Protection. (1991). 1990 Recommendations of the International Commission on Radiological Protection: ICRP Publication 60, 21 (1–3). Oxford: ICRP

International Commission on Radiological Protection (ICRP). (2004). Managing Patient Dose in Digital Radiology. A report of the international commission on radiological protection. *Annals of ICRP*, 34 (1), 1-73..

International Commission on Radiological Protection. (2005). Basis of dosimetric quantities used in radiological protection'. Draft for discussion by Task Group of ICRP Committee 2. Available from: http://www.icrp.org/docs/physics_icrp_found_doc_for_web_consult.pdf

International Commission on Radiological Protection (ICRP). (2006). The optimisation of radiological protection: Broadening the process, ICRP 101. *Annals of ICRP, 36*(3), 69-87.

International Commission on Radiological Protection (ICRP). (2007). The 2007 recommendations of the ICRP on radiological protection, publication 103. *Annals of ICRP*, 37(2-4), 1-332.

International Commission on Radiation Units and Measurements. (1993). Quantities and units in Radiation Protection Dosimetry. Report 51. Bethesda, USA: ICRU
International Commission on Radiation Units and Measurements. (1996).Medical Imaging – The Assessment of Image Quality. ICRU Report 54. Bethesda, Maryland: ICRU

Ionising Radiation((IR)[ME](MedicalExposure)). (2000). The ionising radiation (medical exposure) regulations 2000.Statutory instrument. Available from: http://www.legislation.gov.uk/uksi/2000/1059/ contents/made. No. 1059. London:HMSO.

Ionising Radiation (Medical Exposure) (Amendment) Regulations (2006). London: HMSO. Available from: http://www.opsi.gov.uk/si/si2006/20062523.htm (Accessed 25th of September, 2015).

Jang, K., Kweon, D.C., Lee, J.W., Choi, J., Goo, E.H., Dong, K.R., Lee, J.S., Jin, G., & Seo, S. (2011). Measurement of Image Quality in CT Images Reconstructed with Different Kernels. *Journal of the Korean Physical Society*, 58(2), 334-342

Jessop, M., Thompson, J.D., Coward, J., Sanderud, A., Jorge, J., de Groot, M., Lança L., & Hogg, P. (2015). Lesion detection performance: comparative analysis of low-dose CT data of the chest on two hybrid imaging systems. *Journal of Nuclear Medicine Technology*, 43(1), 47-52. doi: 10.2967/jnmt.114.147447.

Jin-Woo Choi, J., Lee, L., Choi, S., Heo, M., Huh, K., Yi, W., Kang, S., Han, D., Kim, E. (2015). Relationship between physical factors and subjective image quality of cone-beam computed tomography images according to diagnostic task. *Oral and Maxillofacial Radiology*, 119(3), 357–365

Jones, K.A. (2008). Using Automatic Exposure Control in Digital Radiography. Presented at The American Association of Physicists in Medicine Annual Meeting, Houston, Texas. Retrieved from: http://www.aapm.org/meetings/amos2/pdf/35-9964-61632-988.pdf

Jones, K., Polman, R., Willis, C., & Shepard, J. (2011). One Year's Results from a Server-Based System for Performing Reject Analysis and Exposure Analysis in Computed Radiography. *Journal of Digital Imaging*, 24(2), 243–255.

Johnston, J., & Fauber, T.L. (2015). Essentials of Radiographic Physics and Imaging (2nd ed.). Missouri: Elsevier

Johnson, J., & Kline, J.A. (2010). Intraobserver and interobserver agreement of the interpretation of pediatric chest radiographs. Emergency Radiology, 17(4), 285-90. doi: 10.1007/s10140-009-0854-2

Joyce, M., McEntee, M., Brennan, P.C., & O'Leary, D. (2013). Reducing dose for digital cranial radiography: The increased source to the image-receptor distance approach. *J Med Imaging Radiation Science*, 44, 180–187.

Kashani, H., Varon, C.A., Paul, NS., Gang, G.J., Van Metter, R., Yorkston, J., & Siewerdsen, J.H.(2010). Diagnostic performance of a prototype dual-energy chest imaging system ROC analysis. *Academic Radiology*, 17(3), 298-308. doi: 10.1016/j.acra.2009.10.012

Keating, M., & Grange, S. (2011). Image quality in the anteroposterior cervical spine radiograph: Comparison between moving, stationary and non-grid techniques in a lamb neck. *Radiography*, 17(2), 139-144.

Kessel, B., Sevi, R., Jeroukhimov, I., Kalganov, A., Khashan, T., Ashkenazi, I., Bartal, G., Halevi, A., & Alfici, R. (2007). Is routine portable pelvic X-ray in stable multiple trauma patients always justified in a high technology era? *Injury*, 38(5), 559-563. doi:10.1016/j.injury.2006.12.020

Knight, S.P. (2014) . A paediatric X-ray exposure chart. *Journal of Medical Radiation Sciences*, 61(3), 191–201. doi: 10.1002/jmrs.56

Korim, M.T., Reddy, V.R., Gibbs, D., & Wildin, C. (2012). Is the lateral radiograph necessary for the management of intra-capsular proximal femoral fractures? *Radiography*, 18(2), 109–111

Ko¨rner, M., Weber, C.H., Wirth, S., Pfeifer, K.J., Reiser, M.F., & Treitl, M. (2007). Advances in digital radiography: physical principles and system overview. *Radiographics*, 27, 675–86. DOI: http://dx.doi.org/10.1148/rg.273065075

Kroft L.J.M, Veldkamp W.J.H, Mertens B.J.A, van Delft J.P.A, & Geleijns J. (2007). Dose reduction in digital chest radiography and perceived image quality. *British Journal of Radiology*,80, 984–8.

Krupinski, E.A. (2010). Current perspectives in medical image perception. *Attention Perception and Psychophysics*, 72(5). doi:10.3758/APP.72.5.1205.

Kumar, R. (2014). *Research Methodology A Step-by-Step Guide for Beginners* (4th ed.). London: SAGE Publications Ltd

Kupinski, M.A. (2012). *Evaluation and Image Quality in Radiation-Based Medical Imaging*. In C. Grupen, I. Buvat (Eds.), Handbook of Particle Detection and Imaging (pp. 1083-1093). Berlin: Springer-Verlag. DOI. 10.1007/978-3-642-13271-1_43

Lanca, L., & Silva, A. (2013). *Digital Imaging Systems for Plain Radiography*. New York: Springer.

Lança, L., Franco, L., Ahmed, A., Harderwijk, M., Marti, C., Nasir, S., Ndlovu, J., Oliveira, M., Santiago A.R., & Hogg, P. (2014). 10 kVp rule – An anthropomorphic pelvis phantom imaging study using a CR system: Impact on image quality and effective dose using AEC and manual mode. *Radiography*, 20(4) , 333-338. doi:10.1016/j.radi.2014.04.007

Lanca, L., Andersen, E.N., Carvalho, G., van Gerwen, M., Jorge, J., Kleiker, M., Markali, B., Nightingale, P., Hogg, P. (2016). Are physical measures good indicators of clinical image quality at low dose levels, a pilot study. Paper presented at the European Congress of Radiology, Vienna, Austria. Retrieved from: http://repositorio.ipl.pt/bitstream/10400.21/6295/1/Are%20physical%20measures%20good%20indicators%20of%20clinical%20image%20quality%20at%20low%20dose%20levels.pdf

Lance, S., Pons, P., Guy, J., Chapleu, W., Butler, F., & McSwain, N. (2011). Prehospital Spine Immobilization for Penetrating Trauma- Review and Recommendations From the Prehospital Trauma Life Support Executive Committee. *Journal of Trauma,* 71(3), 763-770.

Le, N.T.T., Robinson, J., & Lewis, S.J. (2015). Obese patients and radiography literature: what do we know about a big issue? *Journal of Medical Radiation Science*. 62(2), 132–141. doi: 10.1002/jmrs.105

Lecerf, G., Fessy, M.H., Phillippot, R., Massin, P., Giraud, F., Flecher, X., Girard, J., Mertl, P., Marchetti, E., & Stindel, E. (2009). Femoral offset: Anatomical concept, definition, assessment, implications for preoperative templating and hip arthroplasty. *Orthopaedics & Traumatology: Surgery & Research,* 95(3), 210–219,

Lee, C., & Porter, K. (2007). The prehospital management of pelvic fractures. *Emergency Medicine Journal*, 24(2), 130-133. doi: 10.1136/emj.2006.041384

Leong, W., Koay, Y., Haughton, D., Blanckley, S., & Morehead, J. (2012). Lateral X-ray view of the hip in fracture of proximal femur: Is it necessary*? Injury Extra*, 42(10). DOI: 10.1016/j.injury.2012.07.336

Linsenmaier, U., Krotz, M., Kanz, K.G., Russ, W., Papst, E., Rieger, J., Mutscher, W., & Pfeifer. K.J. (2001). Evaluation of spine boards for X-Ray diagnostics. *Rofo,* 173(11), 1041-1047.

Lo, W.Y., & Puchalski, S. (2008). Digital image processing. *Veterinary Radiology and Ultrasound*, 49(1), 42-47. DOI: 10.1111/j.1740-8261.2007.00333.x

Long, B.W., Frank, E.D., & Ehrlich, R.A. (2013). *Radiography Essentials for Limited Practice* (4th ed.). Dallas: Saunders

Lorusso, J.R., Fitzgeorge, L., Lorusso, D., & Lorusso, E. (2015). Examining Practitioners' Assessments of Perceived Aesthetic and Diagnostic Quality of High kVp–Low mAs Pelvis, Chest, Skull, and Hand Phantom Radiographs. *Journal of Medical Imaging and Radiation Sciences*, 46, 162-173

Ludewig, E., Richter, A., & Frame, M. (2010). Diagnostic imaging--evaluating image quality using visual grading characteristic (VGC) analysis. *Vetinary Research Communications*, 34(5), 473-479.

Lundin, M. (2012). Aspects on Image Quality in Radiologic Evaluation of the Urinary Tract. (Medical Dissertation), Linköping University, Sweden. Retrieved from: http://liu.diva-portal.org/smash/get/diva2:516406/FULLTEXT01.pdf

Lyra, M.E., Kordolaimi, S.D., & Salvara, A.N. (2010). Presentation of Digital Radiographic Systems and the Quality Control Procedures that Currently Followed by Various Organizations Worldwide. *Recent Patents on Medical Imaging*, 2, 5-21 5

Ma, W.K., Hogg, P., Tootell, A., Manning, D., Thomas, N., Kane, T., Kelly, J., McKenzie, M., & Kitching, J. (2013a). Anthropomorphic chest phantom imaging – The potential for dose creep in computed radiography. *Radiography*, 19(3), 207-211.

Ma, W.K., Hogg, P., Tootell, A., Manning, D., Thomas, N., Kane, T., Kelly, J., McKenzie, M., & Kitching, J . (2013b). Variation of visual image quality using CR technology, relationship with E. *Radiography*, 19(1), 85-86

Ma, W.K., Hogg, P., & Norton, S. (2014). Effects of kilovoltage, milliampere seconds, and focal spot size on image quality. *Radiological Technology*, 85(5), 479-485

Malone, J., Guleria, R., Craven, C., Horton, P., Järvinen, H., Mayo, J., O'reilly, G., Picano, E., Remedios, D., Le Heron, L., Rehani, M., Holmberg, O., & Czarwinski, R.

(2012). Justification of diagnostic medical exposures: some practical issues. Report of an International Atomic Energy Agency Consultation. *British Journal of Radiology*, 85(1013), 523–538. doi: 10.1259/bjr/42893576

Manning, D.J., Ethell, S., Donovan, T., & Crawford, T. (2006). How do radiologists do it? The influence of experience and training on searching for chest nodules. *Radiography*, 12(2), 134–142

Manning, D., Ethell, S., & Donovan, T. (2004). Detection or decision errors? Missed lung cancer from the posteroanterior chest radiograph. *British Journal of Radiology*, 77(915), 231-235. DOI:10.1259/bjr/28883951

Manning-Stanley, A.S., Ward, A.J., & England, A. (2012). Options for radiation dose optimisation in pelvic digital radiography: A phantom study. *Radiography*, 18, 256-263

Månsson, L.G. (2000). Methods for the Evaluation of Image Quality: A Review. *Radiation Protection Dosimetry*, 90(1-2), 89-99

Mantiuk, R.K., Tomaszewska, A., & Mantiuk, R. (2012). Comparison of Four Subjective Methods for Image Quality Assessment. *Computer Graphics Forum*, 31(8), 2478-2491. Retrieved from: http://mmi.tudelft.nl/pub/hantao/SPIE10REDI.pdf

Marchiori, D. (2004). Clinical Imaging: With Skeletal, Chest, & Abdominal Pattern Differential (2nd ed.). St.Louis: Elsevier Health Sciences

Martin, C.J. (2007). Optimisation in general radiography. *Biomedical Imaging and Interventional Journal*, 3(2), e18. doi: 10.2349/biij.3.2.e18

Martin, C.J. (2011). Effective dose: Practice, purpose and pitfalls for nuclear medicine. *Journal of Radiological Protection*, 31, 205–219.

Massoud, E., & Diab, H.M. (2014). Optimization of Dose to Patient in Diagnostic Radiology Using Monte Carlo Method. *Journal of Cell Science & Therapy*, 5,155. doi: 10.4172/2157-7013.1000155

Mattsson, S., & Soderberg, M. (2013). Dose Quantities and Units for Radiation Protection. In S. Mattsson, C. Hoeschen (Eds.), *Radiation Protection in Nuclear Medicine*. Berlin: Springer. doi 10.1007/978-3-642-31167-3_2

McConnell, J., Eyres, R., & Nightingale, J. (2005) Interpreting Trauma Radiographs, Malden: Blackwell Publishing

McConnall, J. (2011). *Index of Medical Imaging*. Chichester; Wiley and Sons

McEntee, M.F., Nikolovski, I., Bourne, R., Pietrzyk, M.W., Evanoff, M.G., Brennan, P.C., & Tay, K.L. (2013). The effect of JPEG2000 compression on detection of skull fractures. *Academic Radiology*, 20(6), 712-20. doi: 10.1016/j.acra.2013.01.021.

McKinnis, L.N. (2013). *Fundamentals of Musculoskeletal Imaging* (4th ed.). Philadelphia: F.A. Davis Company

Mekiš, N., Mc Entee, M.F., & Stegnar, P. (2010). PA positioning significantly reduces testicular dose during sacroiliac joint radiography. *Radiography* 16(4), 333-338.

Merle, C., Waldstein. W., Pegg, E.C., Streit, M.R., Gotterbarm, T., Aldinger, P.R., Murray, D.W., & Gill, H.S. (2013). Prediction of three-dimensional femoral offset from AP pelvis radiographs in primary hip osteoarthritis. *European Journal of Radiology*, 82(8), 1278-85.

Mettler, F.A., Huda, W., Yoshizumi, T.T., & Mahesh, M. (2008). Effective doses in radiology and diagnostic nuclear medicine: a catalog. *Radiology*, 248(1), 254

Metz, C.E. (2006). Receiver operating characteristic analysis: a tool for the quantitative evaluation of observer performance and imaging systems. *Journal of American College of Radiology*, 3, 413-422.

Moore, C.S., Wood, T.J., Beavis, A.W., & Saunderson, R.J. (2013). Correlation of the clinical and physical image quality in chest radiography for average adults with a

computed radiography imaging system. *British Journal of Radiology*, 86, 1027. doi: 10.1259/bjr.20130077

Moores, B.M. (1993). The Role of Phantoms in Standardisation of the Radiological Process. *Radiation Protection Dosimetry*, 49(1-3), 19-26.

Mori, M., Imai, K., Ikeda, M., Iida, Y., Ito, F., Yoneda, K., & Enchi, Y. (2013). Method of measuring contrast-to-noise ratio (CNR) in nonuniform image area in digital radiography. *Electronics and Communications in Japan*, 96(7), 32--41. DOI: 10.1002/ecj.11416

Morrell, RE. (2006). Dosimetry and Optimisation in High Dose Fluoroscopic and Fluorographic Procedures. (PhD thesis), University of Nottingham, Nottingham. Retrieved from: http://eprints.nottingham.ac.uk/10181/

Mothiram, U., Brennan, P.C., Lewis, SJ., Moran, B., & Robinson, J. (2014). Digital radiography exposure indices: A review. *Journal of Medical Radiation Sciences*, 61(2), 112-118.

Mraity, H. (2015). Optimisation of radiation dose and image quality for AP pelvis radiographic examination. (PhD thesis), Salford University, Salford. Retrieved from: http://usir.salford.ac.uk/36914/

Mraity, H., England, A., Cassidy, S., Eachus, P., Dominguez, A., & Hogg, P. (2013). Development and validation of a psychometric scale for assessing pelvis image quality. Conference paper at Liverpool: United Kingdom Radiological Congress

Mraity, H., England, A., & Hogg, P. (2014a). Developing and validating a psychometric scale for image quality assessment. *Radiography*, 20(4), 306-311.

Mriaty, H., England, A., Akhtar, I., Aslam, A., De Lange, R., Momoniat, H., Nicoulaz, S., Ribeiro, A., Mazhir, S., & Hogg, P. (2014b). Development and validation of a psychometric scale for assessing PA chest image quality : A pilot study. *Radiography*, 20(4), 312-317.

Mucci, B., Murray, H., Downie, A., & Osborne, K. (2013). Interrater variation in scoring radiological discrepancies. *British Journal of Radiology*, 86,1028. doi: 10.1259/bjr.20130245

Mutch, S.J., & Wentworth, S.D. (2007). Imaging the neonate in the incubator: an investigation of the technical, radiological and nursing issues. *British Journal of Radiology*, 80, 902-910.

Muhogora W.E, Ahmed N.A, Almosabihi A, Alsuwaidi J.S, Beganovic A, Ciraj-Bjelac O, Kabuya F.K, Krisanachinda A, Milakovic M, Mukwada G, Ramanandraibe M.J, Rehani M.M, Rouzitalab J, & Shandorf C. (2008). Patient doses in radiographic examinations in 12 countries in Asia, Africa, and Eastern Europe: initial results from IAEA projects. *American Journal of Roentgenology*, 190(6), 1453-61 . doi: 10.2214/AJR.07.3039.

Naqvi, G.A., Iqbal, S., Reynolds, T., Braithwaite, I., & Banim, R. (2012). Is a lateral view essential in management of hip fracture? *European Journal of Radiology*, 81(11), 3394-96

National Council on Radiological Protection and Measurements (NCRP). (1988). Quality Assurance for Diagnostic Imaging. NCRP Report No. 99. Bethesda, MD: NCRP

National Council on Radiation Protection and Measurements (NCRP). (1989). Medical X-Ray, Electron Beam and Gamma-Ray Protection for Energies Up to 50 MeV (Equipment Design, Performance and Use). Report No. 102. Bethesda: NCRP

Neitzel, U. (1992). Grids or air gaps for scatter reduction in digital radiography: a model calculation. *Medical Physics*, 19(2), 475-81.

National Institute for Health and Care Excellence (NICE). (2011). Inditherm patient warming mattress for the prevention of inadvertent hypothermia. London: NICE. Available from: http://www.nice.org.uk/guidance/mtg7/resources/factsheet-11851885

Norrman, E., & Persliden, J. (2005). Factorial experiment on image quality and radiation dose. *Radiation Protection Dosimetry*, 114(1-3), 246–252. doi:10.1093/rpd/nch557

Obaid, A.K., Barleben, A., Porral, D., Lush, S., & Cinat, M. (2006). Utility of plain film pelvic radiographs in blunt trauma patients in the emergency department. *The American Surgeon*, 72(10), 951-954.

Obuchowski, N.A. (2004). How Many Observers Are Needed in Clinical Studies of Medical Imaging? *American Journal of Roentgenology*, 182 (4), 867-869

Ofori, E., Antwi, W., Scutt, D., & Ward, M. (2012). Optimization of patient radiation protection in pelvic X-ray examination in Ghana. *Journal of Applied Clinical Medical Physics*,13 (4), 3719

Oremus, M., Oremus, C., Hall, G.B., &McKinnon, M.C. (2012). Inter-rater and test–retest reliability of quality assessments by novice student raters using the Jadad and Newcastle–Ottawa Scales. *BMJ Open*, 2 (4), e001368. doi:10.1136/bmjopen-2012-001368

Papp, J. (2010). Quality Management in the Imaging Sciences (4th ed.). St.Louis: Mosby

Paul, L., Docquier, P.L., Cartiaux, O., & Banse, X. (2008). Measurement of radiographic magnification in the pelvis using archived CT scans. *Acta Orthop*, 74, 623-626

Pelli, D.G., & Farell, B. (1995). *Handbook of optics. Fundamentals, techniques, and design*. New York: McGraw-Hill

Pelvis radiographic anatomy. (n.d.). WikiRadiography, retrieved 15 October, 2015 from: http://www.wikiradiography.net/page/Pelvis+Radiographic+Anatomy

Perez, M. (2013). What do we need from ICRP in medicine? Justification of medical exposure In: The second international symposium on the system of radiological protection. United Arab Emirates: ICRP. Available online: http://www.icrp.org/docs/Maria%20Perez%20referral%20criteria%20and%20clinical%20decision%20support%20radiological%20protection%20aspects%20for%20justification.pdf

Périard, M.A., & Chaloner, P.(1996). Diagnostic X-Ray Imaging Quality Assurance: An Overview. *The Canadian Journal of Medical Radiation Technology*, 27(4), 171-177.

Persliden, J., & Carlsson, G.A. (1997). Scatter rejection by air gaps in diagnostic radiology. Calculations using a Monte Carlo collision density method and consideration of molecular interference in coherent scattering. *Phys Med Biol*, 42(1),155-75.

Petoussi-Henss, N., Bolch, W.E., Eckerman, K.F., Endo, A., Hertel, N., Hunt, J., Pelliccioni, M., Schlattl, H., & Zankl, M. (2010). ICRP Publication 116. Conversion coefficients for radiological protection quantities for external radiation exposures. *Annals of the ICRP*, 40(2-5):1-257. doi: 10.1016/j.icrp.2011.10.001.

Phantoms, sectional. (2014). The Phantom laboratory. Sectional lower Torso SK250. Retrieved June, 1st, 2015, from http://www.phantomlab.com/library/pdf/sectional_ SK250DS.pdf

Pinto, A., & Brunese, L. (2010). Spectrum of diagnostic errors in radiology. *World Journal of Radiology*, 2(10), 377–383. doi: 10.4329/wjr.v2.i10.377

Poletti, J.L., & McLean, D. (2005). The effect of source to image-receptor distance on effective dose for some common X-ray projections. *British Journal of Radiology*, 78(933), 810-815.

Poole, G.V., & Ward, E.F. (1994). Causes of mortality in patients with pelvic fractures. *Orthopedics*, 17(8), 691-696.

Pradhan, A.S., Kim, J.L., & Lee, J.I. (2012). On the use of "effective dose" (*E*) in medical exposures. *Journal of Medical Physics*, 37(2), 63–65. doi: 10.4103/0971-6203.94739
Quaghebeur, G., Bhattacharya, JJ., Murfitt, J. (1997). Radiologists and visual acuity. *European Radiology*, 7(1), 41-43

Ramanaidu, S., Maria, S., Ng, K., George, J., & Kumar, G. (2006). Evaluation of radiation dose and image quality following changes to tube potential (kVp) in conventional paediatric chest radiography. *Biomedical Imaging Intervention Journal.* 2(3), e35. doi: 10.2349/biij.2.3.e35

Reed, W.M., Ryan, J.T., McEntee, M.F., Evanoff, M.G., & Brennan, P.C. (2011). The effect of abnormality-prevalence expectation on expert observer performance and visual search. *Radiology*, 258(3), 938-43. doi: 10.1148/radiol.10101090

Reis C, Gonçalves J, Klompmaker C, Barbara, A.R., Bloor, C., Hegarty, R., Lagrange, T., Temming, N., Sonnesyn, M., Rokeness, H., Yamasathien, A., & Hogg, P. (2014). Image quality and dose analysis for a PA chest X-ray: Comparison between AEC mode acquisition and manual mode using the 10 kVp rule. *Radiography*, 20, 339–45.

Robinson, P.J.A., Wilson, D., Coral, A., Murphy, A., & Vrow, P. (1999). Variation between experienced observers in the interpretation of accident and emergency radiographs. *British Journal of Radiology*,72, 323–30.

Rosner, B. (2006). *Fundamentals of biostatistics* (6th ed.). Belmont: Thomson-Brooks/Cole

Rosner, B. (2010). *Fundamentals of biostatistics* (7th ed.). Boston: Cengage Learning
Reid-Paul, TS. (2011). *Radiologic Technology at a Glance*. New York: Cengage Learning

Samei, E., Badano, A., Chakraborty, D., Compton, K., Cornelius, C., Corrigan, K., Flynn, M.J, Hemminger, B., Hangiandreou, N., Johnson, J., Moxley, M., Pavlicek, W., Roehrig, H., Rutz, L., Shepard, J., Uzenoff, R., Wang, J., & Willis, C. (2005a). Assessment of Display Performance for Medical Imaging Systems: Report of the American Association of Physicists in Medicine (AAPM) No. 93 Task Group 18, Madison: AAPM

Samei, E., Dobbins, J.T., Lo, J.Y., & Tornai, M.P. (2005b). A framework for optimising the radiographic technique in digital x-ray imaging. *Radiation Protection Dosimetry*, 114(1-3), 220-229

Samei, E. (2009). Effective DQE (eDQE) and speed of digital radiographic systems: An experimental methodology. *Medical Physics*. 36(8): 3806–3817 . doi: 10.1118/1.3171690

Samei, E., Ranger, N.T., MacKenzie, A., Honey, I.D., Dobbins, J.T., & Ravin, C.E. (2008). Detector or System? Extending the Concept of Detective Quantum Efficiency to

Characterize the Performance of Digital Radiographic Imaging Systems Radiology. *Radiology*, 249(3), 926–937.

Samei, E., Ranger, N.T, & Chen, Y. (2006). Intercomparison of methods for image quality characterization. I. Modulation transfer function. Medical Physics,33, 1454–65

Sandborg, M., & Önnerth, M. (2004). Comparison of human observer efficiency in pelvis radiographs in two different anatomical regions. Report from The Department of Radiation Physics, Linkoping University, Sweden. Retrieved from: http://liu.diva-portal.org/smash/get/diva2:328215/FULLTEXT01.pdf

Sandborg, M., McVey, G., Dance, D., & Alm Carlsson, G. (2001a). Schemes for the optimization of chest radiography using a computer model of the patient and x-ray imaging system. *Medical Physics*, 28(10), 2007-2019.

Sandborg, M., Tingberg, A., Dance, D.R., Lanhede, B., Almén, A., McVey, G., Sund, P., Kheddache, S., Besjakov, J., Mattsson, S., Månsson, L.G., & Alm Carlsson, G. (2001b). Demonstration of correlations between clinical and physical image quality measures in chest and lumbar spine screen–film radiography. *British Journal of Radiology*, 74(882), 520-528.

Sandborg, M., Dance, D.R., Carlsson, G.A., & Persliden, J. (1993). Selection of anti-scatter grids for different imaging tasks: the advantage of low atomic number cover and interspace materials. *British Journal Radiology*, 66(792), 1151-63.

Schmidt, P.W., Dance, D.R., Skinner, C.L., Smith, I.A., & McNeill, J.G. (2000). Conversion factors for the estimation of effective dose paediatric cardiac angiography. *Physics in Medicine and Biology*, 45(10), 3095-3107.

Schramek, G., Stoevesandt, D., Reising, A., Kielstein, J.T., Hiss, M., & Kielstein, H. (2013). Imaging in anatomy: a comparison of imaging techniques in embalmed human cadavers. *BMC Medical Education*, 13, 143.

Schueler, B.A. (1998). Clinical applications of basic x-ray physics principles. *RadioGraphics,* 18(3), 731-744.

Schultz, F.W., Geleijns, J., Spoelstra, F.M., & Zoetelief, J. (2003). Monte Carlo calculations for assessment of radiation dose to patients with congenital heart defects and to staff during cardiac catheterization. *British Journal of Radiology,*76(909), 638-647.

Seeram, E., Davidson, R., Bushong, S., & Swan, H. (2013). Radiation dose optimization research: Exposure technique approaches in CR imaging – A literature review. *Radiography*, 19(4), 331-338.

Seeram, E., Bushong, S., Davidson, R., & Swan, H. (2014). Image quality assessment tools for radiation dose optimization in digital radiography: An overview. *Radiologic technology, 85*(5), 555-562.

Shaw, L. (2005). *Anatomy and physiology*. Cheltenham : Nelson Thornes.

Shephard, C.T. (2003). *Automatic exposure control. Radiographic image production and manipulation.* New York: McGraw-Hill

Shepard, S.J., Wang, J., Flynn, M., Gingold, E., Goldman, L., Krugh, K., Leong, D.L., Mah, E., Ogden, K., Peck, D., Samei, E., Wang, J., & Willis, C.E. (2009). An exposure indicator for digital radiography: AAPM Task Group 116 (executive summary). *Medical Physics*, 36(7), 2898-914.

Shier, D., Butler, J., & Lewis, R. (2008). *Hole's essentials of human anatomy and physiology*. London : McGraw-Hill Higher Education.

Shoker, H. (2010). Taking the Pressure off NHS Resources: Walsall Hospital's NHS Trust Pilots ArjoHuntleigh's Pressure Ulcer Prevention and Outcome Assessment, ArjoHuntleigh Getinge Group

Siebers, R. (2001). Data Inconsistencies in Abstracts of Articles in Clinical Chemistry. *Clinical Chemistry*, 47(1), 149. Retrieved from: http://www.clinchem.org/content/47/1/149.long

Škrk, D., Zdešar, U., & Žontar, D. (2006). Diagnostic reference levels for X-ray examinations in Slovenia. *Radiology Oncology*, 40(3), 189–95

Sorenson, J.A., & Floch, J. (1985). Scatter rejection by air gaps: an empirical model. *Medical Physics*. 12(3), 308-16.

Sprawls, P. Radiation Quantities and Units. The Physical Principles of Medical Imaging online. Available from: http://www.sprawls.org/resources/RADQU/ (Accessed 26 June, 2015)

Sprawls, P. (1995). *Physical Principles of Medical Imaging* (2nd ed.). Madison, WI: Medical Physics Publishing Corporation

Stone, M. (2012). Procedure for the Handling of Bariatric / Heavy Patients. .Manual Handling Policy. October,Version 5, Nottingham NHS. Retrieved from: http://www.nuh.nhs.uk/about-us/our-policies-and-procedures/health-and-safety-policies-and-procedures/

Stryker. (2012). Stryker Prime X Imaging Stretcher: Image quality. Access. Mobility. Switzerland: Stryker. Available online from: http://patienthandling-eu.stryker.com/~/media/patienthandling/doc/spec%20sheets/uk%20eng%20spec%20sheets/prime_x_spec_sheet_2012_en.ashx

Sun, Z., Lin, C,, Tyan, Y., & Ng, K.H. (2012). Optimization of chest radiographic imaging parameters: a comparison of image quality and entrance skin dose for digital chest radiography systems. *Clinical Imaging*, 36(4), 279-86.

Sund, P., Båth, M., Kheddache, S., & Månsson, L.G. (2004). Comparison of visual grading analysis and determination of detective quantum efficiency for evaluating system performance in digital chest radiography. *European Radiology*, 14(1), 48-58.

Talbot, R., Smith, Z., & Dykes, L. (2007). Mountain Casualties in Snowdonia. Conference Poster at the International Wilderness Medicine, Aviemore. Retrieved from:

http://www.scribd.com/doc/219351697/Mountain-Casualties-in-Snowdonia-2007-summary-Conference-Poster

Tang, K., Wang, L., Li, R., Lin, J., Zheng, X., & Ca, G. (2012). Effect of Low Tube Voltage on Image Quality, Radiation Dose, and Low-Contrast Detectability at Abdominal Multidetector CT: Phantom Study. *Journal of Biomedicine and Biotechnology,*2012, 130-169. DOI: 10.1155/2012/130169

Tapiovaara, M. (2006). Relationships between physical measurements and user evaluation of image quality in medical radiology – a review. In: STUK Helsinki: Radiation and Nuclear Safety Authority. Available from: https://www.julkari.fi/bitstream/handle/10024/124751/stuk-a219.pdf?sequence=1

Taylor, J.R. (1997). An *Introduction to Error Analysis: The Study of Uncertainties if Physical Measurements (2nd ed.).* Sauselito: University Science Books

Taylor, E., Hewitt, K., Reeves, R.A., Hobbs, S.H., & Lawless, WF. (2013). Group Decision-making: Consensus Rule Versus Majority Rule. *Procedia Technology*, 9, 498-504. http://dx.doi.org/10.1016/j.protcy.2013.12.055.

The National Clinical Guideline Centre. (2011). The Management of Hip Fracture in Adults. London: National Clinical Guideline Centre. Retrieved from: www.ncgc.ac.uk

The Royal College of Radiologists. (2006). Standards for the reporting and interpretation of imaging investigations. London: RCR

The Royal College of Radiologists, Society and College of Radiographers, Institute of Physics and Engineering in Medicine. (2008). *A Guide to Understanding the Implications of the Ionising Radiation (Medical Exposure) Regulations in Radiotherapy*. London: The Royal College of Radiologists

The Royal College of Radiologists. (2011). Standards of practice and guidance for trauma radiology in severely injured patients. London: RCR

The Royal College of Radiologists. (2012a). iRefer: making the best use of clinical radiology (7th ed.). London: Royal College of Radiologists.

The Royal College of Radiologists. (2012b). Picture archiving and communications system (PACS) and guidelines on diagnostic display devices. London: RCR

The Royal College of Radiologists. (2014). Quality assurance in radiology reporting: peer feedback. London: RCR

The Royal College of Radiologists Society and College of Radiographers and British Institute of Radiology. (2015). A guide to understanding the implications of the Ionising Radiation (Medical Exposure) Regulations in diagnostic and interventional radiology. London: The Royal College of Radiologists

The Society and College of Radiographers. (2013a). Code of Professional Conduct. London: SOR. Retrieved from: http://www.sor.org/learning/document-library/code-professional-conduct

The Society and College of Radiographers. (2013b). Preliminary Clinical Evaluation and Clinical Reporting by Radiographers: Policy and Practice Guidance. London: SCoR. Retrieved from: http://www.sor.org/learning/document-library/preliminary-clinical-evaluation-and-clinical-reporting-radiographers-policy-and-practice-guidance

Theodore, N., Hadley, M., Aarabi, B., Dhall, S., Gelb, D.E., Hurlbert, J.R., Rozzelle, C.J., Ryken, T.C., & Walters, B.C. (2013). Pre-hospital Cervical Spinal Immobilization After Trauma. Neurosurgery, 72, 22-34. doi: 10.1227/NEU.0b013e318276edb1

Thompson, J.D., Manning, D.J, & Hogg, P. (2013). The Value of Observer Performance Studies in Dose Optimization: A Focus on Free-Response Receiver Operating Characteristic Methods. *Journal of Nuclear Medicine Technology*, 41, 1–8. doi: 10.2967/jnmt.112.116566

Thompson, B. (2012). Bariatric In-Patient Handling Guidelines. Version 1.2: NHS FORTH VALLEY . Retrieved from:

http://www.nhsforthvalley.com/__documents/ig/policies_areawide_riskmanagement/manual_handling__bariatric_patient_policy.pdf (Accessed 26 of June 2015)

Thornbury, J. R., Fryback, D. G., Patterson, F. E., & Chiavarini, R. L. (1977). Effect of screen/film combinations on diagnostic certainty: Hi-Plus/RPL versus Lanex/Ortho G in excretory urography. *American Journal of Roentgenology*, 130(1), 83-87

Tingberg, A., Herrmann, C., Lanhede, B., Almén, A., Sandborg, M., Mc Vey, G., Mattson, S., Panzer, W., Besjakov, J., Månsson, L.G., Kheddache, S., Alm Carlsson, G., Dance, D.R., Tylén, U., & Zankl, M. (2004). Influence of the characteristic curve on the clinical image quality of lumbar spine and chest radiographs. *British Journal of Radiology*, 77, 204–215

Tingberg, A. (2000). Quantifying the quality of medical X-ray images: an evaluation based on normal anatomy o the lumbar spine and chest radiography. (PhD thesis), Lund Univeristy, Malmo, Sweden: Department of Radiation Physics. Retrieved from: https://lup.lub.lu.se/search/publication/40610

Tingberg, A., Båth, M., Håkansson, M., Medin, J., Besjakov, J., Sandborg, M., Alm-Carlson, G., Mattsson, S., & Mansson, L.G. (2005). Evaluation of image quality of lumbar spine images: a comparison between FFE and VGA . *Radiation Protection Dosimetry*, 114, 1-3, 53 – 61

Tingberg A, & Sjöström D.(2005). Optimisation of image plate radiography with respect to tube voltage. Radiation Protection Dosimetry,114, 286–93. doi.10.1093/rpd/nch536

Tjiang, H.H., Richardson, D. (2011). Radiation exposure from diagnostic imaging in trauma patient presenting to emergency department. *Medical Student Journal of America*, 3 (2), 4-11

Tootell, A., Szczepura, K., & Hogg, P. (2014). An overview of measuring and modelling dose and risk from ionising radiation for medical exposures. *Radiography*, 20(4), 323-332

Trapp, J. V., & Kron, T. (2008). An introduction to radiation protection in medicine. New York: Taylor & Francis.

Trout, E.D., Kelley, J.P., & Larson, V.L. (1975). A comparison of an air gap and grid in roentgenography of the chest. *American Journal of Roentgenology*, 124(3), 404-411

Tugwell, J., Everton, C., Kingma, A., Oomkens, D.M., Pereira, G.A., Pimentinha, D., Rouiller, C.A.I., Stensrud, S.M., Kjelle, E., Jorge, J., & Hogg, P. (2014). Increasing source to image distance for AP pelvis imaging – Impact on radiation dose and image quality. *Radiography*, 20(4), 351-355

Tugwell, J. (2014*).* Here comes a trolley…Imaging the trolley bound patient – current working practices and experience. *Imaging and Therapy Practice*. September 2014. Available on: http://content.yudu.com/Library/A31snf/ImagingampTherapyPra/resources/17.htm

Uffmann, M., & Schaefer-Prokop, C. (2009). Digital radiography: the balance between image quality and required radiation dose. *European Journal of Radiology*, 72(2), 202-208.

Ullman, G., Sandborg, M., Dance, D.R., Hunt, R., & Alm Carlsson, G. (2004). Optimisation of chest radiology by computer modelling of image quality measures and patient effective dose. Report 97. Sweden: Department of Medicine and Care Radio Physics Faculty of Health Sciences. Retrieved from: http://www.diva-portal.org/smash/get/diva2:328150/FULLTEXT01.pdf

Ullman, G. (2008). Quantifying image quality in diagnostic radiology using simulation of the imaging system and model observers. (Medical Dissertation, Linköping University, Sweden). Retrieved from: http://liu.diva-portal.org/smash/get/diva2:18076/FULLTEXT01.pdf

Ulrich, R., & Miller, J. (2004). Threshold estimation in two-alternative forced-choice (2AFC) tasks: the Spearman-Karber method. *Percept Psychophys*, 66(3), 517-533.

Uppot, R.N., Sahani, D.V., . Hahn, P.F., Gervais, D., & Mueller, P.R. (2007). Impact of Obesity on Medical Imaging and Image-Guided Intervention. American Journal of Roentgenology, 188(2), 433-440

van Teijlingen, E., & Hundley, V. (2002). The importance of pilot studies. *Nursing Standard*, 16(40), 33-36

van der Plaats, G.J., & Vijlbrief, P. (1980). Medical X-Ray Techniques in Diagnostic Radiology: A textbook for radiographers and Radiological Technicians. The Hague: Springer

Vanderlan, W., Tew, B., & McSwain, N. (2009). Increased risk of death with cervical spine immobilization in penetrating cervical trauma. *Injury*, 40(8), 880-883. doi: 10.1016/j.injury.2009.01.011

Vassileva, J. (2002). A phantom for dose-image quality optimization in chest radiography. *British Journal Radiology*, 75(898), 837-842.

Vennart, W. (1997). ICRU Report 54: Medical imaging—the assessment of image quality. Radiography , 3(3) , 243 - 244

Verdun, F.R., Denys, A., Valley, J.F., Schnyder, P., & Meuli, R.A. (2002). Detection of low-contrast objects: experimental comparison of single- and multi-detector row CT with a phantom. *Radiology*, 223(2):426-31

Vickery, D. (2001). The use of the spinal board after the pre-hospital phase of trauma management. *Emergency Medicine Journal*. 18, 51-54

Vladimirov, A. (2010). Comparison of image quality test methods in computed radiography. (MSc Thesis), University of Tratu, Estonia. Retrieved from: http://dspace.utlib.ee/dspace/bitstream/handle/10062/15191/Vladimirov_Anatoli.pdf;jsessionid=80A1A82F275CF25DA0B99383FFB3DACB?sequence=1

Vucich, J.J (1979) The role of anatomic criteria in evaluation of radiographic images. In: A.G. Haus (Ed). The Physics of Medical Imaging. (pp. 573–87), New York: American Association of Physics in Medicine

Yu, L., Leng, S., Chen, L., Kofler, J.M., Carter, R.E., & McCollough, C.H. (2013). Prediction of human observer performance in a 2-alternative forced choice low-contrast detection task using channelized Hotelling observer: impact of radiation dose and reconstruction algorithms. *Medical Physics*, 40(4). doi: 10.1118/1.4794498.

Wales News Service (2015, 19th January). Wales Online. Retrieved from: http://www.walesonline.co.uk/news/wales-news/war-hero-89-kept-waiting-8476248

Wall, B.F., Haylock, R., Jansen, J.T., Hillier, M.C., Hart, D., & Shrimpton, P.C. (2011). Medical x-rays: radiation risks by age and sex of patient. Public Health England. Retrieved online: *https://www.gov.uk/government/.../HPA-CRCE-028_for_website.pdf*

Wall, B.F. (2006). Response to "Radiation dose measurement and optimisation". *British Journal of Radiology*, 79(940), 356–58. doi: http://dx.doi.org/10.1259/bjr/34749787

Wall, B.F., Kendall, G.M., Edwards, A., Bouffler, S., Muirhead, C.R., & Meara, J.R. (2006). What are the risks from medical X-rays and other low dose radiation? *The British Journal of Radiology*, 79, 285–294

Walker, S., Allen, D., Burnside, C., & Small, I. (2011). Determining the relationship between exposure factors, dose and exposure index value in digital radiography. *Synergy Imaging and Therapy*; October, 14-17

Watkins, M.W., & Pacheco, M. (2000). Interobserver Agreement in Behavioral Research: Importance and Calculation. *Journal of Behavioral Education*, 10(4), 205-212

Whitley, S.A., Jefferson, G., Holmes, K., Sloane, C., Anderson, C., Hoadley, G. (2015). *Clark's positioning in radiography* (13th ed.). London: CRC Press

Williams, M.B., Krupinski, E.A., Strauss, K.J., Breeden, W.K., Rzeszotarski, M.S., Applegate, K., Wyatt, M., Bjork, S., & Seibert, J.A. (2007). Digital radiography image quality: image acquisition. *Journal of the American College of Radiology*, 4, 371-388.

Williams, L. (2006). Pelvis and hips. In: B. Carver, E. Carver (Eds.), *Medical imaging: technique, reflection and evaluation*, (pp. 121-133). Philadelphia: Churchill Livingstone Elsevier

Williams, S., Hackney, L., Hogg, P., & Szczepura, K. (2014). Breast tissue bulge and lesion visibility during stereotactic biopsy – A phantom study. *Radiography*, 20, 271-76

Winslow, J.F., Hyer, D.E., Fisher, R.F., Tien, C.J., & Hintenlang, D.E. (2009). Construction of anthropomorphic phantoms for use in dosimetry studies. *Journal of Applied Clinical Medical Physics*, 10(3). doi:10.1120/jacmp.v10i3.2986.

Woods, J., & Messer, S. (2009). Focusing on dose. *Synergy Imaging & Therapy Practice*, September, 16-20.

Woodward, A. (2011). Digital Radiography: Exposure Factor Selection and ALARA. Presented in the Radiological Society of North America Scientific Assembly and Annual Meeting, November 26 - December 2,Chicago IL. Retrieved from: http://archive.rsna.org/2011/11001030.html