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AN EVALUATION OF DIGITAL RADIOGRAPHY IN THE IMAGING OF THE NEONATAL CHEST

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A thesis submitted in partial fulfilment of the requirements of
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ABSTRACT

Katrina Elizabeth Klaasen Borthwick

Master of Philosophy

An Evaluation of Digital Radiography in the Imaging of the Neonatal Chest

Neonatal chest radiography is an area where there has been very limited research. The introduction of Computed Radiography (CR) has provided a new imaging modality that can be used to acquire neonatal chest radiographs and possibly reduce the radiation dose. The aim of this thesis was to design a simple phantom that reproduced the attenuation and scattering characteristics expected for a neonatal chest, and to develop a methodology for assessing image quality in terms of spatial resolution and contrast.

Prior to undertaking the experimental phase, a questionnaire was sent out to ascertain the availability of CR in hospitals undertaking paediatric radiography. The results of the questionnaire provided information on the clinical areas where CR was installed and the reasons for selecting CR. The experimental phase of the study involved acquiring images of the phantom with a test object using Screen Film Radiography (SFR) and CR at the exposures used in the Neonatal Unit (NNU), and at half this exposure. The CR images were then assessed on both hard copy and soft copy and compared to SFR which is still considered the gold standard for neonatal chest radiography.

The results indicated that soft copy CR was best for viewing the images, particularly at the reduced exposure. As a result it may be possible to acquire follow up images in NNU at a lower exposure, therefore reducing the radiation dose to the patient.

CONTENTS

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GLOSSARY OF ABBREVIATIONS

ADC	Analogue to Digital Converter
AEC	Automatic Exposure Control
A&E	Accident and Emergency
AP	Antero-Posterior
CH	Children's Hospital
CR	Computed Radiography
CRT	Cathode Ray Tube
CT	Computed Tomography
DDR	Direct Digital Radiography
DGH	District General Hospital
DICOM	Digital Imaging and Communications in Medicine
DMax	Maximum Film Density
DQE	Detective Quantum Efficiency
DSR	Digital Selenium Radiography
ESD	Entrance Surface Dose
FFD	Focus to Film Distance
FPD	Flat Panel Detector
GUHT	Grampian University Hospital Trust
HIS	Hospital Information System
IP	Imaging Plate
IT	Information Technology
ITU	Intensive Care Unit
kVp	Kilovoltage Peak
LCD	Liquid Crystal Display
$Lpmm^{-1}$	Line Pair per Millimeter
LRE	Log Relative Exposure
mAs	Milliampere Second
MRI	Magnetic Resonance Imaging
MTF	Modulation Transfer Function
NHS	National Health Service
NIP	Needle Imaging Plate
NNU	Neonatal Unit
NRPB	National Radiological Protection Board

PACS	Picture Archiving and Communications System
QA	Quality Assurance
RACH	Royal Aberdeen Children's Hospital
RE	Relative Exposure
RIS	Radiology Information System
RSNA	Radiological Society of North America
Se	Selenium
SFR	Screen Film Radiography
Si	Silicon
SiV	Sykehuset I Vestfold
SPECT	Single Positron Emission Computed Radiography
TFT	Thin Film Transistors
TLD	Thermoluminescent Dosemeter
TT	Transmitted Through
UK	United Kingdom
US	United States
UTH	University Teaching Hospital
VLBW	Very Low Birth Weight
ITU	Intensive Care Unit
kVp	Kilovoltage Peak
LCD	Liquid Crystal Display
$Lpmm^{-1}$	Line Pair per Millimeter
LRE	Log Relative Exposure
mAs	Milliampere Second
MRI	Magnetic Resonance Imaging
MTF	Modulation Transfer Function
NHS	National Health Service
NIP	Needle Imaging Plate
NNU	Neonatal Unit
NRPB	National Radiological Protection Board

PACS	Picture Archiving and Communications System
QA	Quality Assurance
RACH	Royal Aberdeen Children's Hospital
RE	Relative Exposure
RIS	Radiology Information System

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This thesis is dedicated to my husband Herman and my parents Kate and Ramsay Borthwick

CHAPTER 1

1. Introduction

1.1 Background

Since 1895, when WK Roentgen discovered x-rays, methods of medical imaging have developed rapidly and are now considered to be a "...major contribution to health care..." (Osteaux et al 1996:166). However it is only in the last 30 years that an alternative method of image acquisition for conventional (screen film) radiography (SFR) has been developed. Digital imaging technology originated with the introduction in the 1970s of Computed Tomography (CT) scanners.

As technology improved manufacturers began to investigate the possibility of developing it as an alternative to SFR. As 60-70% of examinations in neonatal radiography are performed using SFR, any new technique that can improve image quality and possibly reduce patient dose is of interest. As a result, in the early 1980s the first Computed Radiography (CR) system was introduced for general radiography and in the 1990s the first Direct Digital Radiography (DDR) system was introduced.

In recent years there has been an "...increasing acceptance that a move to all-digital technology represents the future for medical imaging departments" (Bury et al 1998:923). With ever increasing demands on Radiology departments to be more efficient and cost effective any advances in imaging technology needs to be assessed.

The enactment in the United Kingdom (UK), of the Ionising Radiation (Medical Exposure) Regulations 2000 (IR(ME)R 2000) focused attention on working practices within Radiology departments, and individual accountability. Written protocols in all Radiology departments serve as guidelines as to what is an acceptable indication for a particular x-ray examination. This is aimed at limiting the number of unnecessary examinations undertaken, so reducing patient dose. The importance of this can be appreciated when it is realised that for all sources of ionising radiation, man-made

sources account for 15% of the total and of this, 90% can be attributed to medical x-rays (IPSM 1992).

This is of particular significance in neonatal radiography as recent years have seen great advances in foetal and neonatal medicine and it is no longer unusual for neonates with a gestational age of 24 weeks to survive. These neonates can weigh as little as 500g and are classed as Very Low Birth Weight (VLBW) and pose unique challenges for the imaging modality and staff, particularly as these "...neonates can be regarded as potentially having the greatest remaining lifespan of any patient, which together with their radiosensitivity and potentially large number of radiographs performed, demands dose optimization" (Lowe et al 1999:55).

However, it is important to appreciate the value of medical x-rays as a diagnostic tool and that "The potential benefit of any radiographic examination must outweigh the potential harm" (Cook 2001: 230). In order to monitor patient doses the IR(ME)R 2000 regulations require all Radiology departments to establish dose reference tables for all examinations. These reference doses are calculated in terms of the Entrance Surface Dose (ESD) which is defined as "...the absorbed dose to air at the point of intersection of the x-ray beam axis with the entrance surface of the patient..." (IPSM 1992:5).

The exposure factors required to produce an image in neonatal radiography are often at the lowest limit of the equipment's range and therefore careful selection of radiographic technique is important. The introduction of CR and DDR has provided another possibility for limiting dose but this requires further investigation to determine its suitability for neonatal chest radiography. In addition "Screen-film combinations have been used for close to 100 years and the x-ray detection characteristics of these systems are well known" (Huda et al 1997:1621), and therefore SFR remains the gold standard for neonatal chest radiography. A detailed description of each of the modalities can be found in Appendix 1.

1.2 Literature Review

In order to identify the imaging modalities most frequently used in neonatal chest radiography and to investigate the possibility of dose reduction, a review of the literature was conducted.

Using Medline (US National Library of Medicine) and a combined search strategy using the key words "neonatal", "chest radiography" and "digital" a search of the PubMed database was conducted in February 2001. The results of this initial search were limited and a further search was done using the additional key words, "image quality", "radiation dose" and "CR". After reviewing the results of the initial searches a further search was done for the articles most frequently cited in the references. As digital radiography is a rapidly developing field regular searches of Medline were made every three months to check for new articles.

From the results it was apparent that research into neonatal chest radiography has been limited. The majority of the studies that used CR dated from the early 1990s, when CR began to be more affordable. In addition there was a number of articles published in the mid 1990s on SFR as a result of the publication of the European Guidelines on Quality Criteria for Diagnostic Radiographic Images in Paediatrics 1996 (EUR 16261 1996). These guidelines advised on the best exposure factors and the acceptable level of radiation dose for a wide range of examinations, including chest radiography in newborns. Only three articles were identified that dealt with DDR in neonatal chest radiography, Rapp-Bernhardt et al (2003), Rapp-Bernhardt et al (2005) and Smaei et al (2003), a reflection of the limited availability of this imaging modality.

A further aim of the literature review was to identify the different methods used to assess image quality and to measure the radiation dose. It was necessary to consider these two factors together, as reduced dose may produce a non-diagnostic image, and therefore be of no benefit to the patient. Neonates are particularly vulnerable to the long term effects of radiation exposure as

> "Radiation exposure in the first 10 years of life is estimated, for

certain detrimental effects, to have an attributable lifetime risk three to four times greater than after exposures between the ages of 30 and 40 years, and five to seven times greater when compared to exposures after the age of 50 years." (EUR 16261 1996:4).

Therefore any imaging modality that can reduce the patient dose and maintain image quality needs investigation.

After articles by Cohen et al (1991), Arthur & Pease (1992), de Silva (1997), Samei et al (2003) and Rapp-Bernhardt (2005) were reviewed it became apparent that the opinion of Weatherburn et al (2000) that there is "...uncertainty in the literature about the magnitude and direction of any change in dose that can be achieved for radiographic examinations..." (Weatherburn et al 2000:708) is well warranted.

A major problem was the assessment of the actual level of dose reduction reported in studies due to the wide range of variables involved. Every imaging system has unique characteristics relating to the x-ray equipment, image receptor and the type of automatic film processor. It was therefore necessary to look at all aspects of the imaging systems when looking at dose (Lowe et al 1999). A further problem was the wide variation in the weight range of neonates in a NNU, with 0.5Kg to 5kg, quoted by Wraith et al (1995). This is an issue as weight is

"An important determinant of the level of dose received by individuals from diagnostic x-ray examination and is a confounding factor when assessing and comparing radiation doses to patients in x-ray departments" (NRPB R318 2000:1).

From the literature three different methods of assessing image quality and radiation dose were identified. These were studies using animal models, radiographic phantoms and clinical studies.

1.2.1 *Animal Studies*

Animal studies are a valuable means of assessing imaging systems, particularly in the case of neonatal radiography. Selection of the appropriate animal model can replicate the attenuation and scattering expected for neonates without the ethical implications of unnecessarily irradiating neonates.

The disadvantage of using an animal model was that in a number of studies the animals were destroyed at the end of the study. In addition not all hospitals have access to animal research departments and therefore the experimental methods cannot be easily reproduced. When reviewing the literature a number of studies using an animal model were identified and are reported on below.

Broderick et al (1992) investigated the latitude of a CR system using a fixed milliampere seconds (mAs) and a variable kilovoltage (kVp), and an animal model to represent a neonate. Four rabbits were used weighing between 2.4Kg and 4.2Kg, values representative of the upper weight range found in Neonatal Units (NNU). The wide latitude of CR, has according to Broderick et al (1992), a particular advantage in neonatal chest radiography as "In no other clinical situation do relatively minor variations in exposure settings result in images which are under penetrated, over penetrated, or lacking adequate contrast" (Broderick et al 1992:346). In SFR the latitude (breadth of exposure range that would produce a diagnostic image) is very narrow and therefore the room for error is consequently very small, CR has an advantage particularly in the reduction of retakes due to exposure errors. A detailed discussion on latitude can be found in Appendix 2.

Images were acquired as the kVp was increased from 40kVp to 80kVp in five kVp steps and from 80kVp to 150kVp in 10kVp steps, with the mAs constant at 1mAs. Paired images for SFR and CR were acquired for each rabbit at the different exposure values so that each rabbit acted as its own control. For SFR image acquistion was stopped at 110kVp as anatomical structures were no longer visible.

The results indicated that a diagnostic image of a rabbit's chest was obtained with SFR for the range of 60kVp to 65kVp at 1mAs, but for CR the kVp range was 40kVp to 150kVp at 1mAs. The paired images for each rabbit were assessed by three readers and image quality was scored by the visibilty of selected regions of interest, there was no attempt to identify subtle structures of the chest, for example blood vessels. The results clearly demonstrated the wide latitude of CR compared to SFR.

Broderick et al (1993) published a second paper that used eight rabbits that weighed between 2.6Kg and 4.6Kg to represent neonates, where the aim was to compare SFR and CR when the kVp was fixed and the mAs varied. The kVp was fixed at 60kVp and the mAs increased from 0.1mAs to 256mAs by doubling the previous value. For each rabbit a SFR and CR image was acquired at each exposure level, but in the case of SFR image acquisition stopped at 16mAs as the films were completely black. The findings showed that for SFR the range of mAs that produced a diagnostic image was 0.9mAs to 2.0mAs and for CR the range was 0.4mAs to 256mAs. The results again demonstrated the wide latitude of CR. Images were assessed using the same broad descriptions as used for the 1992 study.

The results indicated that CR represented a 60% decrease in exposure but the authors do not stipulate the speed of the CR system and therefore it cannot be assumed that the reduction in exposure was as great as stated, as the SFR system may have been slower. As Schaetzing (2003) noted "...the fact that you may be able to reduce dose with CR relative to your current screen-film system does not make CR a lower dose system. One could have used a different, higher speed S/F system and achieved the same result" (Schaetzing 2003:17). Of particular relevance to neonatal chest radiography was the finding that at low exposures on CR quantum mottle can obscure fine lung detail and that this could affect diagnosis in the clinical environment.

Don et al (1994) again used rabbits to simulate neonates in a study that compared the detection of pneumothoraces for SFR and CR. In mechanically ventilated neonates the incidence of spontaeous pneumothorax is between 6 and 10% and therefore of significance in the treatment of these patients (Don et al 1994).

The investigators used three rabbits with a weight range of 2Kg to 3Kg and induced different sizes of pneumothorax and then imaged the rabbits using both SFR and CR. The pneumothoraces were induced by the introduction of a catheter into the posterior pleural space and the progressive introduction of air in 4ml steps. Images of each rabbit were acquired using both SFR and CR until between 24 and 28ml air had been introduced. The paired images were then compared for the visibilty of the pneumothorax. Exposure parameters were kept the same for both modalities as was the collimation.

The results indicated that for 168 observations there was no difference (p=0.25) in the identification of a pneumothorax between the two modalities. In addition there was no difference (p=0.43) between SFR and CR for the mean number of signs of pneumothorax identified.

Don et al (1999) again used three rabbits with a weight range of 2Kg to 3Kg to compare SFR and CR after inducing pulmonary oedema in varying degrees. The study also investigated the impact of reducing the exposure for CR on the detection of pulmonary oedema. Images of each rabbit were acquired using 60kVp and 1mAs for SFR, for CR, images were acquired using 60kVp at 0.9mAs and 1.1mAs, 70kVp at 0.9mAs and 0.56mAs and finally 81kVp at 0.56mAs.

Images were assessed by four readers for the presence of an opacity and for image quality. The findings indicated that there was no difference (p>0.05) in detection between SFR and CR regardless of the level of exposure. For the image quality there was also no statistical difference between SFR and CR.

As a result of the increased kVp and the reduced mAs a 20% exposure reduction was achieved, however this does not indicate that CR is a lower dose system as the same dose reduction could be obtained for SFR, if the same exposure factors were used. In addition as a result of "...reducing milliampere seconds there is a concomitant increase in the noise (quantum mottle) which could be confused with findings such as respiratory distress syndrome" (Don et al 1999:456).

At the 2004 meeting on the Radiological Society of North America (RSNA), Puig et al (2004) presented a paper that used animal models to simulate VLBW neonates and

compared SFR to a portable DDR system. The DDR system was the CXDI-31 from Canon (Canon Inc. Medical Equipment Group, Tochigi, Japan), and this was the first report of its use in neonatal radiography. In addtition this was the first study that looked at this particular group of neonates.

The rabbit used weighed 1200g and the rat only 450g, reflecting the weight range expected for very premature neonates. The DDR images were evaluated using soft copy, and the findings indicated that using DDR there was a substantial reduction in radiation dose, by a factor of nine to ten, however the DDR system used was twice the speed of the SFR. A major concern with the study was that the initial exposure values appeared to be very high. For the rabbit the ESD was 135μGy, a value almost three times the upper limit of 50μGy for neonatal chest radiography in the UK. In the case of the rat the ESD was 49μGy, although under the limit it is still exceedingly high for such a low weight. When compared to values from clinical studies the discrepancy became apparent, Wraith et al (1995) quote 37μGy and McParland et al (1996) obtained a value of 16.4 μGy. In both these studies SFR was used and according to Puig et al (2004) the DDR system was lower dose.

With DDR the optical density is established by the software with no regard for the exposure and as a result of the wide latitude, digital imaging can compensate for 500% over exposure and 80% under exposure (Artz 1997). This will result in an image that appears correctly exposed but where the dose could be excessive.

To simulate lung lesions foreign bodies were placed on the animal's chests, and the images were assessed by two radiologists for visibilty of lesions, and intrapulmonary structures to evaluate the image quality. The results showed that when the ESD for the rabbit was reduced to 11μGy from an original ESD of 135μGy, the images were noisy but did not significantly affect the ability of the readers to detect lesions. In the case of the rat the ESD was again reduced to 11μGy from an original value of 49μGy, the images were considered as being at least as good as SFR but image assessment was hampered by the small image size.

1.2.2 *Phantom Studies*

The main advantage of a phantom study is the avoidance of unnecessary irradiation of neonates or animals and the ethical issues that arise. In addition, phantom studies ensure that the images are directly comparable where as for clinical studies changes in the patient's clinical condition can alter the appearance of the images. A major disadvantage of a phantom study is that it does not replicate patient movement both voluntary and involuntary (respiration and heart). However in the case of neonates they are invariably supported in position for the radiograph and exposure times used are so short as to make involuntary movement of negligible importance. Compared to animal studies phantom studies provide a simpler approach that does not require ethical permission.

Jones et al (2001) developed an anthropomorphic phantom to use in a study that aimed to measure the ESD for neonatal chest, abdominal and combined chest and abdominal radiography using CR. As there appeared to be no commercially available phantom the authors developed their own using polymethylmethacrylate (Perspex) as this material has a mass attenuation coefficient similar to human skeletal muscle.

The size of the phantom was determined from reviewing radiographs of neonates imaged in the NNU, and was 21.8cm long, 13cm broad and 8cm thick and was considered comparable to the torso of 2.5kg neonate. Two air filled cavities were created to simulate the presence of air in the lungs. Images were acquired using the exposure factors used in the NNU and collimation was kept consistent for each projection. The dose was measured by an ionisation chamber as the available thermoluminescent dosemeters (TLD) did not have a high enough sensitivity.

The results indicated that for chest radiography the ESD was 56.7μGy, abdomen 73.6μGy and for combined chest abdominal radiograph 71.5μGy. These values are somewhat higher than for the clinical studies by Wraith et al (1995) and McParland et al (1996), but the weights of the neonates in these studies were lower. One finding of note was the influence of the collimated area on the radiation dose, and that if all other exposure parameters are kept constant the effective dose to the patient will

increase if the area irradited is increased. Therefore "...good standards of radiographic practice are more important than choice of technique" (Jones et al 2001:926).

Rapp-Bernhardt et al (2005) compared CR to the CXDI-31(Canon Inc. Medical Equipment Group, Tochigi, Japan) portable Flat Panel Detector (FPD) using an anthropomorphic phantom, to represent a paediatric chest. However the phantom used was an adult one and therefore two separate images were required to image it completely when using the FPD due to the size (24x30cm) compared to the CR plate (35x43cm). To assess image quality 50 different templates were produced with different catheters and simulated pathology present. These templates were placed over the phantom and images were acquired.

The authors referred to altering the digital speed but in real terms this involved reducing the mAs for DDR by 50% compared to the CR system. The difference in collimation used for acquiring the CR images and the FPD images would have had an impact on the image quality and also the dose received by the phantom, as discussed above. Another problem with the study was that the stated aim was to simulate conditions for paediatric radiography but an adult phantom was used. Adult chests have a different tissue composition compared to children and particularly neonates, where the presence of the thymus and the relatively large heart shadow produce low contrast images.

Four readers assessed the images on hard copy and scored the images according to the visibilty of the catheters and simulated pathology. Although the readers were blinded to the method of image acquisition, CR and DDR had a "...distinctly different appearance..." (Rapp-Bernhardt et al 2005:490) and therefore there was an element of bias in the results. These indicated that reduced exposure DDR was as good as full exposure CR for identifying simulated lung disease and catheters. The authors comment that a clinical trial is necessary as phantoms do not take account of patient movement and respiration. Another issue with the study was the use of hard copy to review the images, rather than soft copy which has greater scope for post processing the images to enhance appearance.

1.2.3 *Clinical Studies*

Although both animal and phantom studies provide a great amount of data with regard to dose and image quality, clinical studies are necessary to confirm the findings due to the many variables involved in imaging. In addition, experience in Radiology departments has shown that the assessment of image quality is subjective and determined by the personal preference of the reader. The level of dose reduction achievable for a phantom or animal study may not produce a diagnostic image in a clinical situation. Therefore despite the ethical considerations the majority of the articles reviewed referred to clinical studies.

Arthur & Pease (1992) compared a total of 741 neonatal chest radiographs, 386 acquired using CR and 355 using SFR, using the same exposure factors and concluded that image quality was comparable, despite the theoretical lower resolution of the CR system. Of particular concern to the authors was the fact that there is no direct means of assessing images for the correct exposure, as CR corrects the optical density regardless of exposure. Therefore incorrectly exposed images will not be identified, and as a result patients could receive an unnecessary over exposure. In addition doubts were expressed as to the reliability of the "S" number as an indicator of the exposure to the CR plate. The use of CR did not significantly alter the repeat rate, as the majority of retakes required were for technical reasons. The major weakness of the article was the lack of statistical data and as a result the findings cannot be generalised.

Cohen et al (1991) compared 150 neonatal chest images, 50 SFR images and 50 CR images at the conventional exposure and 50 CR images with the mAs reduced by 50%. The images were only obtained when clinically indicated avoiding unnecessary irradiation of the neonates. There was no attempt made to obtain paired images for direct comparison, therefore images were assessed on a random basis. Three readers assessed the images for visibility of anatomical structures and film density. In addition, for the CR images only, edge enhanced and non edge enhanced paired images were compared to ascertain if there was an improvement in the image quality.

The results indicated that there was a preference ($p=0.17$) for full exposure CR compared to half exposure CR for lung, bone, soft tissue and the mediastinum. For SFR, when compared to the half exposure CR images, there was a preference ($p<0.01$) for SFR for visualisation of lung, bone and soft tissue. For the visualisation of tubes there was no statistically significant difference between any of the images.

For the second part of the study on edge enhancement, results indicated no major benefit with the use of edge enhancement. As with Arthur & Pease (1992), concern was raised that incorrect exposures could go undetected with CR. However as no detail of the speed of the CR system was provided it cannot be certain what the true exposure difference between SFR and CR was. The images were not paired and therefore no true comparison between the imaging systems could be made.

Huda et al (1996) investigated the impact of mottle on the diagnostic qualtiy of paediatric chest films. They compared CR and SFR images acquired in a paediatirc intensive care unit with the exposure dictated by patient size. The images were reviewed by five readers for the level of mottle and radiographic image quality. The images were not paired and included a wide range of patient sizes.

The top score was classed as being equivalent to a 200 speed CR system, three times slower that the 600 speed SFR system used, and therefore required three times the exposure to produce that quality of image. The intermediate group, with acceptable level of mottle and good image quality was classed as equivalent to 400-600 speed CR, and therefore would require up to a 33% increase in exposure compared to SFR. For the CR images the level of quantum mottle at 600 speed resulted in an undiagnostic image.

Maccia et al (1996) published the EUR16261 guidelines and as a result there was a number of articles published that looked at methods of dose reduction in neonatal chest radiography. As a result of the guidelines dose reference levels for all radiographic examinations were introduced with a maximum ESD of 80μGy for neonatal chest radiography recommended. In the UK the National Radiological Protection Board (NRPB) set the limit for ESD at 50μGy, therefore all Radiology

deparments had to review their radiographic technique and find methods of reducing the ESD to acceptable limits.

Wraith et al (1995) investigated the level of dose reduction that could be achieved by changing radiographic technique to that advised by the EUR 16261 (1996) guidelines for SFR. To calculate the ESD an equation that used the tube output and exposure parameters was used. The use of TLDs (thermoluminescent dosemeters) was not considered because of the infection control risks, possible artefact formation and also the TLDs available were not sufficiently sensitive to measure the low doses used.

Prior to undertaking clinical trials to investigate the impact of changes in technique, Wraith et al (1995) undertook phantom studies to assess the possible level of dose reduction . Images were acquired of a 5cm block of Tissue Equivalent (TE) Perspex and a test object, that allowed resolution and contrast to be measured. Only if the results of the phantom study were satisfactory were the changes used in a clinical trial. An increase of 10kVp reduced the ESD from 62µGy on the original system to 36µGy, a value under the NRPB limit. The image quality was assessed using the criteria laid down in the EUR 16261(1996) guidelines for neonatal chest radiography.

One point raised by the study was the need for equipment manufacturers to take account of the special requirements of neonatal imaging as currently the "... combinations of exposure factors available for neo-natal radiography are restricted by the limited number of mAs settings ... unit operated near the lower end of the exposure range" (Wraith et al 1995:1080). In addition the authors noted that changes in the patients' clinical condition could affect the image quality and therefore a more objective means of comparing image quality was needed, for example test objects.

A similar study by McParland et al (1996) investigated the impact of increased kVp on the ESD and the image quality for SFR. Unlike the study by Wraith et al (1995) paired images were used to compare conventional exposure technique to the reduced exposure technique. Images were acquired within 48 hours of each other and only when clinically indicated.

Prior to the clinical study a phantom study was carried out using a 4.2cm block of TE Perspex to represent a neonate. As the kVp was increased the mAs was reduced to maintain the correct optical density and to enable the ESD to be calculated. After ascertaining a suitable exposure setting the clinical trial was carried out.

From 363 images acquired in the NNU, 35 matched pairs of chest radiographs were obtained. These were assessed by three readers and scored according to the visibility of anatomical structures, as specified in the EUR 16261 (1996) guidelines. A dose reduction from 20μGy to 16.4μGy was achieved with no difference ($p<0.0005$) in the image quality for the two techniques. Again this paper emphasised the need for a phantom study to be done prior to clinical studies to ensure that the technique was appropriate.

Lowe et al (1999) investigated the variation in ESD for neonatal chest radiography across five NNUs, and the potential relationship between image quality and radiographic technique. Prior to undertaking the clinical study the exposure parameters for each site were evaluated, with particular attention to the speed of the imaging system, using a 5cm block of TE Perspex. The results indicated that the nominal speed quoted by the manufacturer did not correspond with the actual speed measured, and that the values varied for each site.

For the clinical study, dose was calculated in terms of ESD from the data recorded for each examination and the results revealed "...an appreciable variation in ESDs not only between sites but also within sites, with little difference between sites radiographic practices to account for the variation of doses between sites" (Lowe et al 1999:57). To assess the image quality six readers reviewed all the images and used a seven point system to identify anatomical landmarks.

Results for image quality indicated an 11% ($p=0.015$) variation between the sites but for the ESDs the variation was 39% ($p<0.000$). It was therefore concluded that there was "...no correlation of image quality to ESD" (Lowe et al 1999:58). In an attempt to explain the wide variation in ESDs, the radiographic technique from all sites was reviewed, and poor collimation was identified as a factor that could influence the

dose. However the main factor appeared to be the variation in speed of the imaging systems, with those that used table top processors being the slowest. As a result it was recommended that greater consideration be given to the actual speed of a system and that main department processors are used for developing images.

Armpilia et al (2002) compared two methods of measuring radiation dose in NNUs, one indirect and the other direct. The indirect method used the following equation to calculate ESD:

" $ESD(\mu Gy)=output(\mu GymAs^{-1}) \times mAs \times BSF \times ISL \times [(\mu_{en}/\rho)_{tis}(\mu_{en}/\rho)_{air}]$

Where the ISL factor is an inverse-square law correction from the focus-to-chamber distance (100cm) to the focus-to-skin distance (FSD), and $(\mu_{en}/\rho)_{tis}$ and $(\mu_{en}/\rho)_{air}$ are the mass energy absorption coefficient for tissue and air, respectively" (Armpilia et al 2002:591). BSF is the backscatter factor used and this was 1.1±5%.

The direct method of measurement used a LiF:Mg, Cu, P TLD (Lithium Fluoride: Magnesium, Copper, Phosphorous thermoluminescent dosemeter) that had a lower detection limit and greater sensitivity compared to those discarded by Wraith et al (1995) and Jones et al (2001). Prior to the clinical study a series of images of the TLDs were acquired with the use of a solid water phantom to represent a neonate. At 4cm and 5cm thicknesses the TLD was seen on the image and as a result it was decided to place the TLDs on the shoulder of the neonate for chest radiography and not in the centre of the primary beam.

A total of 95 radiographs were reviewed with an average ESD was 36±6μGy, below the reference level recommended by NRPB (50μGy). When the two dose measurement methods were compared the dose levels were similar but a reasonable correlation was not seen. It was thought that the position of the TLDs affected the results, and to clairfy this, measurements were taken for centre field and the edge and compared, the difference was 7%. From the study it could be concluded that TLDs were not a suitable method for the measurement of dose in neonates as they introduce artefacts and therefore could not be placed in the centre of the primary beam.

Samei et al (2003) evaluated a prototype portable FPD (Flat Panel Detector) (Paxscan 2520, Varian Medcal Systems, Salt Lake City, USA) and compared it to a CR system in a NNU. Only 30 neonates were included in the study, a CR image was acquired at the normal exposure and the FPD at 25% of the exposure, at the same time. The study refers to the inclusion of neonates smaller than the detector but the relevance of this is not clear, as it is only necessary to have the area to be examined on the plate.

Images were reviewed using soft copy and the six readers were asked to identify the tip of a catheter, but as Rapp-Bernhardt et al (2005) noted this did not provide a particular challenge for either imaging modality. The readers were blind to the image acquisition system but as the FPD images "...had a distinctly different appearance compared to CR images ... due to differences in post-processing procedures used in the two imaging systems" (Samei et al 2003:604) a bias could be present. There was no difference ($p>0.05$) between the CR and the FPD.

The exposure factors used were not clearly indicated with only the kVp stated and that the mAs was as low as the unit could go. The authors state that the exposure was reduced to 25% but this does not take account of the difference in speed of the two imaging systems. As Rapp-Bernhardt et al (2005) points out, comparing a 200 speed CR system to a 800 speed FPD does not constitute a true dose reduction.

Rapp-Bernhardt et al (2005) compared SFR to the Canon CXDI-31 portable FPD where the exposure for the FPD was reduced by 50%, in a follow up study to their 2003 work using a phantom. The authors stated that the patients used in the study were premature but images included in the study were from a 2 year old and two 3 month old babies, not neonates. At least two images were acquired, one using SFR and another using FPD at half the mAs, for each patient. These images were only acquired when there was a clinical indication and the paired images were compared to ensure that there was only minimal variation in the appearances. Exposure parameters were kept constant bar the change in mAs but no control was used to ensure that collimation was kept consistent, a frequent failing in clinical studies that can affect the image quality.

The images were evaluated on hard copy by four paediatric radiologists with 480 observations made. The results indicated that the FPD was significantly better for pulmonary vasculature (p=0.02), subdiaphragmatic lung (p=0.02), unobscured lung (p=0.01) and the pedicles of vertebral bodies (p=0.002). There was no significant difference between systems for retrocardiac lung (p=0.05) or intervertebral spaces (p=0.06). In the case of catheters (p=0.03) and stomach tube (p=0.04) the FPD was significantly better than SFR.

There was a possible bias in the results as the digital images had a higher level of noise and greater edge enhancement, and in addition laser film differs in appearance to conventional film. Use of hard copy does not take full advantage of the benefits of digital imaging. One major concern was that the authors did not give an indication of the age and weight range of the children involved in the study and therefore it was difficult to conclude if the patients were neonates or older.

1.2.4 *Conclusion*

The literature review indicated that there has been a limited degree of research into neonatal chest radiography. One consistent factor was the importance of evaluating the image quality in relation to the radiation dose. A major difficulty in the assessment of dose reduction was the number of papers that did not specify the speed of the two imaging systems that were compared, leaving the reader unsure of the true dose reduction, if any. In addition the sample sizes of animals and neonates used in the various studies was limited.

A number of studies compared SFR to CR using both full exposure and reduced exposure but none compared them to SFR at the reduced exposures. By including reduced exposure SFR it would be possible to assess the degree of exposure reduction that CR can achieve by comparing like images. The clinical and phantom studies that investigated CR and DDR only considered neonate weights of 2.5Kg or greater and did not consider the lower birth weights of 1Kg or less.

There is a need for the development of a simple and reproducible methodology that can assess the impact of reduced exposure on image quality for both SFR and digtial imaging modalities. An animal study was decided against due to a number of factors. Not all Radiology departments have access to animal research facilities, and there is the need for anaethetists. The physiology of a rabbit is different from that of a neonate in terms of the muscle to fat ratio and the proportion of lung to mediastinum. In addition all the rabbits used were adults and healthy, therefore no account was taken of the affect of pathology on image quality.

A clinical study was not considered due to the ethical considerations, particularly as it was planned to use half exposure SFR, and this could result in undiagnostic images. The majority of neonates do not have normal lungs and their clinical condition can change rapidly so that obtaining comparable images would be very difficult. Undertaking a phantom study would produce consistent images with no concern for the level of exposure.

Prior to starting the experimental phase it was considered important to identify the level of availabilty of CR in Radiology departments that undertook paediatric radiography. This aimed to provide data on the number of hospitals that could possibly benefit from the findings of a phantom study into neonatal chest radiography. A review of the literature identified two surveys that looked at the availability of digital imaging systems. Cohen (1992) looked at the availability of CR in 65 paediatric hospitals throughout the United States (US) and reported that out of 39 (60%) respondents only four had installed CR.

Bauman & Gell (2000) reported on a survey conducted in 1998, that looked at the world wide availability of Picture Archiving and Communications System (PACS). It was assumed that any department with PACS used CR for some, if not all radiographic examinations. Of the 1000 hospitals surveyed, there was a response rate of 36% (n=363). For Europe, 550 questionnaires were sent out, but only 13% (n=72) were returned, of these, 41 had a PACS and another 18 planned to install one within the following two years.

Of the 41 hospitals with PACS, 29 had a bed capacity in excess of 500, 10 had a bed capacity between 200-499, and the remaining two PACS were in hospitals with a bed capacity under 200. As there was no UK study identified it was necessary to conduct one to ascertain the availabilty of CR and its usage.

1.3 Aim of Thesis

The aim of this thesis was to develop a method for evaluating the different imaging modalities used in neonatal chest radiography. After reviewing the literature it was decided to use a radiographic phantom as this placed no restriction on the number of images acquired or the level of exposure used. In addition phantom studies are reproducible in terms of technique.

In order to assess the different modalities, two aspects were considered, image quality and possible dose reduction. In order to assess image quality two criteria were selected, spatial resolution and contrast. Detective Quantum Efficiency (DQE) and Modulation Transfer Function (MTF) were excluded as they measure overall system performance and not the image quality. Both spatial resolution and contrast are simple to assess and influence the final image quality.

Five objectives were identified in order to fulfill the aim of the thesis and these are listed in the next section.

1.4 Objectives of the Thesis

1.4.1 *Quantify the availability of digital imaging systems in paediatric hospitals through-out the United Kingdom (UK). Chapter 2*

1.4.2. *Use sensitometry and film/intensifying screens to quantify the radiation dose to clinically significant points on the neonatal chest radiograph. Chapter 3*

1.4.3 *Identify/modify commercially available phantoms which replicate these radiation doses and permit the evaluation of sharpness and contrast on the radiograph. Chapter 3*

1.4.4. *To compare the image quality and radiation dose for film/screen systems and for digital systems. Chapter 4*

1.4.5. *Make suitable recommendations regarding the use of digital imaging techniques and software tools for neonatal chest radiography. Chapter 5*

CHAPTER 2

2. Methods I: Availability of CR

2.1 Introduction

A questionnaire that aimed to assess the availabilty of CR in UK hospitals undertaking paediatric radiology was designed. It was divided into three sections, the first was aimed at establishing the size of the department and if there was a paediatric radiology service. The second looked at the paediatric workload and the availability of dedicated paediatric x-ray rooms and radiographers. The final section was only relevant to departments that had CR, and related to the date of installation, reasons for selecting CR and the examinations done using CR. DDR was excluded due to the very limited availability.

2.2 Pilot Questionnaire

A pilot questionnaire was sent to five Radiology departments throughout the UK that represented the types of hospital doing paediatric radiography. When returned a number of changes were made in response to the comments provided. The number of questions was reduced from 34 to 23, and a number were reworded to clarify their meaning.

Despite this, one major oversight was the omission of an upper age limit for paediatric patients, as noted by a number of respondents to the final questionnaire. However, from comments included on the questionnaires, the general consensus appeared to be that 16 years of age was the accepted cut off point. A copy of the pilot questionnaire can be found in Appendix 3.

2.3 Final Questionnaire

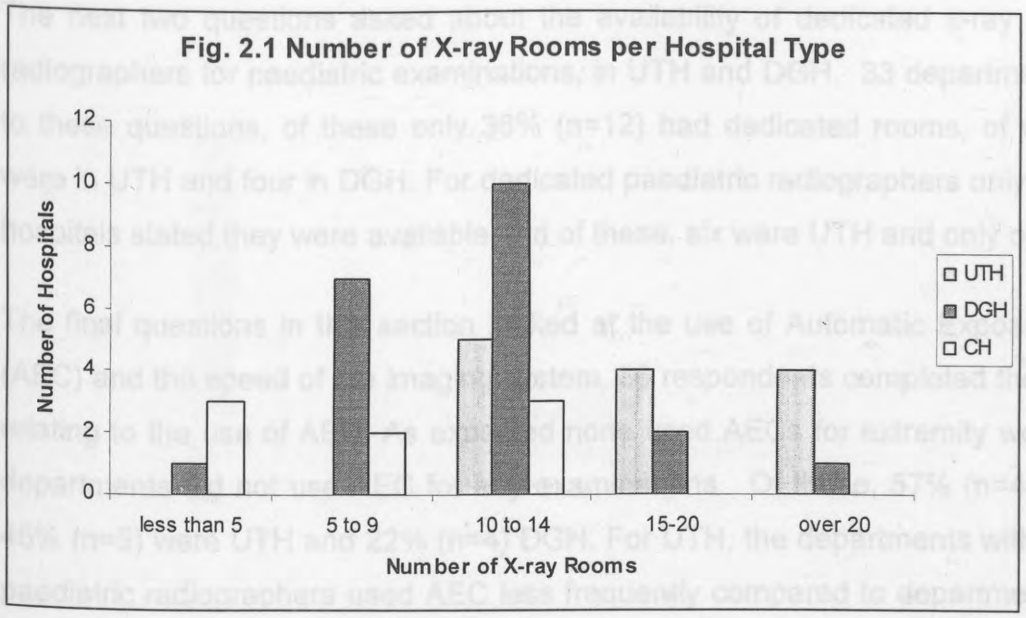
The final questionnaire was sent out in December 2000 to 64 hospitals throughout the UK. The hospitals were randomly selected from the 1999-2000 National Health Service (NHS) Yearbook and listed paediatrics as a speciality. To reflect the different types of hospitals undertaking paediatric radiology the sample included University Teaching Hospitals (UTH), District General Hospitals (DGH) and dedicated Children's Hospitals (CH). The UTH and DGH all had a bed capacity of 500 or greater, in line with the results from the survey by Bauman & Gell (2000). This criterion could not be applied to the CH as none had a bed capacity that exceeded 500. The final survey sample of 64 hospitals comprised 17 UTH, 35 DGH and 12 CH. A copy of the final questionnaire and cover letter can be found in Appendices 4 and 5.

2.4 Results

Of the 64 questionnaires sent out, there was a response of 65.5% (n=42). The response rate from UTH was 82% (n=14), from DGH 57% (n=20), and from CH 66.6% (n=8). However one UTH had no paediatric radiology service and therefore was excluded from the final analysis, leaving 41 hospitals.

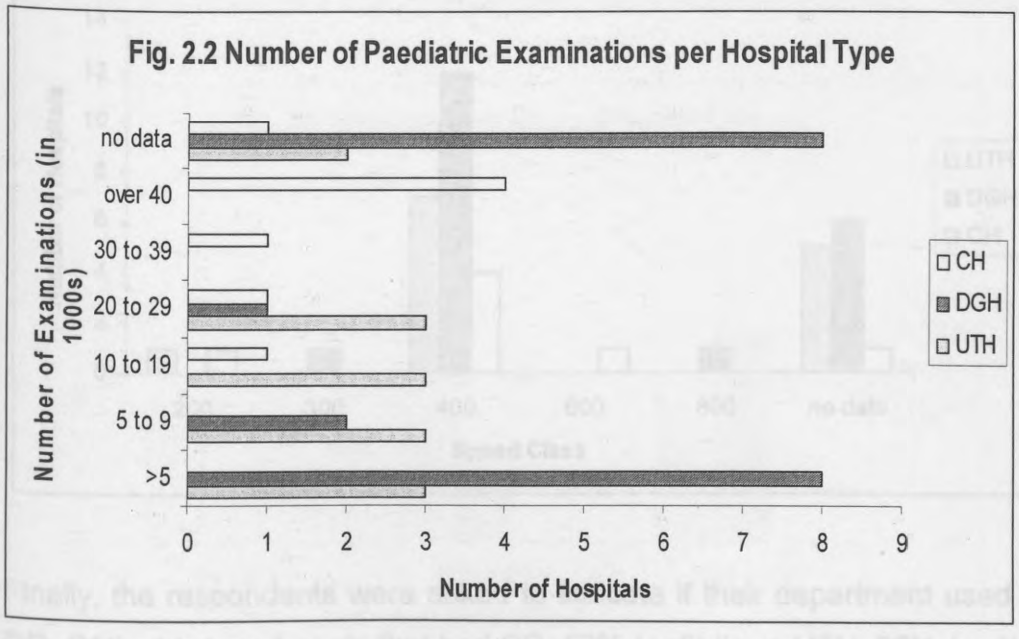
2.4.1 *Results from section 1*

This provided a general overview of the departments, including the number of x-ray rooms. These ranged from one to two up to 25 with the majority of departments, 17 out of the 41, falling in the 10-14 room category, Figure 2.1. The final question in this section asked if the department undertook paediatric radiography.



2.4.2 *Results from section 2*

The first question asked about the number of paediatric x-ray examinations performed per annum, these ranged from 1200 for a DGH to 48000 for a CH. Figure 2.2

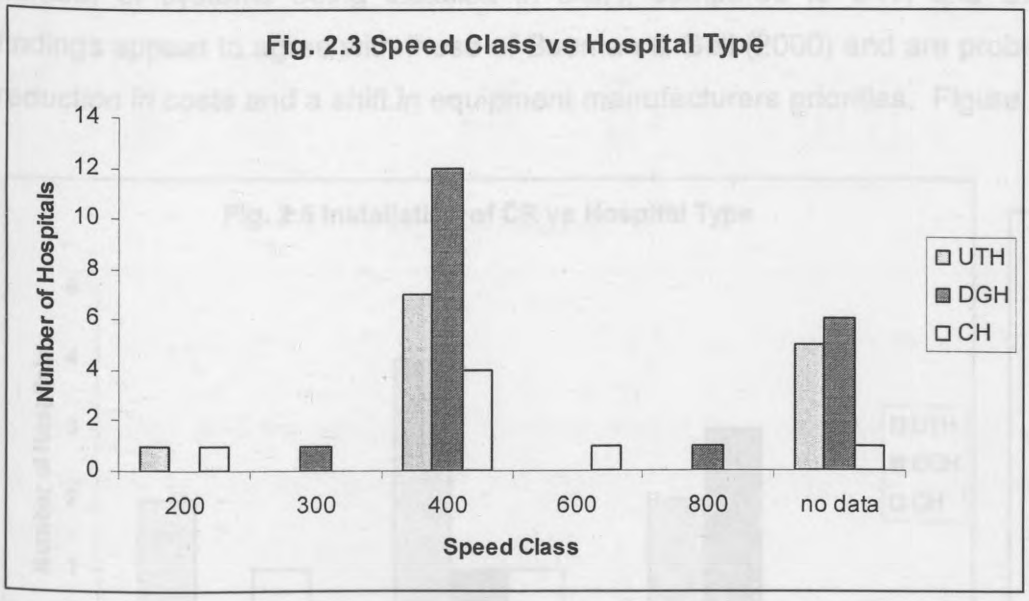


The next two questions asked about the availability of dedicated x-ray rooms and radiographers for paediatric examinations, in UTH and DGH. 33 departments replied to these questions, of these only 36% (n=12) had dedicated rooms, of which eight were in UTH and four in DGH. For dedicated paediatric radiographers only 21% (n=7) hospitals stated they were available and of these, six were UTH and only one a DGH.

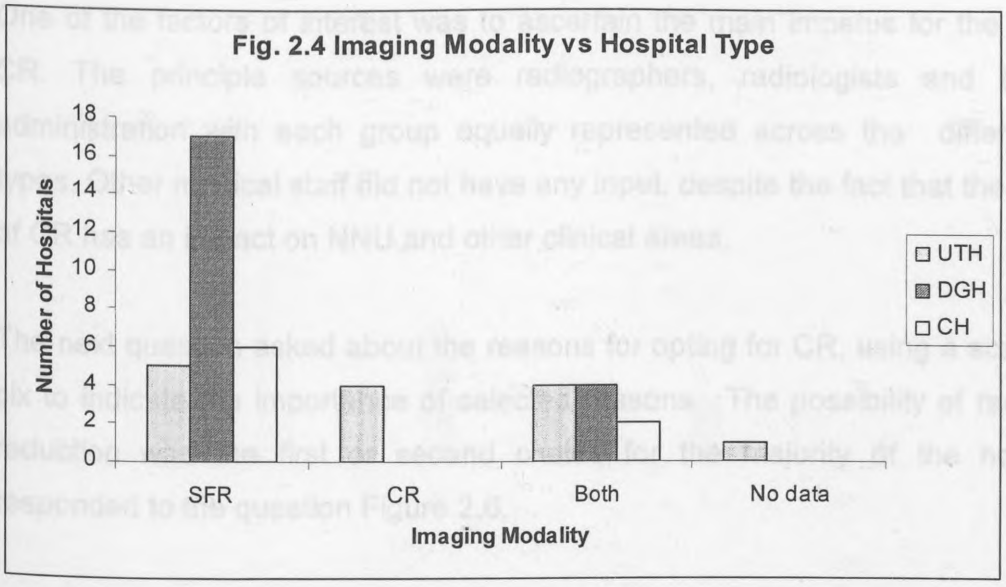
The final questions in this section looked at the use of Automatic Exposure Control (AEC) and the speed of the imaging system. 36 respondents completed the questions relating to the use of AEC. As expected none used AECs for extremity work, and 13 departments did not use AEC for any examinations. Of these, 57% (n=4) were CH, 45% (n=5) were UTH and 22% (n=4) DGH. For UTH, the departments with dedicated paediatric radiographers used AEC less frequently compared to departments with no dedicated staff, probably due to greater experience.

28 departments replied to the question about the speed of the imaging system used. 23 out of 28 used 400 speed system, two departments used 200 system and the other three used 300, 600 or 800. Figure 2.3

Fig. 2.3 Speed Class vs Hospital Type

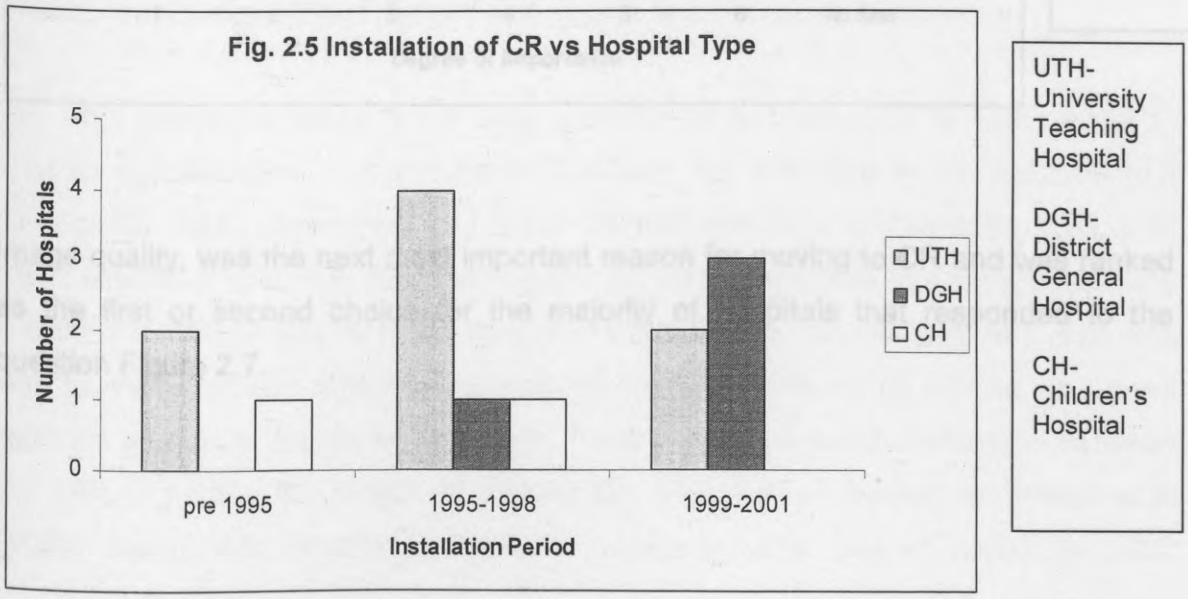


Finally, the respondents were asked to indicate if their department used SFR and/or CR. Of the14 departments that had CR, 57% (n=8) were UTH, 28% (n=4) were DGH, and 14% (n=2) were CHs, however SFR remains the dominant modality Figure 2.4.



2.4.3. *Results from section 3*

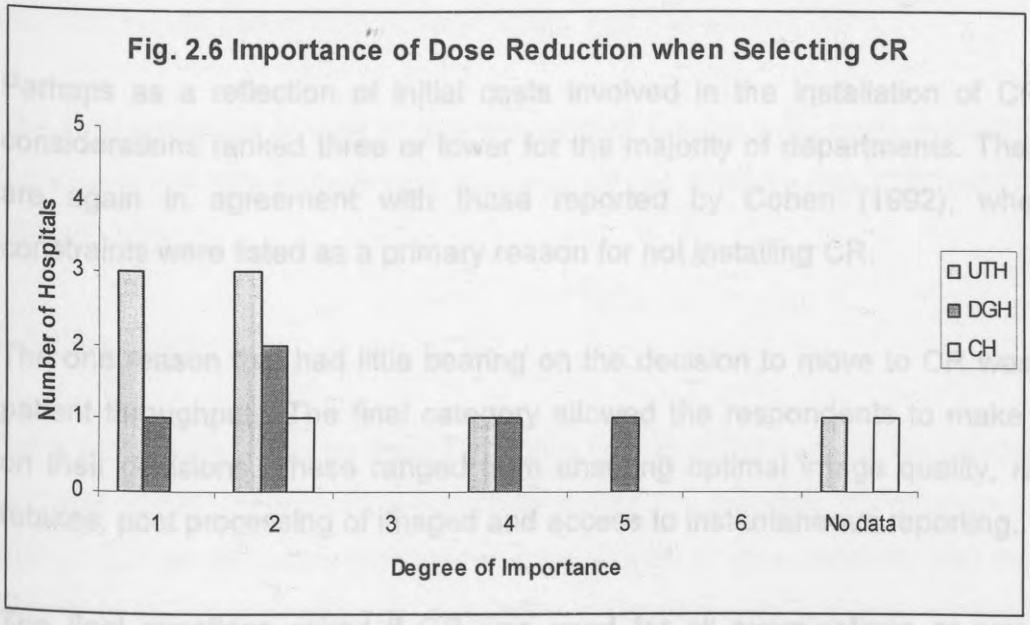
This was only completed by departments that had CR. The first question looked at when CR was installed and the results appeared to indicate a gradual increase in the number of systems being installed in DGH, compared to UTH and CH. These findings appear to agree with those of Bauman & Gell (2000) and are probably due to reduction in costs and a shift in equipment manufacturers priorities. Figure 2.5.



One of the factors of interest was to ascertain the main impetus for the transition to CR. The principle sources were radiographers, radiologists and the hospital administration with each group equally represented across the different hospital types. Other medical staff did not have any input, despite the fact that the introduction of CR has an impact on NNU and other clinical areas.

The next question asked about the reasons for opting for CR, using a scale of one to six to indicate the importance of selected reasons. The possibility of radiation dose reduction was the first or second choice for the majority of the hospitals that responded to the question Figure 2.6.

Fig. 2.6 Importance of Dose Reduction when Selecting CR



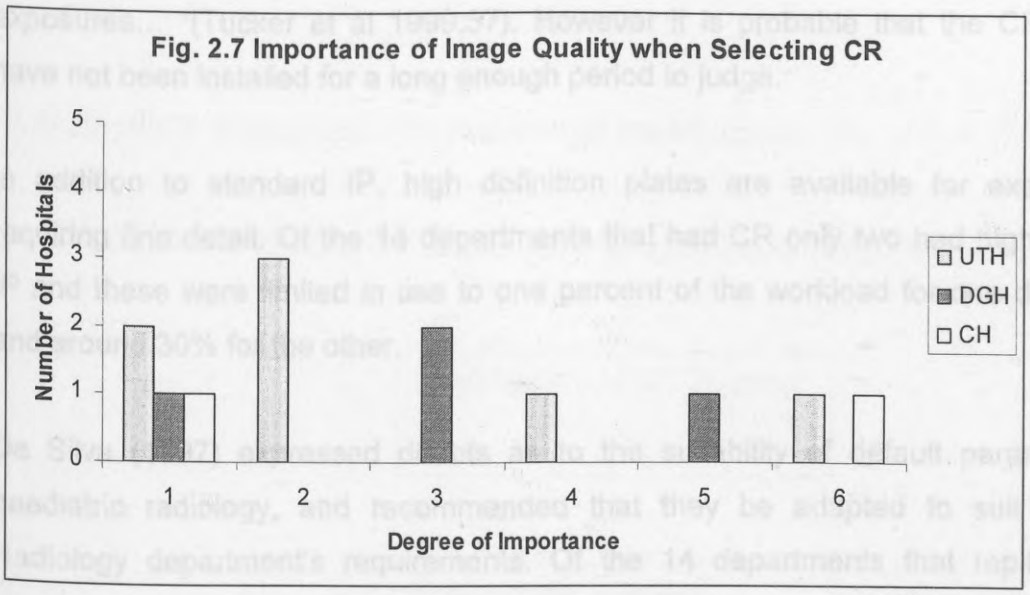
UTH- University Teaching Hospital

DGH- District General Hospital

CH- Children's Hospital

Image quality, was the next most important reason for moving to CR and was ranked as the first or second choice for the majority of hospitals that responded to the question Figure 2.7.

Fig. 2.7 Importance of Image Quality when Selecting CR



UTH- University Teaching Hospital

DGH- District General Hospital

CH- Children's Hospital

Perhaps as a reflection of initial costs involved in the installation of CR, financial considerations ranked three or lower for the majority of departments. These findings are again in agreement with those reported by Cohen (1992), where budget constraints were listed as a primary reason for not installing CR.

The one reason that had little bearing on the decision to move to CR was increased patient throughput. The final category allowed the respondents to make comments on their decisions. These ranged from ensuring optimal image quality, reduction of retakes, post processing of images and access to instantaneous reporting.

The final questions asked if CR was used for all examinations or was limited to specific examinations. In most cases CR was first installed in the Accident and Emergency (A&E) department and NNU. Further questions related to the type of IP used, flexible or rigid, and their working life. Of the departments that responded there was an exact 50/50 split as to the type of IP used. For working life, where a response was provided, seven departments reported a working life of 18 months and three reported periods in excess of two years. There was no particular correlation between the type of IP and the length of working life. This was of interest as Tucker et al (1999) found that flexible IP became unusable after only "...2000 to 3000

exposures... "(Tucker et al 1999:57). However it is probable that the CR systems have not been installed for a long enough period to judge.

In addition to standard IP, high definition plates are available for examinations requiring fine detail. Of the 14 departments that had CR only two had high definition IP and these were limited in use to one percent of the workload for one department and around 30% for the other.

De Silva (1997) expressed doubts as to the suitability of default parameters for paediatric radiology, and recommended that they be adapted to suit individual Radiology department's requirements. Of the 14 departments that replied to the question on the use of default parameters half had altered them.

The final questions related to archives and all respondents used short-term archives but as yet not all had long-term archives. Of the departments that had CR only one had a PACS.

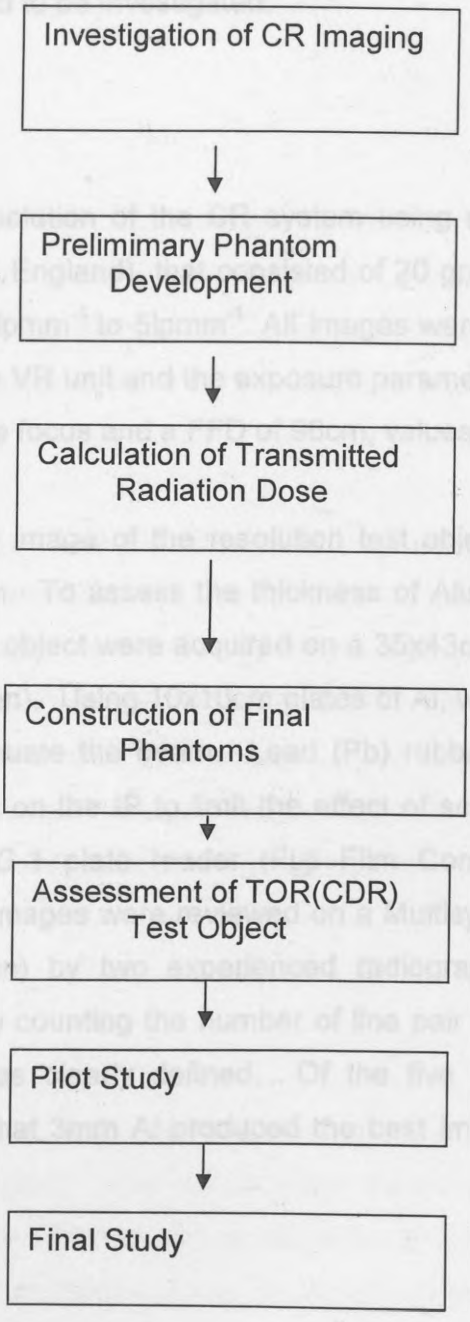
2.5 Conclusion

From the results it can be seen that there is a slow increase in the availability of CR and that NNUs are one of the first areas where it is installed. Comments made at the end of the questionnaire indicated a wide degree of inconsistency with regard to the impact of CR on patient dose. A number of departments had increased the exposure factors compared to SFR. This suggests the need for a study specific to neonatal chest radiography that looks at radiation dose and image quality. Since this questionnaire was analysed there has been further increase in the number of departments moving to CR.

CHAPTER 3

3. Methods II: Design and Assessment of the Phantom

3.1 Flow Chart Describing the Design and Assessment of the Phantom



3.2 Introduction

To assess the effect of exposure reduction on image quality it was necessary to develop a means of producing consistent and comparable images. A phantom study was selected as it ensured greater control of radiographic technique and more consistent image quality. However, before designing the phantom a number of questions relating to CR had to be investigated.

3.3 Question 1

Investigated the spatial resolution of the CR system using a spatial resolution test object (Nuclear Associates, England), that consisted of 20 groups of line pairs giving a range of values from 1.5lpmm^{-1} to 5lpmm^{-1}. All images were acquired using a GE Medical Systems Silhouette VR unit and the exposure parameters were kept constant at 55kVp, 2mAs, 0.6mm fine focus and a FFD of 96cm, values used in the NNU.

To produce a good quality image of the resolution test object it was necessary to attenuate the primary beam. To assess the thickness of Aluminium (Al) required, a series of images of the test object were acquired on a 35x43cm Fuji IP Cassette type C (Fuji Film Company, Japan). Using 10x10cm plates of Al, with a thickness, ranging from 1mm to 3mm to attenuate the beam. Lead (Pb) rubber sheets were used to mask the unexposed areas on the IP to limit the effect of scatter. The IP was then read using a Fuji FCR-XG-1 plate reader (Fuji Film Company Japan) and the neonatal chest algorithm. Images were reviewed on a Multisync LCD 1850E monitor (Fuji Film Company, Japan) by two experienced radiographers, and the spatial resolution was assessed by counting the number of line pair groups seen where the separation of line pairs was clearly defined. Of the five images the consensus between the readers was that 3mm Al produced the best image in terms of density and contrast.

3.4 Question 2

Investigated if changing the magnification at which the images were viewed altered the spatial resolution. The five images from Section 3.2 were viewed at 0.9, 1.8 and 3.8 times magnification and it was concluded that altering the magnification did not alter the spatial resolution. For all further image assessment 1.8 magnification was used as this was the most acceptable to the readers.

3.5 Question 3

De Silva (1997) noted that IP readers read plates from the centre out and that the position of the area imaged on the IP could affect the appearance of the image. In neonatal chest radiography it is often difficult to position the neonate in the middle of the IP and therefore it was necessary to determine if the position of an object on the IP affected the image quality.

Using the 35x43cm IP, 3mm Al and the test object, a series of 12 exposures were made so that the entire IP was covered. Pb rubber was used to mask the areas of the IP not exposed. The images were reviewed by two readers who agreed that there was a minimal loss of clarity at the edges but that it did not detract from the image quality. It would perhaps have been more appropriate to have used a smaller IP and only a single exposure per plate to simulate the procedure in NNU. As a result, for the final experiments it was considered best to place the phantom and test object in the middle of the IP.

3.6 Question 4

Cesar (1997) noted that when using grids a distortion of the grid lines would appear on the CR image due to aliasing. This results when the direction of the grid lines is perpendicular to the direction of the laser that reads the IP. As the spatial resolution test object consisted of linear patterns it was important to know if rotation of the test object would affect the image quality.

Using the 24x30cm Fuji IP Cassette type C (Fuji Film Company, Japan) IP an image of the test object and 3mm Al was acquired with the long edge of the test object parallel to the long edge of the IP. The process was then repeated with the test object rotated through 45°, 90°, 135° and 180°. The images were reviewed by the two readers and the consensus was that rotation did not affect the number of line pairs visualised.

3.7 Phantom Development

A Medline search in December 2002 using the combined keywords "phantom" "contrast" and "spatial resolution" resulted in 297 articles. Of these, only two articles were directly relevant, the majority referred to Magnetic Resonance Imaging (MRI) and Single Photon Emission Computed Tomography (SPECT). The phantom constructed by Chotas et al (1997) was considered too complex for this study and in addition it was designed for adult radiography. Previous literature seaches identified articles that used TE Perspex, with 5cm being considered representative of a 2.5Kg neonate, Wraith et al (1996), Jones et al (2001) and Armpilia et al (2002). Initially TE Perspex was not available therefore commercial Clear Polystyrene (CP) was substituted. As the imaging properties of CP were unknown it was necessary to ascertain how well it attenuated the primary beam.

The CP was cut into a number of 10x10cm pieces each 4mm thick. Using the 35x43cm IP a series of images were acquired of the test object when placed on increasing thicknesses of CP, ranging from 4mm to 48mm, in 4mm steps, using the same exposure parameters as before. The two readers reviewed the images and reached a consensus that the 48mm thickness was best in terms of image density and spatial resolution.

The spatial resolution and contrast were then assessed, contrast was assessed by considering the difference in the appearance of the edge of the test object compared to the background. Contrast was scored using a Likart scale and the results recorded Table 3.1.

1 Low (Poor) Contrast

2 Slightly Improved Contrast

3 Acceptable Contrast

4 Further Improved Contrast

5 High (Good) Contrast

Table 3.1 Results of Assessment of Contrast and Spatial Resolution

	Reader 1		Reader 2	
Thickness CP	Contrast	Line Pairs	Contrast	Line pairs
4mm	1	8	1	8
8mm	1	8	2	8
12mm	2	8	2	9
16mm	2	9	3	9
20mm	3	9	3	9
24mm	3	8	4	8
28mm	3	8	4	8
32mm	4	8	4	8
36mm	4	8	4	8
40mm	5	8	5	7
44mm	5	7	5	7
48mm	5	7	5	7

From Table 3.1 it can be seen that as the spatial resolution improved so did the contrast but as it declined the contrast did not, however further study is required to confirm this trend.

This preliminary work was done using a static x-ray unit as this was the only unit available, normally neonatal chest radiography is done using mobile units. However there are concerns as to the stability of the output of mobile units at the low exposures used in NNU. To investigate this the output of both the NNU mobile unit and a static unit were compared by reviewing the outputs measured over a year. From Table 3.2, it can be seen that the static unit had the greater stability.

Table 3.2 Output data for Static and Mobile Units Measured over 1 year

Output Rm3 at 55kVp 8mAs (μGy)	OutputNNU Mobile at 55kVp 12.5mAs (μGy)
39.1	71.37
38.5	68.69
38.4	70.63
39.0	69.04
39.1	65.98
39.4	71.52
38.4	69.05
38.8	70.09
39.1	71.30
38.9	71.07
39.1	70.11
39.3	70.26
37.9	70.66
39.2	69.93
38.9	71.12
38.4	68.40
37.9	69.71
37.5	70.16
36.8	71.81
36.6	78.51
36.9	66.81
37.1	67.26
SD= 0.885	SD=2.434
Mean= 38.3	Mean=70.1

Output measured every two weeks

This completed the groundwork for the study and from the results an experiment design was developed.

3.8 Quantifying the Radiation Dose Transmitted Through Clinically Significant Points on a Neonatal Chest Radiographs.

To develop a phantom that replicated the attenuation and scattering expected for a neonate, chest radiographs were used to calculate the radiation dose transmitted through two clinically significant points. A means of relating the density of these points to the radiation dose transmitted was then required.

3.8.1 *Production of the characteristic curve*

To eliminate variations in the characteristic curve that arise from the fluctuations in processsing a sensitometer (X-rite 383, single side exposure, X-rite Inc. USA) was used to produce a sensitometric strip, Appendix 6. Due to fluctuations in the automatic film processors a new sensitometric strip was produced each day that data was collected. After processing, the density of each step was measured using a densitometer (Digital Densitometer II, Nuclear Associates, Victoreen Inc. USA) and recorded. The readings were done three times with the densitometer being zeroed after each group of 21 readings and then averaged, this value was used to plot the characteristic curve Table 3.3.

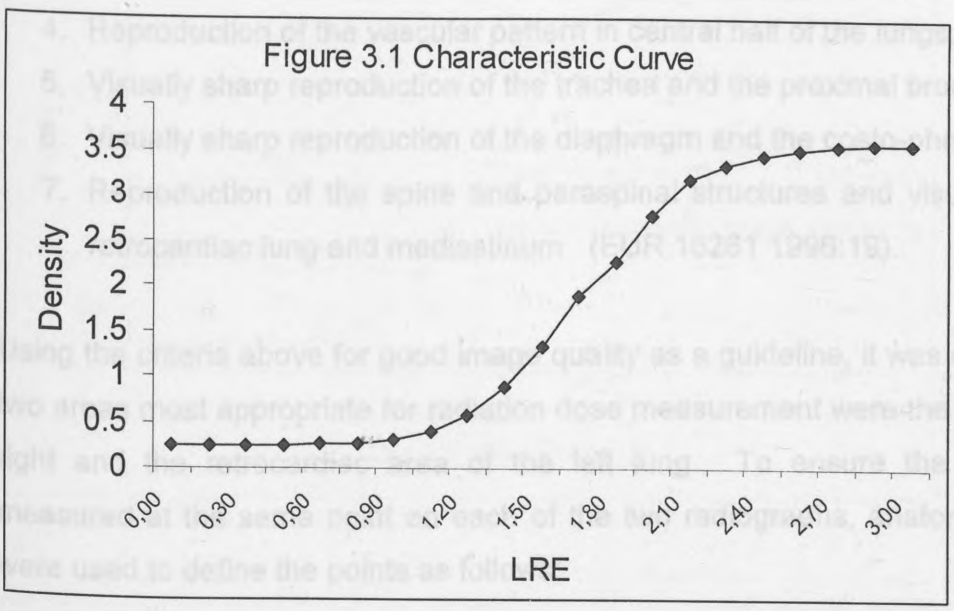
Table 3.3 Density Values for the Sensitometric Strip

Step No.	LRE	Density 1	Density 2	Density 3	Average
1	0	0.25	0.24	0.24	0.24
2	0.15	0.26	0.24	0.24	0.25
3	0.30	0.25	0.24	0.25	0.25
4	0.45	0.26	0.25	0.25	0.25
5	0.60	0.27	0.26	0.26	0.26
6	0.75	0.28	0.27	0.27	0.27
7	0.90	0.32	0.31	0.31	0.31
8	1.05	0.41	0.41	0.40	0.41
9	1.20	0.59	0.58	0.58	0.58
10	1.35	0.86	0.89	0.88	0.88
11	1.50	1.32	1.34	1.33	1.33
12	1.65	1.85	1.92	1.91	1.89
13	1.80	2.06	2.26	2.50	2.27
14	1.95	2.49	2.95	2.91	2.78
15	2.10	3.16	3.18	3.19	3.18
16	2.25	3.25	3.38	3.35	3.33
17	2.40	3.44	3.47	3.45	3.45
18	2.55	3.52	3.53	3.52	3.52
19	2.70	3.56	3.54	3.55	3.55
20	2.85	3.58	3.58	3.57	3.58
21	3.00	3.55	3.58	3.57	3.57

The logarithmic value for the relative exposure (LRE) was used in order to compress the data over a manageable range. The data were then loaded into a spreadsheet (Microsoft Excel, Microsoft USA) and used to produce a characteristic curve, Figure

3.1. The data were also used to draw the characteristic curve by hand on detailed graph paper to enable values to be measured accurately. This was done for all the characteristic curves used in the study, Appendix 7.

Figure 3.1 Characteristic Curve



3.9 Identification of Clinically Significant Points on the Neonatal Chest Radiograph

Admission weights for the NNU in Aberdeen, from June to November 2003, ranged from 560g to 4.8Kg, with a mean weight of 2.28Kg, with the highest frequency of weight being 1Kg. As a result it was decided to select two neonatal chest radiographs for the study, one of a 2.5 Kg neonate, and the other of a 1Kg neonate. Images in Appendix 8.

Thirty chest radiographs for each weight category were selected for review and one from each group was selected for the study. The small sample size reflected the very limited number of chest radiographs that conformed to the image quality guidelines laid down in the European Guidelines on Quality Criteria for Diagnostic Radiographic Images in Paediatrics 1996 (EUR 16261 1996). The criteria for an antero-posterior (AP) chest radiograph (newborn) are as follows:

1. Performed at peak inspiration
2. Reproduction of the thorax without rotation and tilting.
3. Reproduction of the chest must extend from the cervical trachea to T12/L1 (part of the abdomen may be included for special purposes).
4. Reproduction of the vascular pattern in central half of the lungs.
5. Visually sharp reproduction of the trachea and the proximal bronchi.
6. Visually sharp reproduction of the diaphragm and the costo-phrenic angles.
7. Reproduction of the spine and paraspinal structures and visualization of the retrocardiac lung and mediastinum (EUR 16261 1996:19).

Using the criteria above for good image quality as a guideline, it was decided that the two areas most appropriate for radiation dose measurement were the mid lung on the right and the retrocardiac area of the left lung. To ensure the densities were measured at the same point on each of the two radiographs, anatomical landmarks were used to define the points as follows:

Lung: A line drawn vertically from the lateral border of the right first rib and a line drawn from the middle of the seventh thoracic vertebra.

Mediastinum: A line drawn vertically from the midpoint of the left first rib and a line drawn from the middle of the ninth thoracic vertebra.

The density at each point was measured and then plotted on the characteristic curve and the values for LRE found, Figures 3.2 and 3.3. The Relative Exposure (RE) for was then found by taking the anti-log of the LRE. Table 3.4.

Table 3.4 Values for the Points on the Chest Radiographs

Chest Radiograph 1	Density	LRE	RE
Lung	1.71	1.60	39.81
Mediastinum	0.98	1.38	23.98
Chest radiograph 2			
Lung	1.98	1.69	48.97
Mediastinum	1.18	1.45	28.18

Fig.3.2 Characteristic Curve: Chest Radiograph 1

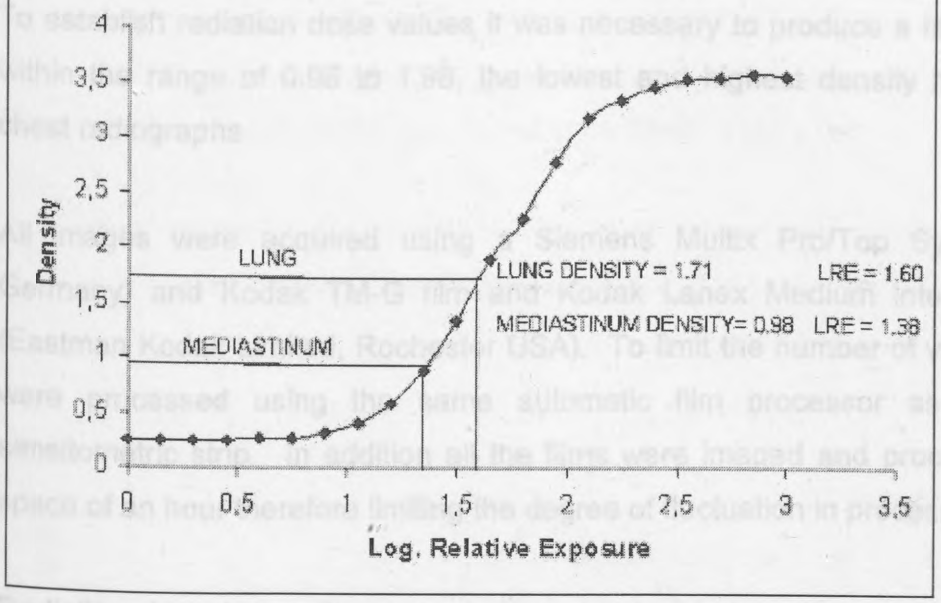
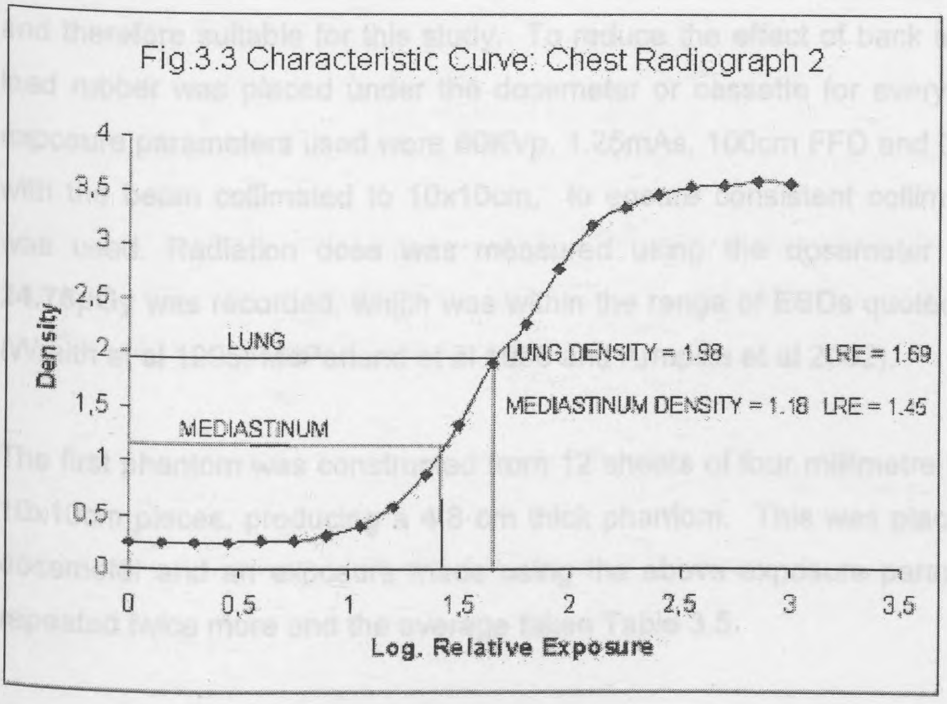


Fig.3.3 Characteristic Curve: Chest Radiograph 2



3.10 Establishing Radiation Dose Values

To establish radiation dose values it was necessary to produce a film with a density within the range of 0.98 to 1.98, the lowest and highest density measured on the chest radiographs.

All images were acquired using a Siemens Multix Pro/Top System (Siemens, Germany) and Kodak TM-G film and Kodak Lanex Medium intensifying screens (Eastman Kodak Limited, Rochester USA). To limit the number of variables, all films were processed using the same automatic film processor as processed the sensitometric strip. In addition all the films were imaged and processed within the space of an hour therefore limiting the degree of fluctuation in processing conditions.

Radiation dose to the film was measured using a dosemeter (Model 6001, Unfors Instruments, Sweden). This was calibrated for measurements in the 50-70 kVp range and therefore suitable for this study. To reduce the effect of back scatter a piece of lead rubber was placed under the dosemeter or cassette for every exposure. The exposure parameters used were 50KVp, 1.25mAs, 100cm FFD and 0.6mm fine focus with the beam collimated to 10x10cm, to ensure consistent collimation a template was used. Radiation dose was measured using the dosemeter and a value of **24.75µGy** was recorded, which was within the range of ESDs quoted in the literature (Wraith et al 1995; McParland et al 1996 and Armpilia et al 2002).

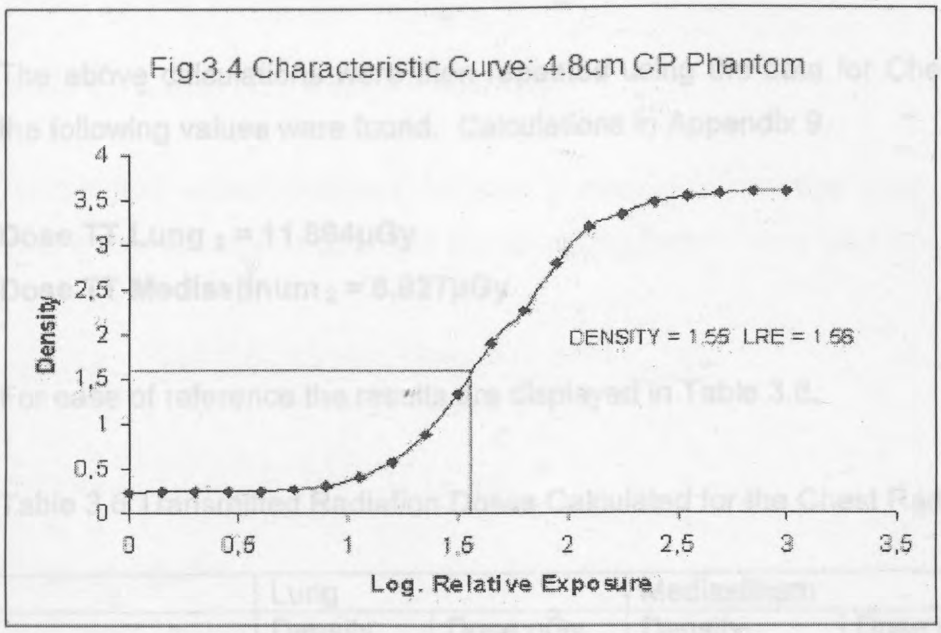
The first phantom was constructed from 12 sheets of four millimetre thick CP cut into 10x10cm pieces, producing a 4.8 cm thick phantom. This was placed on top of the dosemeter and an exposure made using the above exposure parameters, this was repeated twice more and the average taken Table 3.5.

Table 3.5 Radiation Dose Transmitted Through Clear Polystyrene Phantom

	Exposure 1	Exposure 2	Exposure 3	Average	SD
Dose µGy	8.783	8.788	8.813	8.795	0.016

To measure density, the phantom was placed on a cassette and an exposure made using the same exposure parameters as above. The film was then processed and the density measured. The value of **1.55** fell within the required range of densities. This was then plotted on the characteristic curve and a value of **1.56** for LRE was found and from there the RE was found to be **36.30**. Figure 3.4.

Fig.3.4 Characteristic Curve: 4.8cm CP Phantom



From the above data and the data from Table 3.4, it was then possible to calculate the radiation doses transmitted through (TT) the specific points on the chest radiographs using the following equation:

$$\text{Dose TT Lung}_1 = \left(\frac{\text{Dose TT Clear Polystyrene Phantom}}{\text{R E TT Clear Polystyrene Phantom}}\right) \text{x R E TT Lung}_1$$

Substituting the values from above gives the following

$$\text{Dose TT Lung}_1 = \left(\frac{8.795}{36.30}\right) \text{x } 39.81$$

Dose TT Lung $_1$ = 9.645µGy

Using this equation the value for the mediastinum can be calculated

$$\text{Dose TT Med.}_1 = \left(\frac{\text{Dose TT Clear Polystyrene Phantom}}{\text{R E TT Clear Polystyrene Phantom}} \right) \text{x R E TT Med.}_1$$

Substituting the values from above gives the following

$$\text{Dose TT Mediastinum}_1 = \left(\frac{8.795}{36.30} \right) \text{x } 23.98$$

Dose TT Mediastinum $_1$ = 5.810µGy

The above calculations were then repeated using the data for Chest Radiograph 2, the following values were found. Calculations in Appendix 9.

Dose TT Lung $_2$ = 11.864µGy

Dose TT Mediastinum $_2$ = 6.827µGy

For ease of reference the results are displayed in Table 3.6.

Table 3.6 Transmitted Radiation Doses Calculated for the Chest Radiographs

	Lung		Mediastinum	
	Density	Dose µGy	Density	Dose µGy
Chest 1 (2.5 Kg)	1.71	9.645	0.98	5.810
Chest 2 (1.1Kg)	1.98	11.864	1.18	6.827

When TE Perspex became available a control experiment was carried out to check the validity of the methodology. A 5.2cm thick block of TE Perspex was x-rayed using the same exposure parameters as above and the transmitted radiation dose measured, giving a value of **6.52µGy.** Next an image of the TE Perspex was acquired for density measurement and this was then plotted onto the characteristic curve to find the LRE. All the values are displayed in Table 3.7.

Table 3.7 Values for 5.2cm TE Perspex

Density	LRE	RE	Radiation Dose
1.15	1.44	25.54	6.52µGy

The values obtained were then substituted into the equation used previously and the radiation dose transmitted through 5.2cm TE Perspex was calculated.

$$\text{Dose TT 5.2cm TE Perspex} = \left(\frac{\text{Dose TT Clear Polystyrene}}{\text{RE TT Clear Polystyrene}}\right) \text{x RE TT 5.2cm TE Perspex}$$

$$\text{Dose TT 5.2cm TE Perspex} = \left(\frac{8.795}{36.30}\right) \text{x } 27.54$$

Dose TT 5.2cm TE Perspex = 6.67μGy

Having now obtained values for both a measured radiation dose and a calculated one, it was possible to calculate the percentage error using the following equation.

$$\%\,\text{Error} = \left(\frac{\text{Calculated Dose - Measured Dose}}{\text{Calculated Dose}}\right) \text{x } 100$$

$$\%\,\text{Error} = \left(\frac{6.67\mu\text{Gy} - 6.52\mu\text{Gy}}{6.67\mu\text{Gy}}\right) \text{x } 100$$

% Error = 2.24%

An error of 2.24% was considered to demonstrate acceptable reproducibility for the methodology.

3.11 Construction of Phantoms

The next step was to construct radiographic phantoms that would replicate the doses calculated above. Initially 4.8cm of CP was used for calculating the radiation doses, but when the radiation dose transmitted through TE Perspex was measured it was substantially lower than for CP, Table 3.8.

Table 3.8 Variation in Radiation Doses between CP and TE Perspex

	4.8cm CP	5.2cm TE Perspex	% Difference
Radiation Dose	8.795 μGy	6.52 μGy	25.8%

McParland et al (1996), Lowe et al (1999) and Jones et al (2001) considered a 5cm thick block of TE Perspex to be representative of a 2.5Kg neonate. To determine if this applied to the TE Perspex to be used, an image was acquired of the 5.2cm block using the same parameters as above and the density measured. Images were also acquired of 4.2cm, 3cm and 2cm thick blocks of TE Perspex to determine the thickness representative of a 1.1 Kg neonate. After processing, the density of each image was measured and compared to the corresponding density for the chest radiographs Table 3.9.

Table 3.9 Density values for TE Perspex compared to Chest Radiographs

	Density		Density	% Difference
5.2cmTE Perspex	0.93	Chest Rad. Med. 1	0.98	5.3%
3.0cmTE Perspex	1.59	Chest Rad. Lung 1	1.71	7.5%
4.2cmTE Perspex	1.20	Chest Rad. Med. 2	1.18	1.6%
2.0cmTE Perspex	2.12	Chest Rad. Lung 2	1.98	6.6%

Table 3.9 shows that all the values for the TE Perspex were similar to the values measured for the chest radiographs and therefore indicated that these thicknesses were representative of a 2.5Kg and 1.1Kg neonate.

As there is greater attenuation and scattering of the primary beam passing through the mediastinum compared to lung, the phantoms were constructed such that the centre portion was 2cm thicker than the sides to replicate this. The phantoms were constructed from blocks of TE Perspex 20x20cm and 5x20cm and were of varied thickness allowing two phantoms, one 4.2/2cm thick and the other 5.2/3cm thick to be constructed. A schematic of the 4.2/2cm phantom is shown in Figure 3.5.

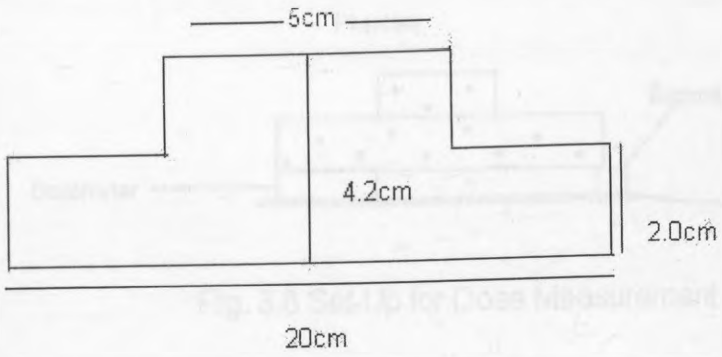


Fig. 3.5 Cross Section of Phantom

3.12 Radiation Dose Measurement

The radiation dose transmitted through the phantoms, was measured using the same procedure as outlined in Section 3.6. All exposure parameters were kept the same, but the collimation was opened up to 20x20cm to include the whole phantom. A template was created to ensure that the collimation was kept consistent.

Radiation dose was measured and recorded for each of thickness of the phantoms, corresponding to lung and mediastinum, Table 3.10. Care was taken that the area of phantom being measured was centred over the dosemeter and that the phantom was kept level by use of a small block of Perspex the same thickness as the dosemeter Figure 3.6. As a result of this placement a two centimeter air gap was produced, however as this was not over the area of measurement it was not considered to influence the results. In addition the air gap thickness was consistent for all the dose measurements conducted in Sections 3.12 and 3.13.

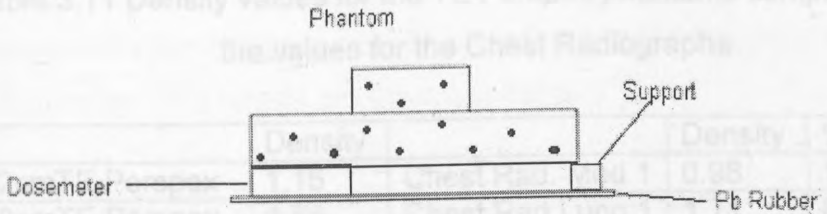


Fig. 3.6 Set-Up for Dose Measurement

Table 3.10 Radiation Dose Values for the TE Phantoms compared to values for Chest Radiographs

	Dose µGy		Dose µGy	% Diff.
5.2cmTE Perspex	6.52	Chest Rad. Med 1	5.810	10.8%
3.0cmTE Perspex	11.93	Chest Rad.Lung 1	9.645	19.1%
4.2cmTE Perspex	7.979	Chest Rad. Med 2	6.827	14.4%
2.0cmTE Perspex	15.36	Chest Rad.Lung 2	11.864	22.7%

All the radiation dose values for the phantoms exceeded the 10% acceptance limit but this was probably a result of the increased field size. To assess the impact of the greater field size on the values for density, each of the phantoms was placed on a cassette and an exposure made. Figure 3.7.

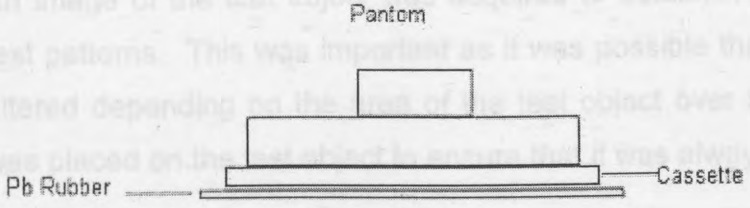


Fig. 3.7 Set-Up for Density Measurement

After processing, the densities of the four different thicknesses were measured, and compared to the density values measured for the two neonatal chest radiographs Table 3.11.

Table 3.11 Density values for the TE Perspex phantoms compared to the values for the Chest Radiographs

	Density		Density	% Difference
5.2cmTE Perspex	1.15	Chest Rad. Med 1	0.98	14.7%
3.0cmTE Perspex	1.86	Chest Rad.Lung 1	1.71	8.06%
4.2cmTE Perspex	1.51	Chest Rad. Med 2	1.18	21.8%
2.0cmTE Perspex	2.28	Chest Rad.Lung 2	1.98	13.1%

From Table 3.11 it can be seen that the percentage difference in the density values for the TE Perspex compared to the chest radiographs exceeded 10% except for the 3cm thickness. When compared to the values obtained with 10x10cm collimation, it became clear that the increase in the area irradiated increased the dose to the film. Further changes to the phantoms were postponed until the impact of the inclusion of the test object on the radiation dose and density had been measured.

3.13 Assessment of the TOR (CDR)Test Object

To assess the spatial resolution and contrast of the images acquired using the phantoms, the TOR (CDR) test object (Leeds Test Objects Limited, Boroughbridge, UK) was used. The test object produced a pattern that was reproducible and easy to interpret. An illustration of the test object pattern can be found in Appendix 10.

An image of the test object was acquired to establish the orientation of the various test patterns. This was important as it was possible that the radiation dose could be altered depending on the area of the test object over the detector. A small marker was placed on the test object to ensure that it was always placed in the same way.

Next the radiation dose for each of the four thicknesses of TE Perspex with the test object was measured. Using the procedure from Section 3.8, the test object was placed on top of the dosemeter, and then each phantom was placed on top. Care was taken that there was no tilting of the phantom as this could effect the reading. Three exposures were made for each thickness of phantom and the radiation doses and the

average taken, to reduce the effect of any output fluctuations. The results were then compared to the values calculated for the corresponding points on the neonatal chest radiographs. The results are shown in Table 3.12

Table 3.12 Radiation Dose Values for the TE Phantoms + TOR(CDR)

compared to values for Chest Radiographs

	Dose µGy		Dose µGy	% Difference
5.2cm +TOR	5.479	Chest Rad. Med 1	5.810	6.04%
3.0cm +TOR	10.06	Chest Rad.Lung 1	9.645	4.12%
4.2cm+ TOR	6.987	Chest Rad. Med 2	6.827	2.28%
2.0cm +TOR	12.793	Chest Rad.Lung 2	11.864	7.26%

The correlation coefficient was calculated (R=0.999) indicating a near perfect correlation between the calculated doses for the chest radiographs and those measured for the phantom and test object.

Next film density was measured for the phantoms and TOR (CDR). The test object was placed on a cassette and the 4.2/2cm phantom placed on top, so that the image of the test object resulted from the attenuated and scattered primary beam. Exposure parameters and collimation were the same as above. After processing, the density values for the two different thicknesses of the phantom were measured using the densitometer. The procedure was then repeated using the 5.2/3cm phantom. Figure 3.8

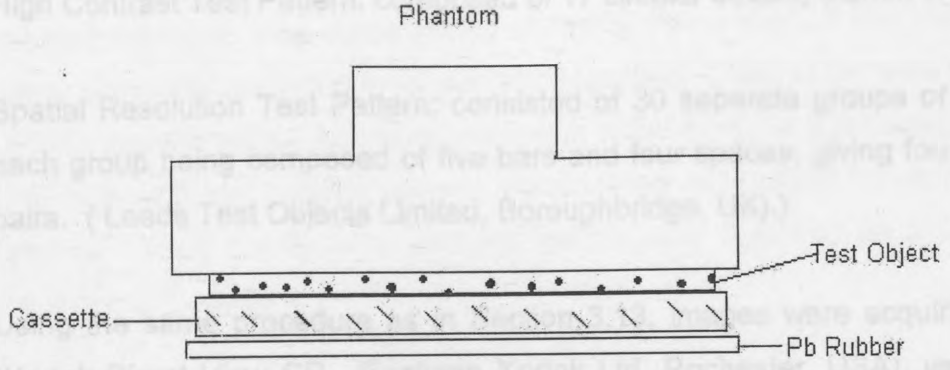


Fig. 3.8 Set-Up for Density Measurement with TOR(CDR)

The densities were compared to the values measured for the two neonatal chest radiographs Table 3.13.

Table 3.13 Comparison of Density Values for TE Perspex Phantoms +TOR (CDR) to values for Chest Radiographs

	Density		Density	% Difference
5.2cm +TOR	0.96	Chest Rad. Med 1	0.98	2.28%
3.0cm +TOR	1.75	Chest Rad.Lung 1	1.71	2.08%
4.2cm+ TOR	1.24	Chest Rad. Med 2	1.18	3.88%
2.0cm +TOR	2.06	Chest Rad.Lung 2	1.98	4.83%

The addition of the TOR (CDR) test object resulted in a correlation coefficient value of (R=0.998) again indicating near perfect correlation between the two sets of density values. The results indicated that both phantoms were suitable for the assessment of image quality.

3.14 Pilot Study

To assess spatial resolution and contrast three test patterns were used.

Low Contrast Test Pattern: comprised of 17 circular details each 11mm in diameter and of gradually changing density.

High Contrast Test Pattern: comprised of 17 circular details, 0.5mm in diameter.

Spatial Resolution Test Pattern: consisted of 30 separate groups of lines and bars, each group being composed of five bars and four spaces, giving four and a half line pairs. (Leeds Test Objects Limited, Boroughbridge, UK).)

Using the same procedure as in Section 3.13, images were acquired using the IP (Kodak Direct View GP, Eastman Kodak Ltd. Rochester, USA), used in the NNU. The IP were then read using a Kodak CR Direct View 8500 System plate reader (Eastman Kodak Ltd. Rochester, USA) using the algorithm for NNU chest

radiographs. The images were then printed out on laser film using a Kodak Dry View 8900 (Eastman Kodak Ltd. Rochester, USA). In addition the DICOM data was burned to a CD so that the images could be read at a different location

Due to pressure of time all images were read at the Sykehuset I Vestfold (SiV), Tonsberg, Norway. SiV has had a hospital wide PACS for over nine years and therefore was considered an ideal location for reviewing the images. Three viewers with different degrees of experience in radiology reviewed the images. Viewer one was a consultant radiologist with 16 years experience, viewer two was a radiographer with 22 years experience and viewer three was a radiology registrar with five years experience.

There were six images for assessment, three for each phantom, two hard copy SFR, two hard copy CR and two soft copy CR. Images were identified by a number only and no indication of the phantom thickness was given. All hard copy images were viewed on the same light box and the viewers were permitted to use any tool that they would use when reporting a neonatal chest radiograph. The soft copy images were all viewed on the same workstation using Totoku MDL 2004A, 4K black and white Liquid Crystal Display (LCD) diagnostic monitors (Totoku Electronics Japan). Again all tools used in diagnostic work were permitted. These workstations undergo regular Quality Assuarance (QA) tests every four weeks and were known to be in good repair.

Spatial resolution was assessed by counting the number of line pairs seen where a clear separation between lines could be identified. This number was then recorded on a form and the values for spatial resolution noted from the manufacturer's handbook. For high and low contrast images each viewer was asked to count the number of circular details clearly seen and the results were recorded on a form. Results are reported in Chapter 4.1

3.15 Main Study

The results of the pilot study highlighted a number of problems with the methodology. The spatial resolution test pattern was only imaged under the thicker part of the phantom. In addition images were only acquired at full exposure. To resolve this two sets of images were acquired for each modality, one for spatial resolution and the other for contrast. In the case of CR images, both hard copy and soft copy images were produced.

3.15.2 *Acquisition of Screen Film Images*

The same exposure parameters of 50kVp, 1.25mAs, 100cm FFD and 0.6mm fine focus were used and the collimation was kept consistent by using the template from the pilot study. To ensure that the relevant areas of the test object were under the correct thickness of the phantom careful placement was required. Figure 3.9 shows an overhead view of the set up used for acquiring a spatial resolution image of equivalent lung area on the phantom.

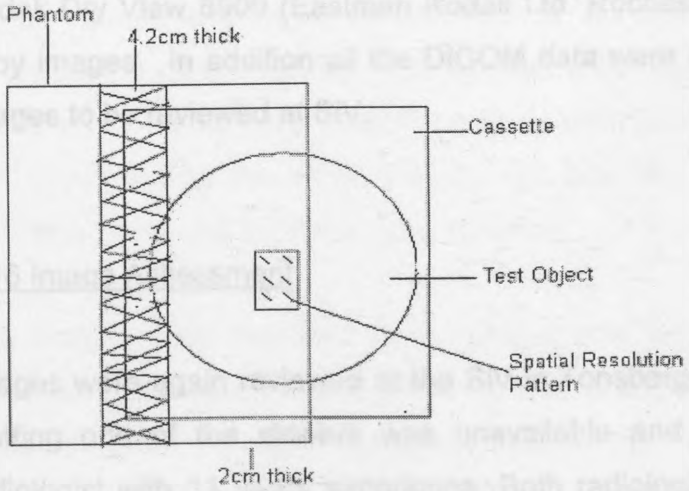


Fig. 3.9 Overhead View of Set-Up for Image Acquisition

The first set of images were of the spatial resolution test pattern with one image for each thickness of the phantoms, giving four images in total. From the pilot study it had been determined that rotating the TOR (CDR) test object through 90° ensured

that the last few contrast discs were over the area of interest. Again images were obtained for each thickness of phantom.

Using the methodology outlined above, a second series of images was acquired using the following exposure parameters, 50kVp, 0.56mAs, 100cm FFD and 0.6mm fine focus, again the collimation was kept the same.

3.15.2 Acquisition of CR Images

The CR images were acquired on the same x-ray equipment and using the same exposure parameters as for SFR. The CR images were obtained on the same day as the SFR images, so limiting any possible variations in the output of the x-ray unit.

Using the methodology described in Section 3.15.1, four series of images were acquired, spatial resolution and high and low contrast at full exposure and at half exposure. The IP were read using a Kodak CR Direct View 8500 System plate reader (Eastman Kodak Ltd. Rochester, USA) using the algorithm for NNU chest radiographs. The images were sent to the PACS for display and to the laser printer, a Kodak Dry View 8900 (Eastman Kodak Ltd. Rochester, USA) for production of hard copy images. In addition all the DICOM data were burned onto a CD to enable the images to be reviewed at SiV.

3.16 Image Assessment

Images were again reviewed at the SiV in Tonsberg, Norway, but due to changes in staffing one of the viewers was unavailable and was replaced by a consultant radiologist with 11 years experience. Both radiologists spend at least 50% of their time in the mammography department where, as part of the routine quality assurance programme, test patterns are regularly reviewed. This then ensured the radiologists familiarity with test patterns. The radiographer had long experience in QA and was familiar with test patterns.

Image assessment was done in two sessions, two weeks apart so as to limit the demand on the radiologists' time and to ensure that concentration was maintained. The first session looked at the images relating to spatial resolution and the second the contrast images.

Each session comprised 16 hard copy images, eight SFR and eight CR images, and eight soft copy images. In the case of the soft copy images these were read twice, first on a standard diagnostic workstation using Totoku MDL 2004A, 4K black and white LCD diagnostic monitors (Totoku Electronics Japan). The second soft copy reading was done on a dedicated mammography workstation using Barco Coronis MFGD 5421 (5MP), 5K black and white Cathode Ray Tube (CRT) monitors (BarcoView, Belgium). All readers used the same workstations for reviewing the images. The hard copy images were mounted on the viewer used for mammography films as this was situated in optimum viewing conditions.

The workstations used all undergo routine QA to assess any deterioration in the monitors. In the case of the mammography workstation this is done every two weeks and for the standard workstation every four weeks. There was no limit of time placed on the viewers and they were permitted to use any tools to enhance the image, as would be the case if looking at a neonatal chest radiograph. For hard copy images this involved the use of a magnifying glass and masking of any extraneous light. For soft copy viewing the viewers could use any tool that would enhance the image including zoom and the magnifying function.

The images were identified by a number only with no indication given as to the thickness of the phantom imaged or the level of exposure used and were presented in a random order. It was not possible however to mask the difference in appearance between the SFR and the hard copy CR images.

For spatial resolution the three viewers were asked to note the number of groups of line pairs where a clear separation between the lines could be identified. The results were recorded on a form and then the actual value for the spatial resolution found from the manual for the TOR (CDR) test object. Appendix 11.

For high and low contrast the viewers were asked to count the number of high contrast discs they could identify and record this result on a score sheet provided. They were then asked to count the number of low contrast discs that could be identified and record the results on the same score sheet. Copies of results are found in Appendix 11

The results were statistically analysed by comparison of means using one way ANOVA and Tukey post hoc test using a statistical and data management programme (SPSS 14.0).

CHAPTER 4

4. Results

4.1 Results of Pilot Study

The results for the images acquired using the methodology described in Section 3.14 were as follows. For the hard copy SFR the mean value for spatial resolution was 3.17lpmm^{-1} (SD 0.30) for the 4.2cm phantom, and 2.18 lpmm^{-1} (SD= 0.30) on hard copy CR. Mean values for the 5.2cm phantom were 3.17lpmm^{-1} (SD=0.29) for hard copy SFR and 2.18 lpmm^{-1} (SD=0.23). There was a difference between viewer three and viewers one and two ($p<0.05$). On soft copy the mean values for the 4.2cm phantom was 2.08lpmm^{-1} (SD=0.59) and for the 5.2cm phantom the mean was 1.87lpmm^{-1} (SD=0.53).

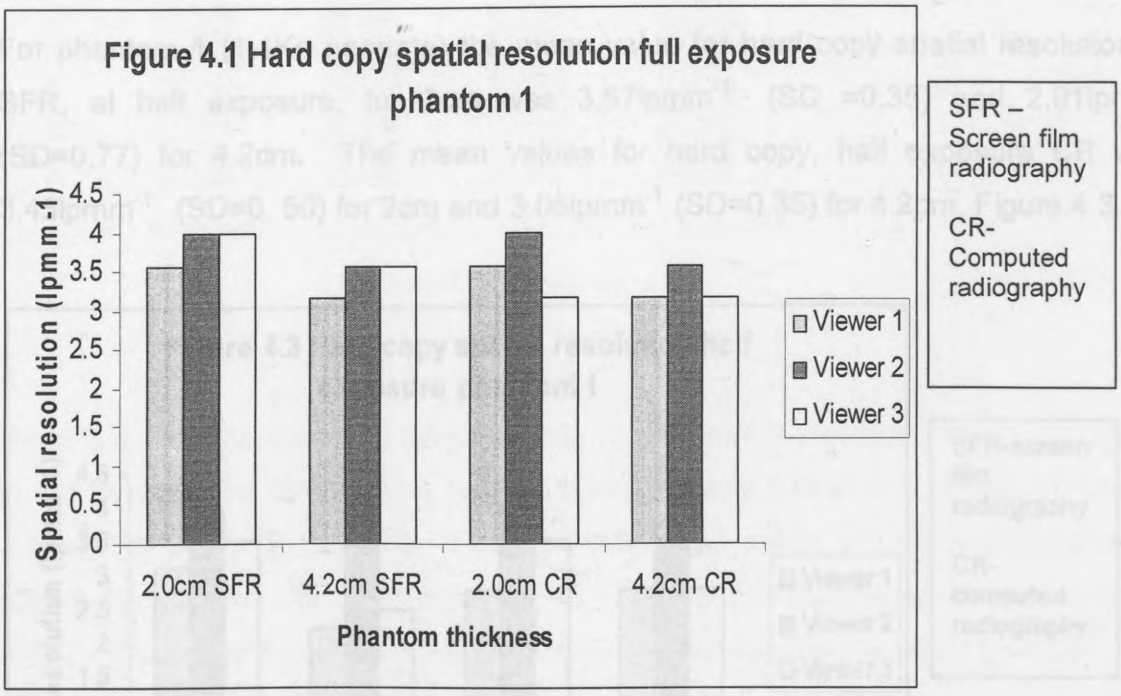
For high contrast on hard copy SFR the mean for the 4.2cm phantom was 15 (SD=0.81) and for CR it was 16 (SD=0.00). Results for the 5.2cm phantom were 15 (SD=0.50) for SFR and 16 (SD=0.50) for CR. Results for high contrast soft copy for the 4.2cm phantom was 16 (SD=1.50) and for 5.2cm phantom 17(SD=0.50). There was no difference between the viewers ($p>0.05$).

For low contrast hard copy SFR mean values were 14 (SD=1.26) for the 4.2cm phantom and 14 (SD=1.26) for the 5.2cm phantom. The mean values for CR hard copy were 15 (SD=0.50) for the 4.2cm phantom and 14 (SD=0.50) for the 5.2cm phantom. Results for low contrast soft copy for the 4.2cm phantom was 16 (SD=1.50) and for 5.2cm phantom 16 (SD=0.50). There was no difference between the viewers ($p>0.05$).

4.2 Results of Main Study

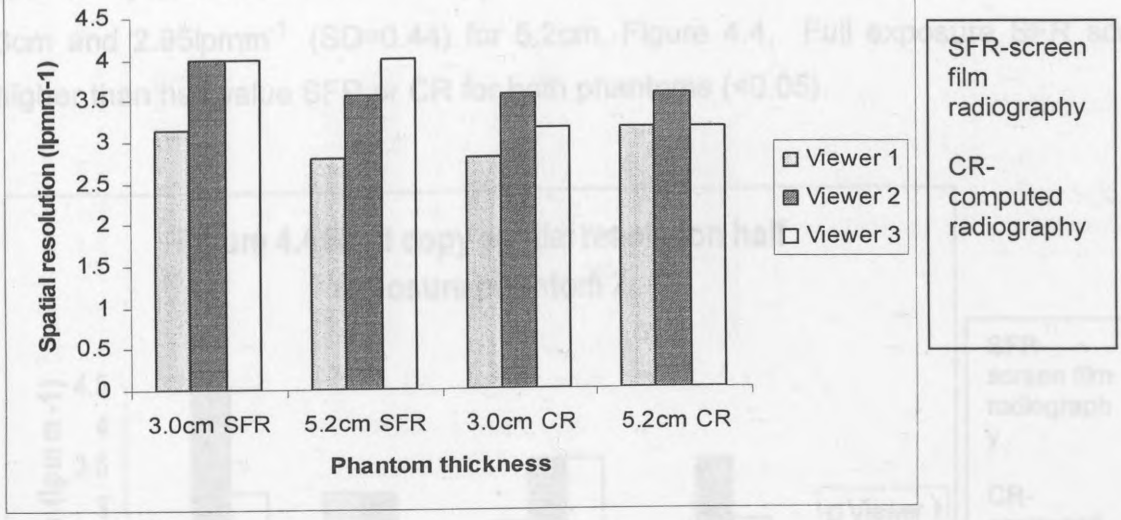
4.2.1 *Results for Spatial Resolution*

The charts used in this chapter are a summary of the raw data that is in Appendix 11. Full exposure SFR was used as the standard to which all other images were compared. For phantom 1 (1.1Kg neonate) the mean value for the hard copy spatial resolution on SFR, at full exposure, for 2cm was 3.85lpmm^{-1} (SD =0.21) and 3.42lpmm^{-1} (SD=0.19) for 4.2cm. The mean values for hard copy, full exposure CR were 3.57lpmm^{-1} (SD=0.35) for 2cm and 3.28lpmm^{-1} (SD=0.19) for 4.2cm. There was no difference ($p>0.05$) for the 2cm thickness, but for 4.2cm there was a difference ($p<0.05$)



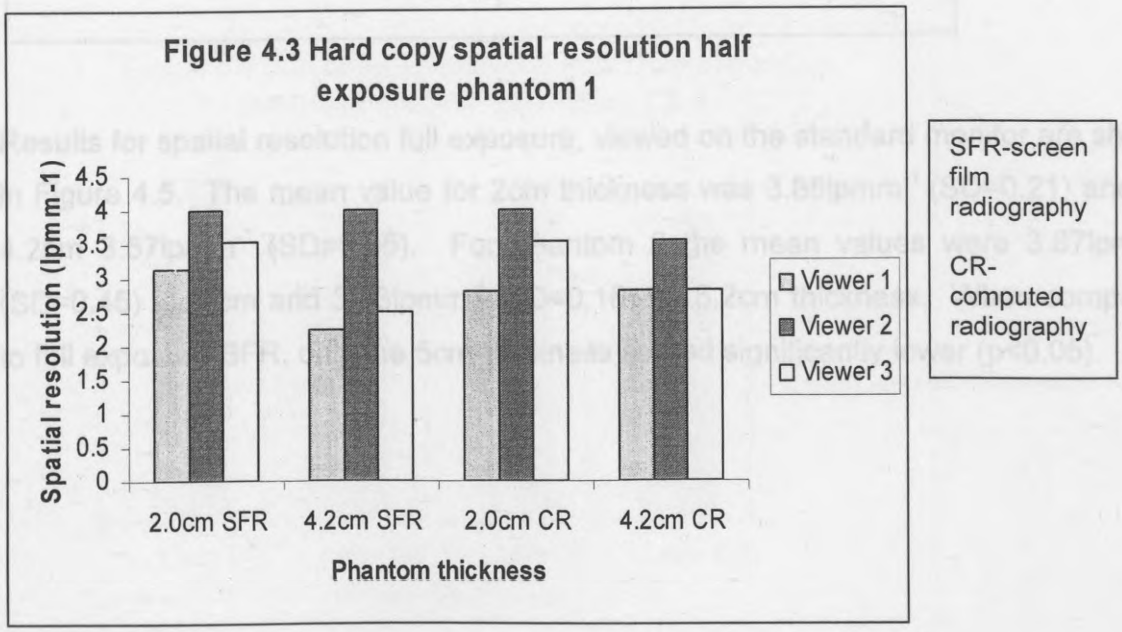
The mean values for full exposure hard copy spatial resolution for phantom 2 (2.5Kg neonate) on SFR were 3.71lpmm^{-1} (SD=0.40) for the 3cm thickness and 3.45lpmm^{-1} (SD=0.49) for 5.2cm. For hard copy CR mean values were 3.17lpmm^{-1} (SD=0.30) for 3cm and 3.28lpmm^{-1} (SD=0.19) for 5.2cm Figure 4.2. SFR scored higher than CR for both thickneses ($p<0.05$).

Figure 4.2 Hard copy spatial resolution full exposure phantom 2



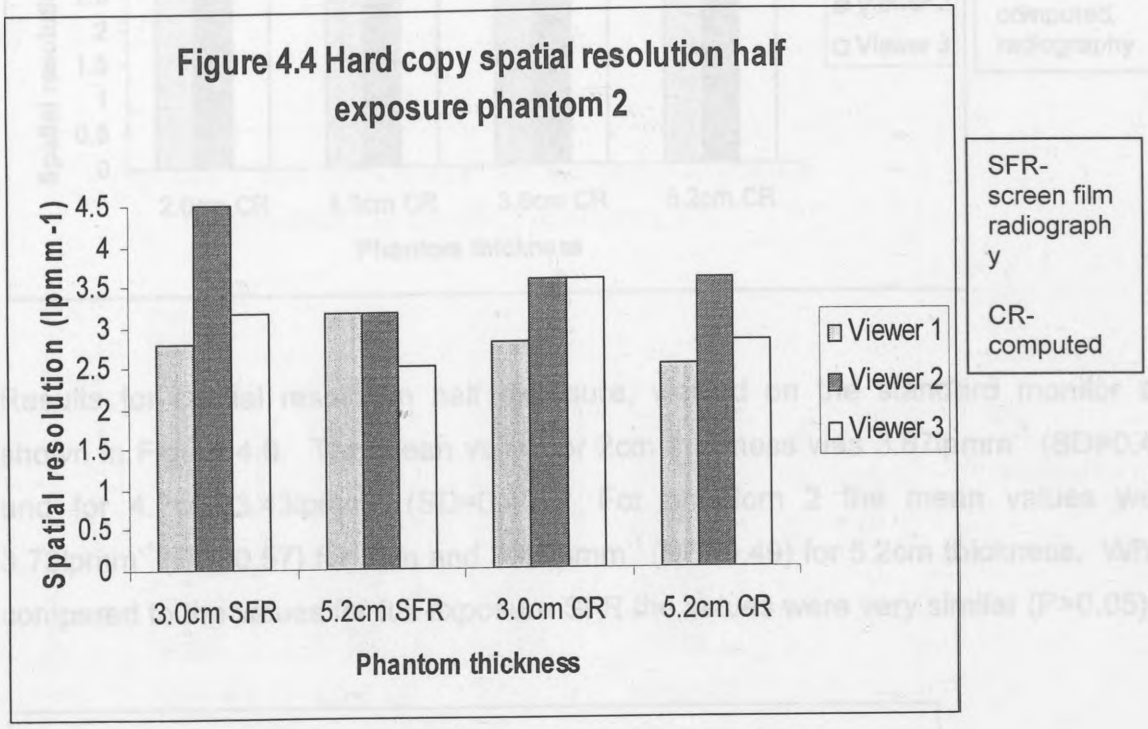
For phantom 1 (1.1Kg neonate) the mean value for hard copy spatial resolution on SFR, at half exposure, for 2cm was 3.57lpmm^{-1} (SD =0.35) and 2.91lpmm^{-1} (SD=0.77) for 4.2cm. The mean values for hard copy, half exposure CR were 3.45lpmm^{-1} (SD=0. 50) for 2cm and 3.05lpmm^{-1} (SD=0.35) for 4.2cm, Figure 4.3.

Figure 4.3 Hard copy spatial resolution half exposure phantom 1



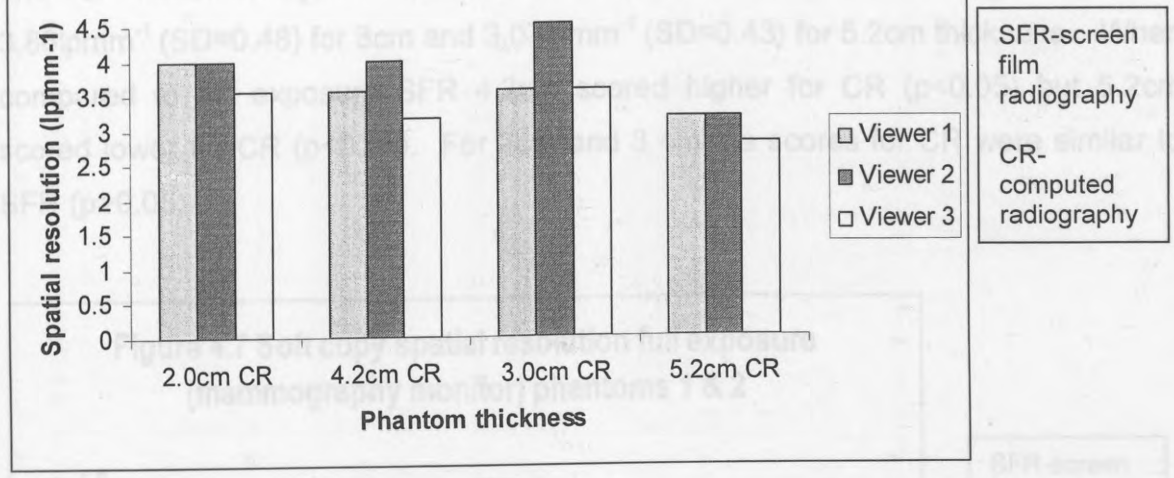
The mean values for half exposure hard copy spatial resolution for phantom 2 (2.5Kg neonate) on SFR were 3.48lpmm^{-1} (SD=0.73) for the 3cm thickness and 2.93lpmm^{-1} (SD=0.30) for 5.2cm. For hard copy CR mean values were 3.30 lpmm^{-1} (SD=0.35) for 3cm and 2.95lpmm^{-1} (SD=0.44) for 5.2cm, Figure 4.4. Full exposure SFR scored higher than half value SFR or CR for both phantoms (<0.05).

Figure 4.4 Hard copy spatial resolution half exposure phantom 2



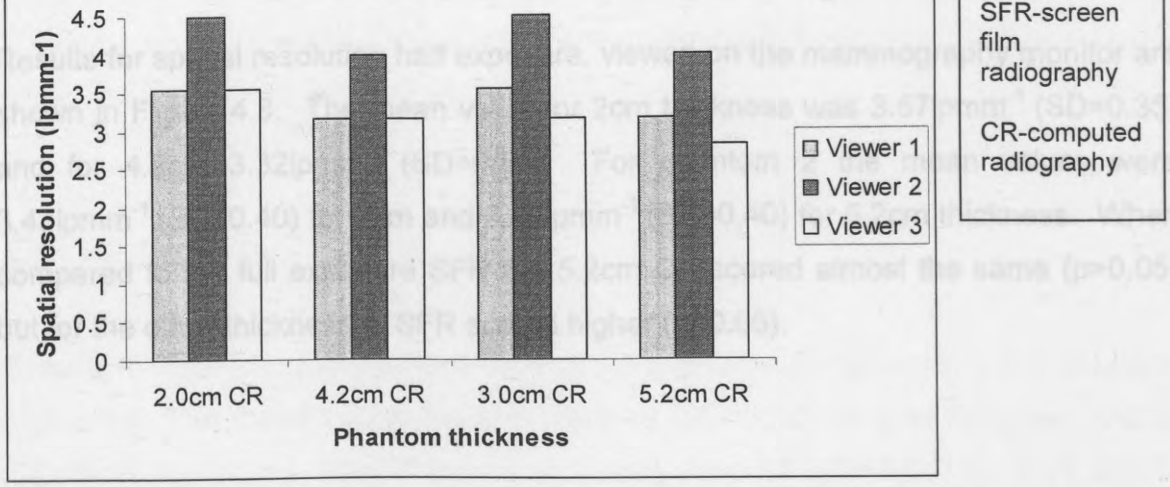
Results for spatial resolution full exposure, viewed on the standard monitor are shown in Figure 4.5. The mean value for 2cm thickness was 3.85lpmm^{-1} (SD=0.21) and for 4.2cm 3.57lpmm^{-1} (SD=0.35). For phantom 2 the mean values were 3.87lpmm^{-1} (SD=0.45) for 3cm and 3.03lpmm^{-1} (SD=0.16) for 5.2cm thickness. When compared to full exposure SFR, only the 5cm thickness scored significantly lower ($p<0.05$).

Figure 4.5 Soft copy spatial resolution full exposure (standard monitor) phantoms 1 & 2



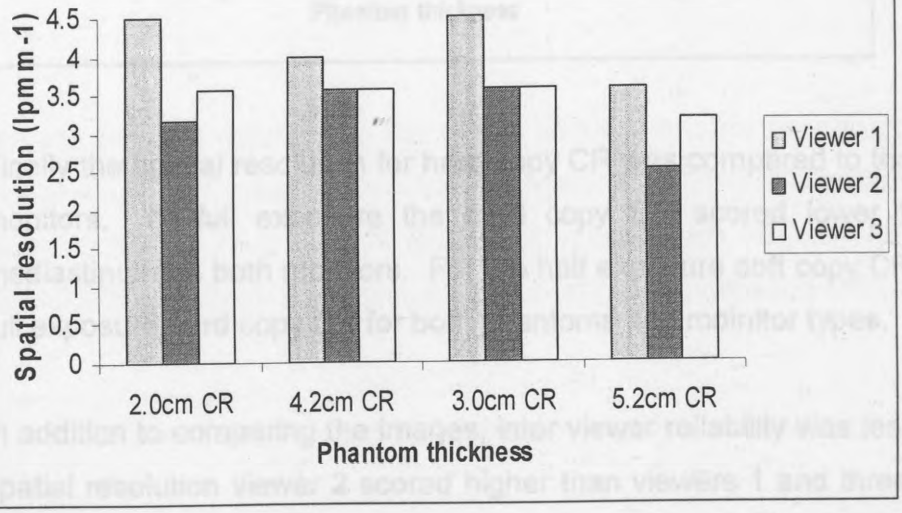
Results for spatial resolution half exposure, viewed on the standard monitor are shown in Figure 4.6. The mean value for 2cm thickness was 3.87lpmm^{-1} (SD=0.45) and for 4.2cm 3.43lpmm^{-1} (SD=0.40). For phantom 2 the mean values were 3.73lpmm^{-1} (SD=0.57) for 3cm and 3.45lpmm^{-1} (SD=0.49) for 5.2cm thickness. When compared to the values for full exposure SFR the values were very similar (P>0.05).

Figure 4.6 Soft copy spatial resolution half exposure (standard monitor) phantoms 1 & 2

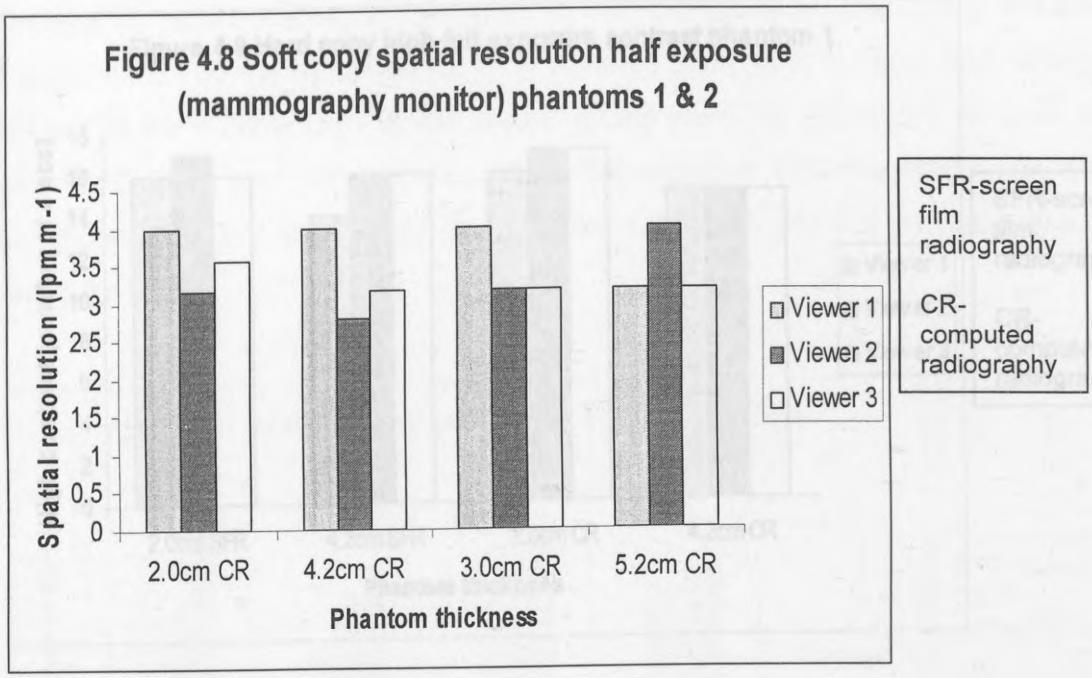


Results for spatial resolution full exposure, viewed on the mammography monitor are shown in Figure 4.7. The mean value for 2cm thickness was 3.73lpmm^{-1} (SD=0.57) and for 4.2cm 3.70lpmm^{-1} (SD=0.21). For phantom 2 the mean values were 3.86lpmm^{-1} (SD=0.48) for 3cm and 3.07lpmm^{-1} (SD=0.43) for 5.2cm thickness. When compared to full exposure SFR 4.2cm scored higher for CR ($p<0.05$) but 5.2cm scored lower for CR ($p<0.05$). For 2cm and 3 cm the scores for CR were similar to SFR ($p>0.05$).

Figure 4.7 Soft copy spatial resolution full exposure (mammography monitor) phantoms 1 & 2



Results for spatial resolution half exposure, viewed on the mammography monitor are shown in Figure 4.8. The mean value for 2cm thickness was 3.57lpmm^{-1} (SD=0.35) and for 4.2cm 3.32lpmm^{-1} (SD=0.50). For phantom 2 the mean values were 3.43lpmm^{-1} (SD=0.40) for 3cm and 3.43lpmm^{-1} (SD=0.40) for 5.2cm thickness. When compared to the full exposure SFR the 5.2cm CR scored almost the same ($p>0.05$) but for the other thicknesses SFR scored higher ($p<0.05$).

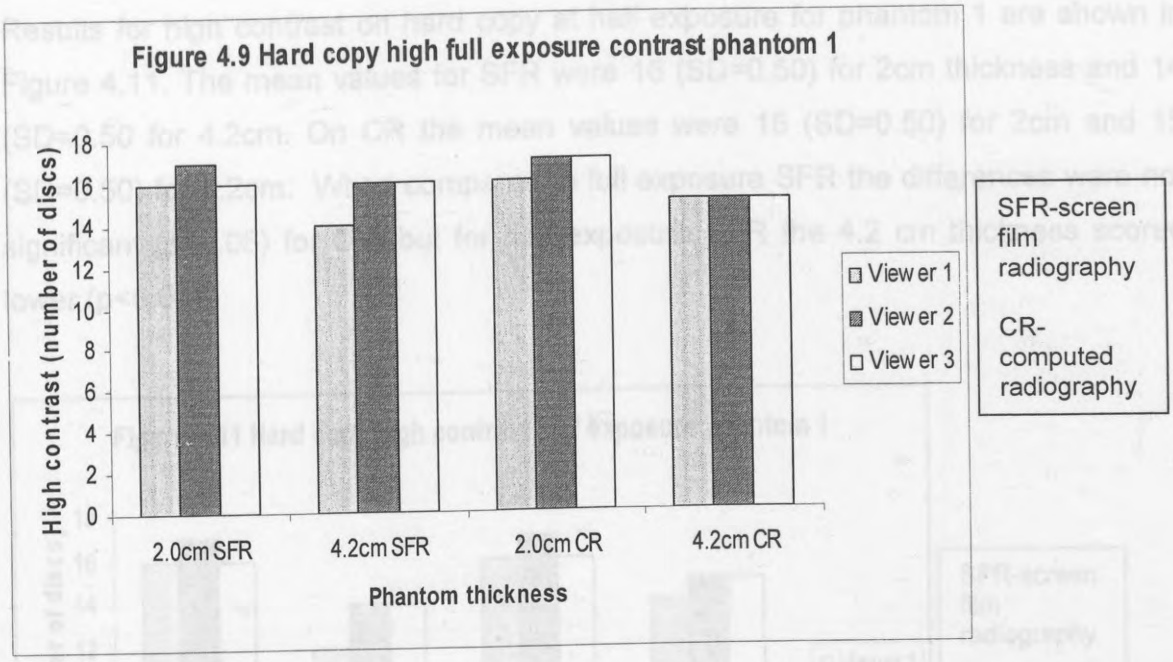


Finally the spatial resolution for hard copy CR was compared to the soft copy for both monitors. At full exposure the hard copy CR scored lower for both lung and mediastinum on both monitors. For the half exposure soft copy CR scored as well as full exposure hard copy CR for both phantoms and moinitor types.

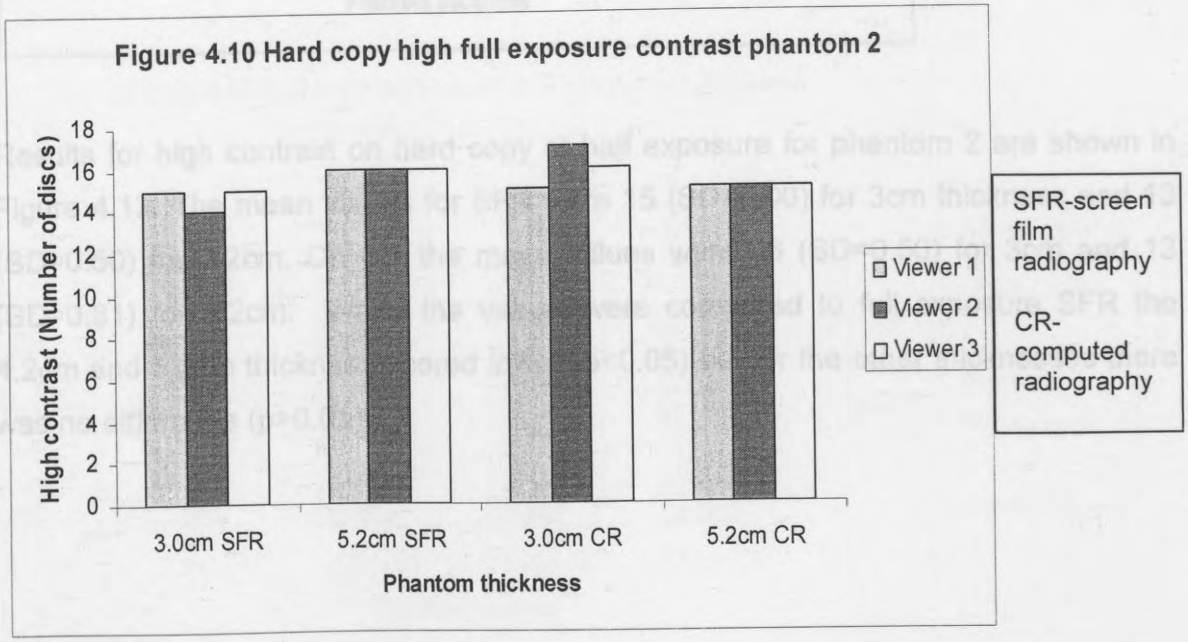
In addition to comparing the images, inter viewer reliability was tested. For hard copy spatial resolution viewer 2 scored higher than viewers 1 and three ($p<0.05$). For soft copy spatial resolution on the standard monitor, viewer 2 again scored higher than viewers 1 and 2 ($p<0.05$). However for the mammography monitor, viewer 1 scored higher than viewers 2 and 3 ($p<0.05$).

4.2.2 *Results for High Contrast Discs*

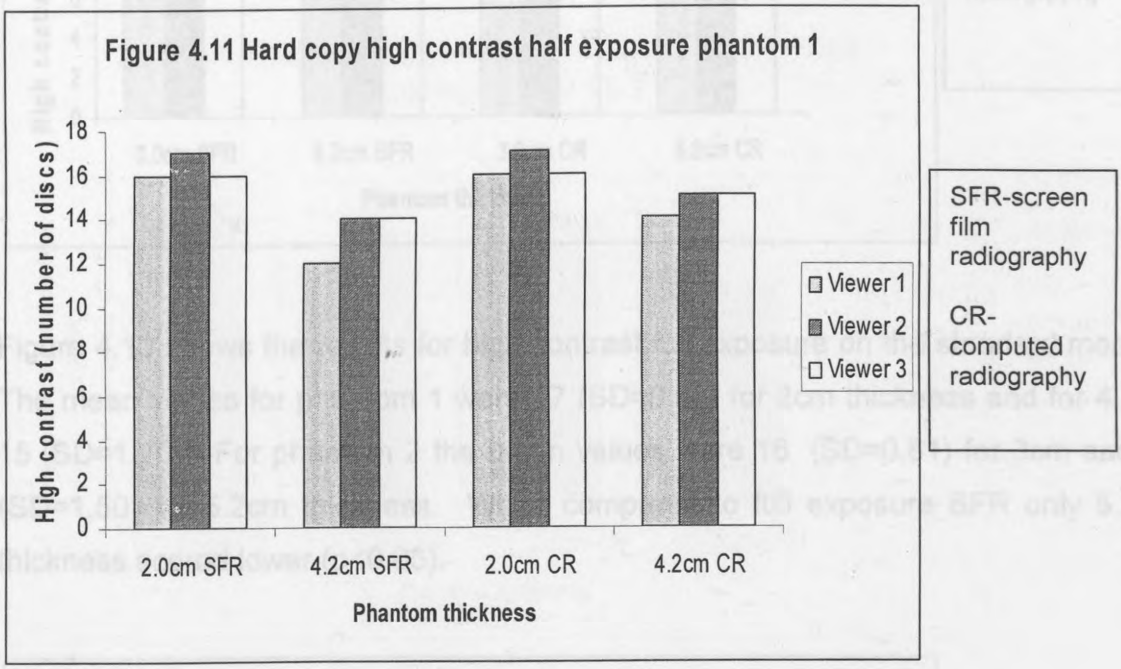
Results for high contrast on hard copy at full exposure for phantom 1 are shown in Figure 4.9. The mean values for SFR were 16 (SD=0.50) for 2cm thickness and 16 (SD=0.00) for 4.2cm. On CR the mean values were 17 (SD=0.50) for 2cm and 15 (SD=0.00) for 4.2cm. The difference in values between SFR and CR was not significant ($p>0.05$)



Results for high contrast on hard copy at full exposure for phantom 2 are shown in Figure 4.10. The mean values for SFR were 15 (SD=0.50) for 3cm thickness and 16 (SD=0.00) for 5.2cm. On CR the mean values were 16 (SD=0.81) for 3cm and 15 (SD=0.00) for 5.2cm. Again there was no difference between SFR and CR ($p>0.05$).



Results for high contrast on hard copy at half exposure for phantom 1 are shown in Figure 4.11. The mean values for SFR were 16 (SD=0.50) for 2cm thickness and 14 (SD=0.50 for 4.2cm. On CR the mean values were 16 (SD=0.50) for 2cm and 15 (SD=0.50) for 4.2cm. When compared to full exposure SFR the differences were not significant ($p>0.05$) for CR, but for half exposure SFR the 4.2 cm thickness scored lower ($p<0.05$).



Results for high contrast on hard copy at half exposure for phantom 2 are shown in Figure 4.12. The mean values for SFR were 15 (SD=0.00) for 3cm thickness and 13 (SD=0.50) for 5.2cm. On CR the mean values were 16 (SD=0.50) for 3cm and 13 (SD=0.81) for 5.2cm. When the values were compared to full exposure SFR the 4.2cm and 5.2cm thickness scored lower ($p<0.05$) but for the other thicknesses there was no difference ($p>0.05$).

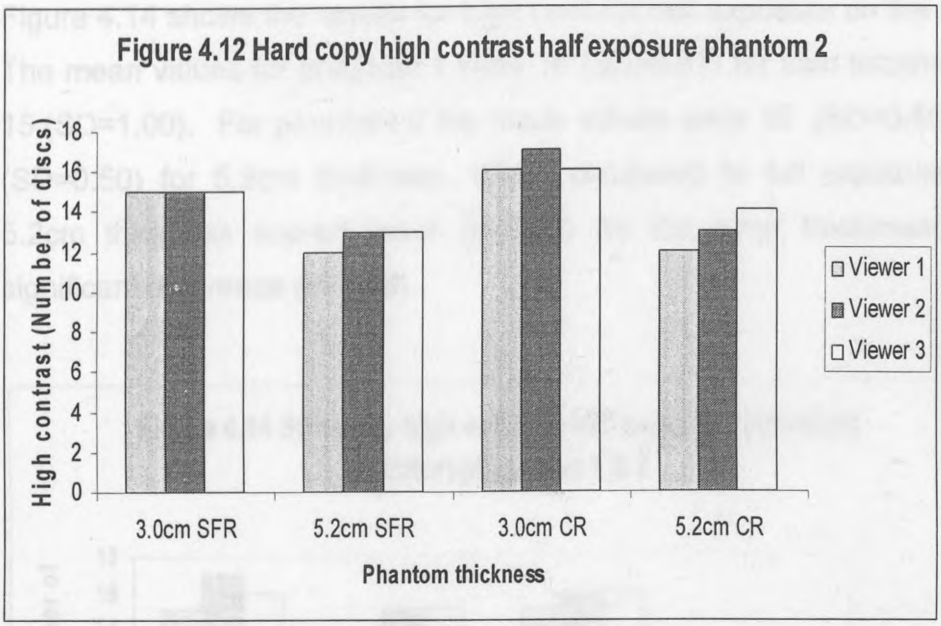


Figure 4.13 shows the results for high contrast full exposure on the standard monitor. The mean values for phantom 1 were 17 (SD=0.50) for 2cm thickness and for 4.2cm 15 (SD=1.70). For phantom 2 the mean values were 16 (SD=0.81) for 3cm and 14 (SD=1.50) for 5.2cm thickness. When compared to full exposure SFR only 5.2cm thickness scored lower ($p<0.05$).

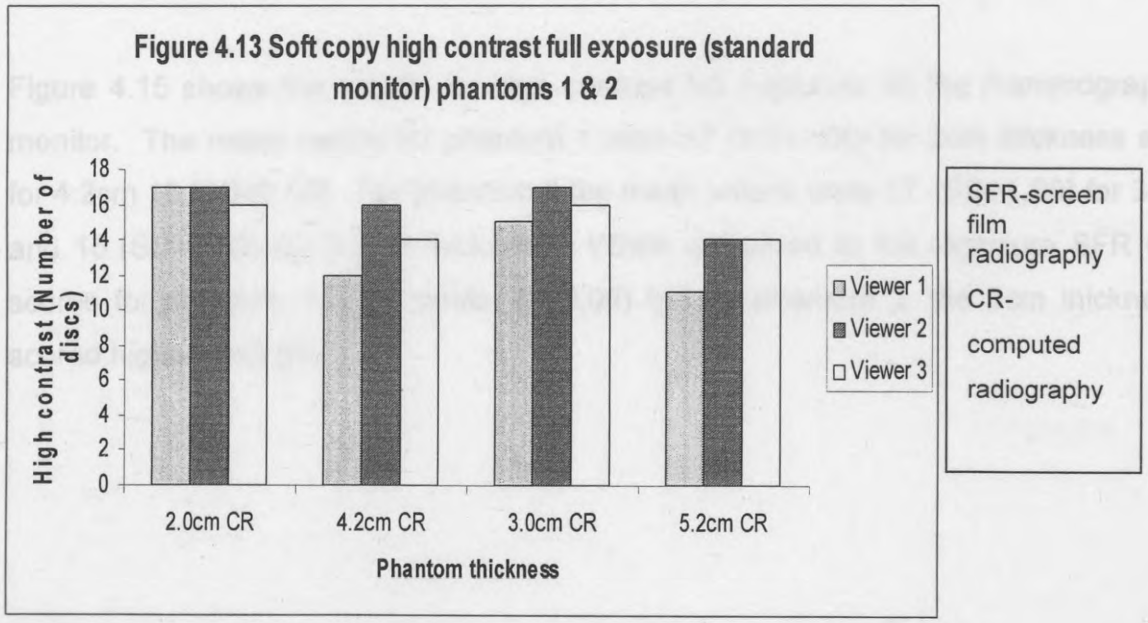


Figure 4.14 shows the results for high contrast half exposure on the standard monitor. The mean values for phantom 1 were 16 (SD=0.81) for 2cm thickness and for 4.2cm 15 (SD=1.00). For phantom 2 the mean values were 16 (SD=0.50) for 3cm and 12 (SD=0.50) for 5.2cm thickness. When compared to full exposure SFR again the 5.2cm thickness scored lower ($p<0.05$) for the other thicknesses there was no significant difference ($p>0.05$).

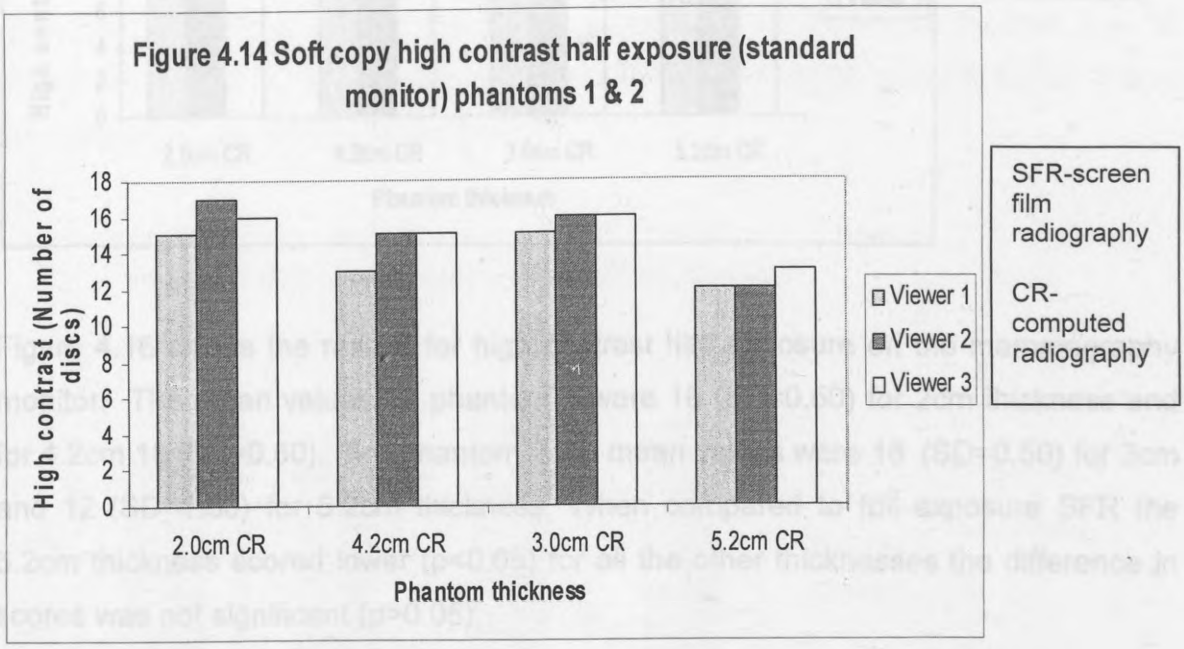


Figure 4.15 shows the results for high contrast full exposure on the mammography monitor. The mean values for phantom 1 were 17 (SD=1.00) for 2cm thickness and for 4.2cm 16 (SD=0.50). For phantom 2 the mean values were 17 (SD=1.00) for 3cm and 15 (SD=0.50) for 5.2cm thickness. When compared to full exposure SFR the scores for phantom 1 were similar ($p>0.05$) but for phantom 2, the 3cm thickness scored higher ($p<0.05$).

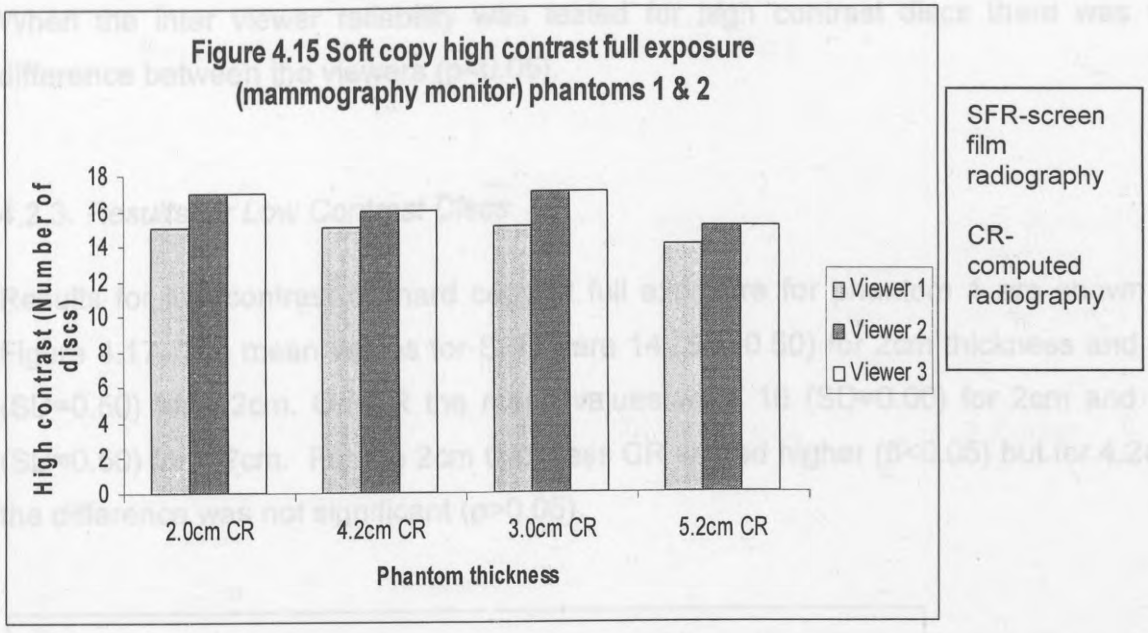
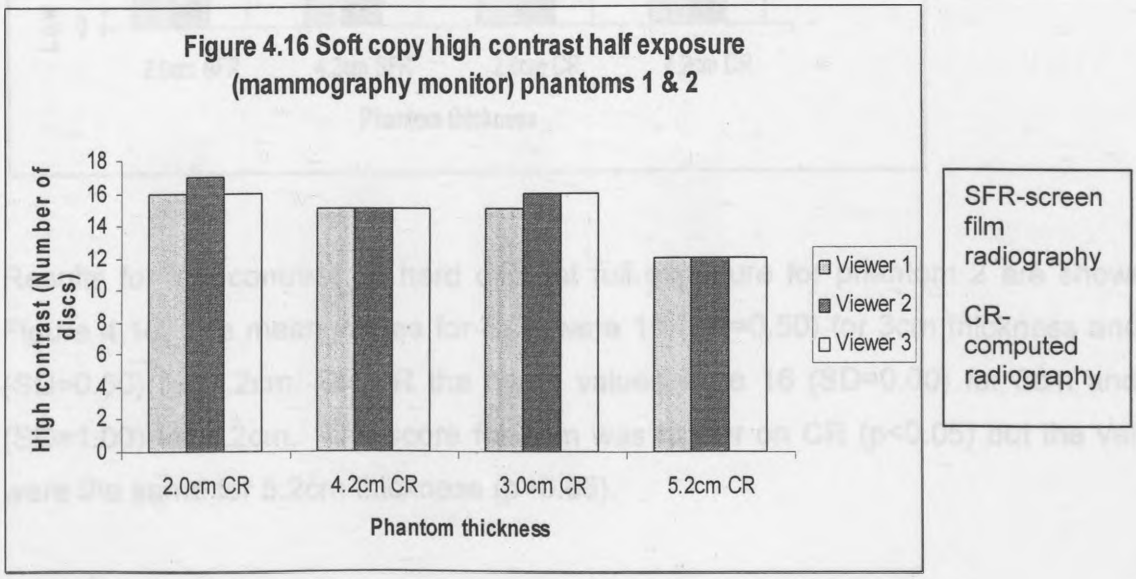


Figure 4.16 shows the results for high contrast half exposure on the mammography monitor. The mean values for phantom 1 were 16 (SD=0.50) for 2cm thickness and for 4.2cm 15 (SD=0.50). For phantom 2 the mean values were 16 (SD=0.50) for 3cm and 12 (SD=1.50) for 5.2cm thickness. When compared to full exposure SFR the 5.2cm thickness scored lower ($p<0.05$) for all the other thicknesses the difference in scores was not significant ($p>0.05$).



When the inter viewer reliability was tested for high contrast discs there was no difference between the viewers ($p<0.05$).

4.2.3. *Results for Low Contrast Discs*

Results for low contrast on hard copy at full exposure for phantom 1 are shown in Figure 4.17. The mean values for SFR were 14 (SD=0.50) for 2cm thickness and 14 (SD=0.50) for 4.2cm. On CR the mean values were 16 (SD=0.00) for 2cm and 15 (SD=0.50) for 4.2cm. For the 2cm thickness CR scored higher ($p<0.05$) but for 4.2cm the difference was not significant ($p>0.05$).

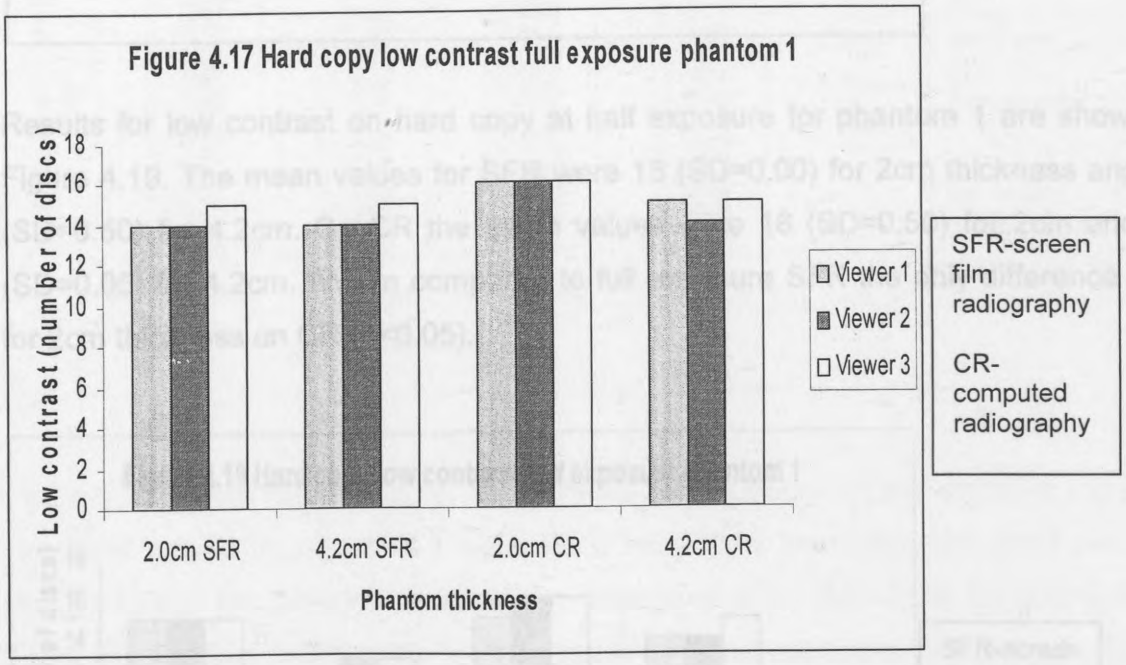


Figure 4.17 Hard copy low contrast full exposure phantom 1

Results for low contrast on hard copy at full exposure for phantom 2 are shown in Figure 4.18. The mean values for SFR were 14 (SD=0.50) for 3cm thickness and 14 (SD=0.50) for 5.2cm. On CR the mean values were 16 (SD=0.00) for 3cm and 14 (SD=1.00) for 5.2cm. The score for 3cm was higher on CR ($p<0.05$) but the values were the same for 5.2cm thickness ($p>0.05$).

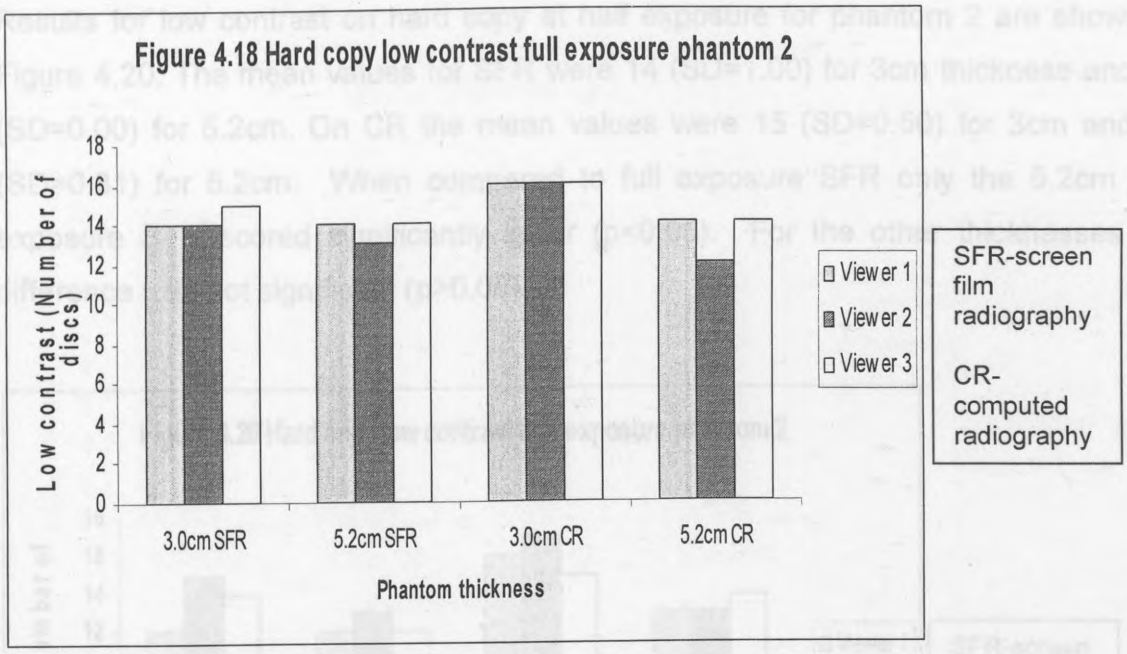


Figure 4.18 Hard copy low contrast full exposure phantom 2

Results for low contrast on hard copy at half exposure for phantom 1 are shown in Figure 4.19. The mean values for SFR were 15 (SD=0.00) for 2cm thickness and 13 (SD=0.50) for 4.2cm. On CR the mean values were 16 (SD=0.50) for 2cm and 14 (SD=0.05) for 4.2cm. When compared to full exposure SFR the only difference was for 2cm thickness on CR ($p<0.05$).

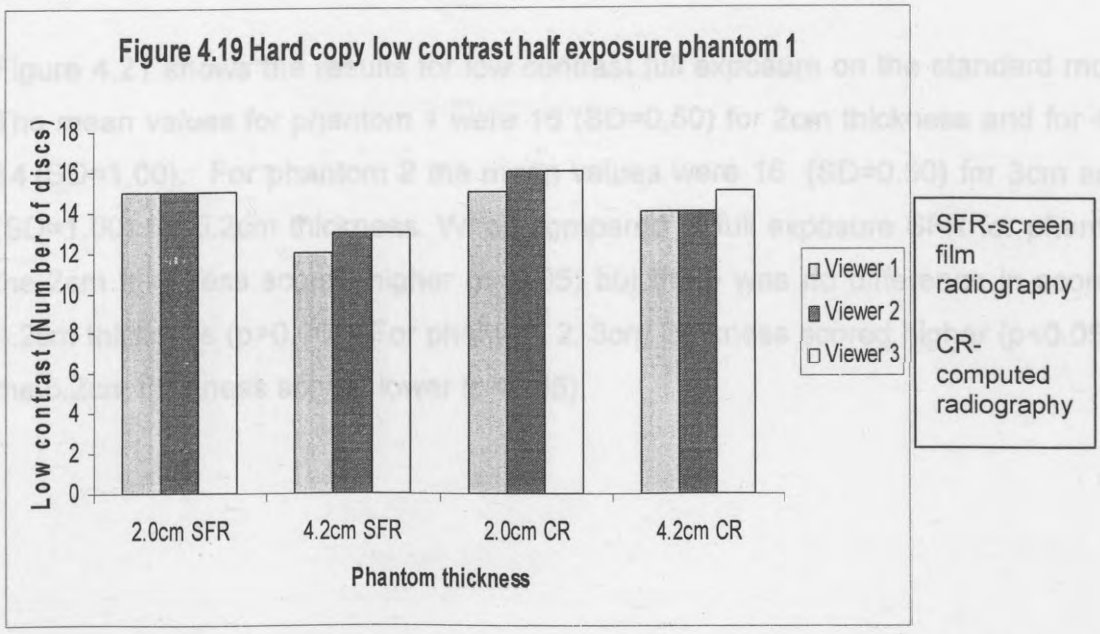


Figure 4.19 Hard copy low contrast half exposure phantom 1

Results for low contrast on hard copy at half exposure for phantom 2 are shown in Figure 4.20. The mean values for SFR were 14 (SD=1.00) for 3cm thickness and 12 (SD=0.00) for 5.2cm. On CR the mean values were 15 (SD=0.50) for 3cm and 13 (SD=0.81) for 5.2cm. When compared to full exposure SFR only the 5.2cm half exposure SFR scored significantly lower ($p<0.05$). For the other thicknesses the difference was not significant ($p>0.05$).

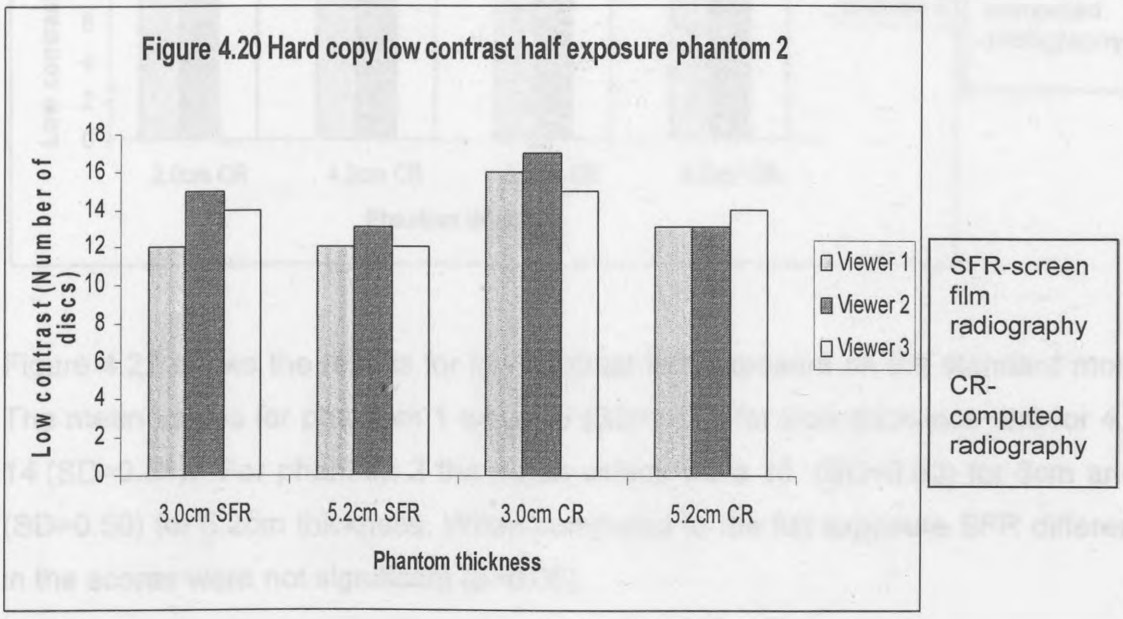


Figure 4.21 shows the results for low contrast full exposure on the standard monitor. The mean values for phantom 1 were 16 (SD=0.50) for 2cm thickness and for 4.2cm 14 (SD=1.00). For phantom 2 the mean values were 16 (SD=0.50) for 3cm and 12 (SD=1.00) for 5.2cm thickness. When compared to full exposure SFR for phantom 1 the 2cm thickness scored higher ($p<0.05$) but there was no difference in scores for 4.2cm thickness ($p>0.05$). For phantom 2, 3cm thickness scored higher ($p<0.05$) and the 5.2cm thickness scored lower ($p<0.05$).

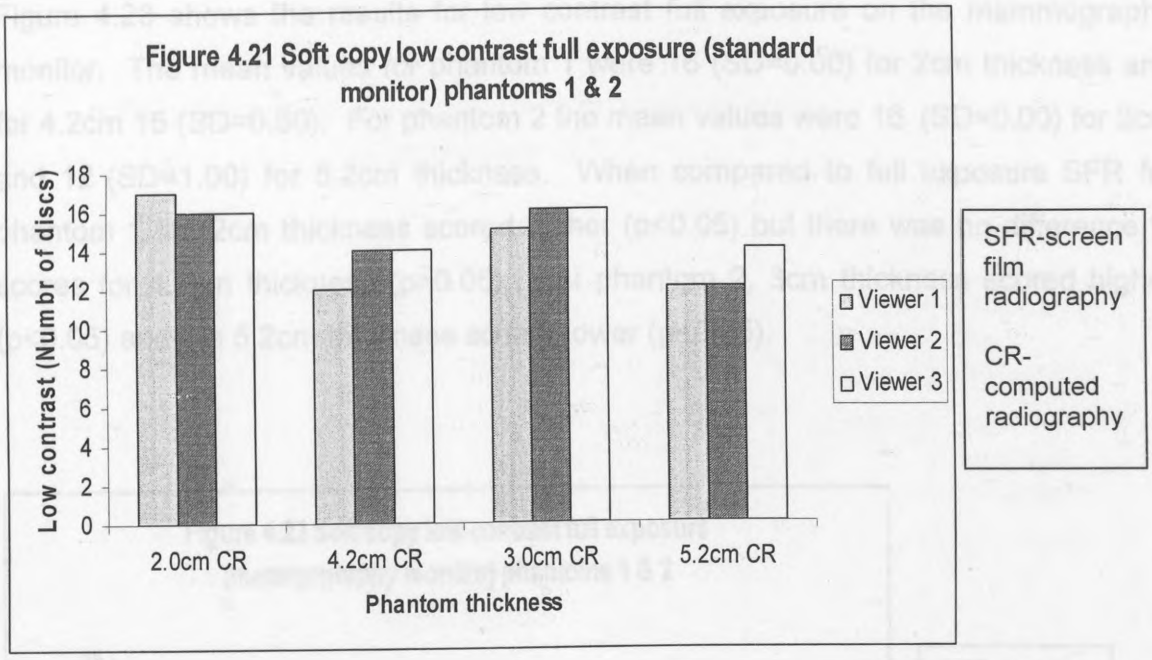


Figure 4.21 Soft copy low contrast full exposure (standard monitor) phantoms 1 & 2

Figure 4.22 shows the results for low contrast half exposure on the standard monitor. The mean values for phantom 1 were 15 (SD=1.00) for 2cm thickness and for 4.2cm 14 (SD=0.81). For phantom 2 the mean values were 15 (SD=0.50) for 3cm and 13 (SD=0.50) for 5.2cm thickness. When compared to the full exposure SFR differences in the scores were not significant ($p>0.05$).

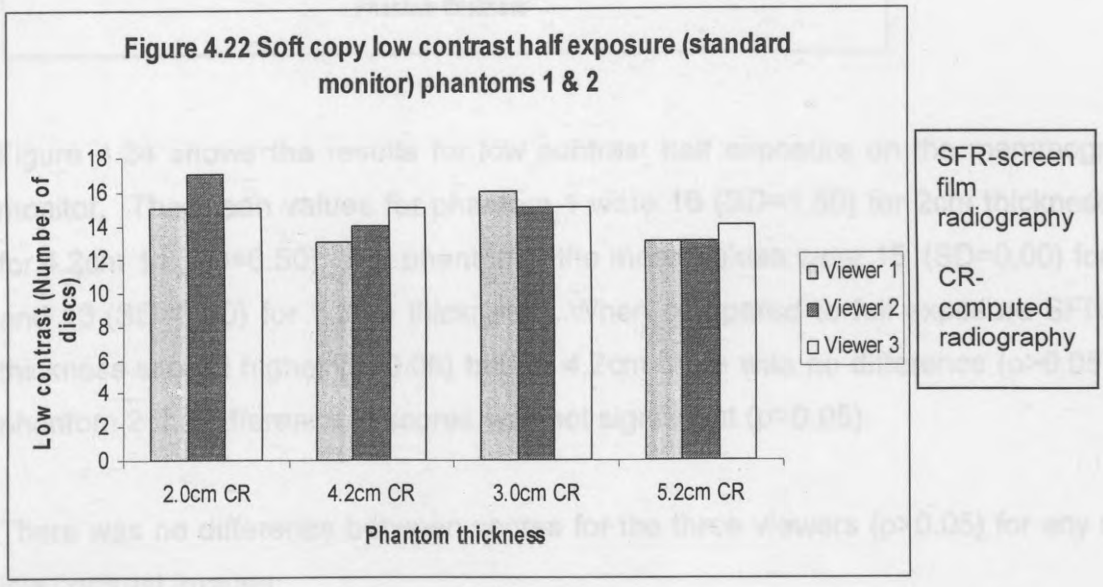


Figure 4.22 Soft copy low contrast half exposure (standard monitor) phantoms 1 & 2

Figure 4.23 shows the results for low contrast full exposure on the mammography monitor. The mean values for phantom 1 were 16 (SD=0.00) for 2cm thickness and for 4.2cm 15 (SD=0.50). For phantom 2 the mean values were 16 (SD=0.00) for 3cm and 12 (SD=1.00) for 5.2cm thickness. When compared to full exposure SFR for phantom 1 the 2cm thickness scored higher ($p<0.05$) but there was no difference in scores for 4.2cm thickness ($p>0.05$). For phantom 2, 3cm thickness scored higher ($p<0.05$) and the 5.2cm thickness scored lower ($p<0.05$).

Figure 4.23 Soft copy low contrast full exposure (mammography monitor) phantoms 1 & 2

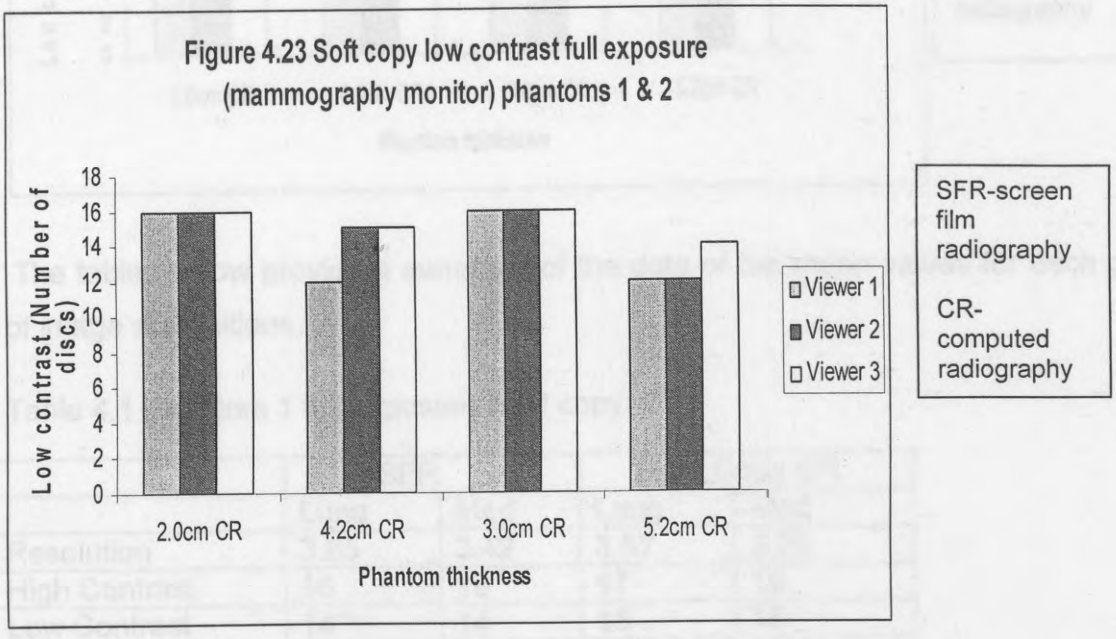
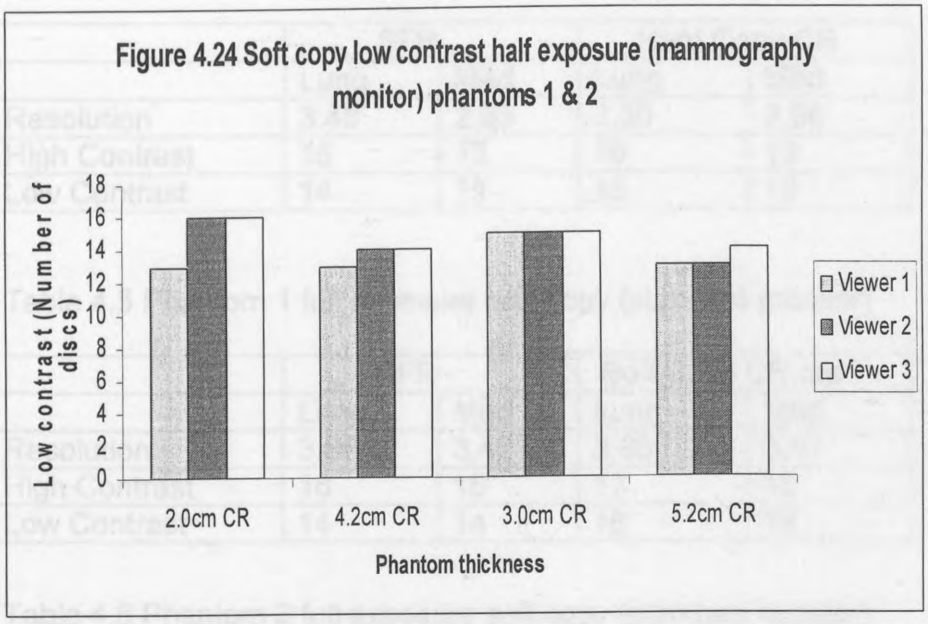


Figure 4.24 shows the results for low contrast half exposure on the mammography monitor. The mean values for phantom 1 were 16 (SD=1.50) for 2cm thickness and for 4.2cm 14 (SD=0.50). For phantom 2 the mean values were 15 (SD=0.00) for 3cm and 13 (SD=0.50) for 5.2cm thickness. When compared to full exposure SFR 2cm thickness scored higher ($p<0.05$) but for 4.2cm there was no difference ($p>0.05$). For phantom 2 the difference in scores was not significant ($p>0.05$).

There was no difference between scores for the three viewers ($p>0.05$) for any of the low contrast images.



The tables below provide a summary of the data of the mean values for each group of image acquisitions.

Table 4.1 Phantom 1 full exposure hard copy

	SFR		Hard Copy CR	
	Lung	Med	Lung	Med
Resolution	3.85	3.42	3.57	3.28
High Contrast	16	16	17	15
Low Contrast	14	14	16	15

Table 4.2 Phantom 2 full exposure hard copy

	SFR		Hard Copy CR	
	Lung	Med	Lung	Med
Resolution	3.71	3.45	3.71	3.28
High Contrast	15	16	16	15
Low Contrast	14	14	16	14

Table 4.3 Phantom 1 half exposure hard copy

	SFR		Hard Copy CR	
	Lung	Med	Lung	Med
Resolution	3.57	2.91	3.45	3.05
High Contrast	16	14	16	15
Low Contrast	15	13	16	14

Table 4.4 Phantom 2 half exposure hard copy

	SFR		Hard Copy CR	
	Lung	Med	Lung	Med
Resolution	3.48	2.93	3.30	3.95
High Contrast	15	13	16	13
Low Contrast	14	12	15	13

Table 4.5 Phantom 1 full exposure soft copy (standard monitor)

	SFR		Soft Copy CR std	
	Lung	Med	Lung	Med
Resolution	3.85	3.42	3.85	3.57
High Contrast	16	16	17	15
Low Contrast	14	14	16	14

Table 4.6 Phantom 2 full exposure soft copy (standard monitor)

	SFR		Soft Copy CR std	
	Lung	Med	Lung	Med
Resolution	3.71	3.45	3.87	3.03
High Contrast	15	16	16	14
Low Contrast	14	14	16	12

Table 4.7 Phantom 1 half exposure soft copy (standard monitor)

	SFR		Soft Copy CR std	
	Lung	Med	Lung	Med
Resolution	3.57	2.91	3.87	3.43
High Contrast	16	14	16	15
Low Contrast	15	13	15	14

Table 4.8 Phantom 2 half exposure soft copy (standard monitor)

	SFR		Soft Copy CR std	
	Lung	Med	Lung	Med
Resolution	3.48	2.93	3.73	3.45
High Contrast	15	13	16	13
Low Contrast	14	12	15	13

Table 4.9 Phantom 1 full exposure soft copy (mammography monitor)

	SFR		Soft Copy CR	
	Lung	Med	Lung	Med
Resolution	3.85	3.42	3.73	3.70
High Contrast	16	16	17	16
Low Contrast	14	14	16	15

Table 4.10 Phantom 2 full exposure soft copy (mammography monitor)

	SFR		Soft Copy CR	
	Lung	Med	Lung	Med
Resolution	3.71	3.45	3.86	3.07
High Contrast	15	16	17	15
Low Contrast	14	14	16	12

Table 4.11 Phantom 1 half exposure soft copy (mammography monitor)

	SFR		Soft Copy CR	
	Lung	Med	Lung	Med
Resolution	3.57	2.91	3.57	3.32
High Contrast	16	14	16	15
Low Contrast	15	13	16	16

Table 4.12 Phantom 2 half exposure soft copy (mammography monitor)

	SFR		Soft Copy CR	
	Lung	Med	Lung	Med
Resolution	3.48	2.93	3.43	3.43
High Contrast	15	13	16	12
Low Contrast	14	12	15	13

5. Discussion of Findings

5.1 Findings

For spatial resolution, hard copy SFR scored higher than hard copy CR regardless of the exposure level. SFR and soft copy spatial resolution scored equally. For high contrast, soft copy scored higher than hard copy SFR and CR. For low contrast, soft copy scored higher than hard copy images. There was minimal difference in the scores for the two monitor types. In summary, image contrast is the more important factor in determining the image quality in neonatal chest radiography.

5.2 Results in Context

The accepted range of values for spatial resolution for SFR is between 4lpmm^{-1} and 7lpmm^{-1}, depending on the film screen combination (Artz 1997; Hufton et al 1998). For CR the values for spatial resolution fall between 2.5lpmm^{-1} and 5lpmm^{-1} depending on the imaging system (Freedman & Artz 1997; Murphey 1997). In this present study the values for SFR ranged from 2.24lpmm^{-1} to 4.50lpmm^{-1} where the lower values refer to images acquired at half exposure. For CR hard copy the values ranged from 2.50lpmm^{-1} to 4lpmm^{-1} and for soft copy these values were between 2.80lpmm^{-1} to 4.50lpmm^{-1}.

As expected SFR scored better for lung and mediastinum compared to hard copy CR at full exposure for both phantoms ($p<0.05$), Figures 4.1 and 4.2. However for half exposure, hard copy CR scored better for the mediastinal areas for both the phantoms, Figures 4.3 and 4.4 but the differences were not significant ($p>0.05$). When the images were viewed on soft copy the 5.2cm thickness scored consistently lower for both monitors at full exposure ($p<0.05$). However when half exposure soft copy CR was compared to full exposure SFR there was no difference in the scores ($p>0.05$). This was probably a result of the digital system compensating for the lower

exposure to maintain an acceptable optical density, where as the SFR images were clearly under exposed for the mediastinal areas.

Arthur & Pease (1991) conducted a study that compared the image quality of SFR to CR for neonatal chest radiographs. Over a three month period 219 SFR and 210 CR neonatal chest radiographs were acquired using the same exposure factors. All the images were acquired when clinically indicated. The images were reviewed by two radiologists for image quality on hard copy. The results indicated that the overall image quality was better for CR ($p<0.05$) compared to SFR. The authors concluded that despite the lower spatial resolution of CR the wide dynamic range and post processing facilities compensated for this. An opinion shared by Huda et al (1997) who reported that "... despite its inferior limiting spatial resolution CR was deemed by radiologists to produce superior images to screen-film for the same radiographic techniques" (Huda et al 1997:1627).

Hufton et al (1998) compared SFR and CR in terms of patient doses for chest, abdomen, pelvis and skull radiography for four different age groups of children. For each of the anatomical areas and age groups, four images were selected, two for each modality and these were compared using the guidelines for image quality set out in EUR 16261 (1996). Six radiologists reviewed the images and despite there being a wide variation between the radiologists there was no significant difference between SFR and CR. No statistical data was included in this paper as the authors planned to publish a second article with the details, this has not occurred. Hufton et al (1998) concluded that "...differences in resolution do not necessarily result in noticeable differences in clinical image quality" (Hufton et al 1998:188).

These results are an indication of the digital systems ability to compensate for low exposure. The differences between hard copy CR and soft copy CR are possibly due to the set up of the laser printer. Depending on the manufacturer and the model of printer default parameters will vary. In addition the individual preference of the radiologists will affect how the image contrast of a laser printer is set up. The poorer resolution for the mediastinum compared to the lungs for all image types is reflected in the clinical situation where the mediastinum is poorly visualised. In neonatal chest

radiography it is important to be able to identify the position of endotracheal tubes, naso-gastric tubes and other catheters therefore if soft copy improves the appearance of the mediastinum this is a major advantage to clinicians.

For high contrast there was no difference in the scores for between SFR and CR ($p>0.05$), Figures 4.9 and 4.10. At the reduced exposure, hard copy CR scored higher than half exposure SFR regardless of phantom or area ($p>0.05$), Figures 4.11 and 4.12. However when compared to full exposure SFR, 4.2cm and 5.2cm thicknesses scored lower for CR ($p<0.05$). Soft copy viewed on the standard monitor indicated that SFR scored higher for mediastinal areas, Figures 4.13. At half exposure the soft copy was as good as hard copy SFR viewed on the standard monitor for both phantoms, except for the 5.2cm thickness ($p<0.05$), Figure 4.14. Results for the mammography monitor were the same as for the standard monitor but the actual scores were higher Figures 4.15 and 4.16.

A possible factor in the variation between the two monitor types is that the standard monitor was a LCD display and the mammography one CRT. At the SiV, CRT monitors were specifically chosen for mammography as they have a higher contrast which is required for identifying micro-calcifications in the breast.

Comparison of hard copy CR to soft copy CR for high contrast, indicated that soft copy was better for the lung and equal to hard copy for the mediastinum at full and half exposure.

The low contrast results were the most important with regard to the study as neonatal chests have inherently low contrast because of the heart size which is proportionately larger than in an adult, as is the thymus. In addition interstitial lung disease is frequently present on neonatal chest radiographs and so lungs are poorly aerated. These factors combine to produce an image with low contrast. SFR scored lower for both 2cm and 3cm thicknesses ($p<0.05$), but for 4.2cm and 5.2cm there was no difference ($p>0.05$), Figures 4.17 and 4.18. At half exposure the hard copy CR scored better than the SFR for 2cm and for 5.2cm ($p<0.05$), Figure 4.19 and 4.20.

When low contrast on SFR was compared to the soft copy on the standard monitor the values for lung were higher and equal for mediastinum, for both phantoms, Figure 4.21. At half exposure the soft copy scored higher for lung and equal to mediastinum for both phantoms on the standard monitor Figure 4.22. The results were similar for the mammography monitor ($p>0.05$), Figures 4.23 and 4.24. However information obtained from a phantom study does not provide data with regard to the clinical situation. A statistical difference in the contrast or spatial resolution detected using a test object may have no impact on clinical images, as image interpretation is a highly subjective area, and influenced by a number of factors, including viewing conditions, viewers experience and the examination type.

The low contrast on hard copy CR was compared to soft copy CR at full and half exposure. At full exposure the soft copy CR scored higher than the hard copy CR for the lungs and poorer for mediastinum, for both phantoms. At half exposure the soft copy was better for both areas compared to hard copy CR. These results are the same as for spatial resolution and high contrast and probably result from the ability to manipulate the soft copy images to produce greater detail, by use of magnification and edge enhancement.

The findings of this study were then compared to previous studies to validate the results. Brill et al (1996) investigated the suitability of high resolution monitors (2.5K x 2K) for reporting neonatal and paediatric radiographs acquired in the NNU and paediatric intensive care unit. 1104 images were reviewed on hard copy CR and soft copy, 863 chest radiographs and 241 abdominal radiographs. Images were reviewed by two paediatric radiologists and the presence / absence of specified catheters, indwelling tubes and pathology indicated. The results showed excellent agreement between hard copy CR and soft copy images with kappa values ranging from 0.93 to 1.00. The conclusion was that soft copy was suitable for interpretation of neonatal radiographs. A direct comparison of findings cannot be made as Brill et al (1995) used clinical images and the resolution of the monitors used was lower than those used in this study.

Razavi et al (1992) conducted a Receiver Operating Characteristic (ROC) study of chest radiographs in children of all ages comparing hard copy CR to soft copy using (2K x 2K) monitors. Five radiologists with a wide range of experience in neonatal radiology were asked to identify four different pathological processes present on 239 radiographs. Images had been selected to demonstrate a range of conditions found in children. The results of the ROC study demonstrated that for pneumothorax all the radiologists performed equally well on soft copy as hard copy, paired t test ($p=0.20$). For linear atelectasis and interstitial lung disease the results again indicated that all the radiologists performed as well on soft copy as hard copy ($p=0.31$) and ($p=0.48$) respectively. For air bronchograms all five radiologists again demonstrated comparable performance ($p=0.19$).

However both the above articles only compared hard and soft copy CR and did not include SFR. In addition these articles are dated Razavi et al (1992) Brill et al (1996) and CR imaging has improved in terms of better IP and improved resolution of monitors.

Weatherburn & Davies (1999) used a test object to produce images at exposures used in an adult ITU, in order to compare SFR to both hard copy and soft copy CR. For each modality three images were acquired at the same exposure and all images were acquired on the same day. The images were read by four medical physicists and the results for the contrast detail curves were "virtually identical" for all three image types at 1mAs. However for images acquired between 8 and 16mAs the hard copy and soft copy CR images were considered to be better than SFR and for images acquired between 16 and 250mAs the CR images improved greatly compared to SFR, demonstrating the wide latitude of CR.

The findings at 1mAs do not agree with the results of this study where soft copy provided greater information at reduced exposure. However the monitor used to review the images in the study by Weatherburn & Davies (1999) had a resolution of 1.5K x 1K, but in this study the standard monitor had a resolution of 4K x 4K and the mammography monitor 5K x 5K. This difference in resolution could explain the

difference in the findings between these studies, and in addition different viewers will have different levels of visual acuity and experience and this will affect the results.

The human eye can discern a density difference of 0.02 in correct viewing conditions, and this may have contributed to the variation in scores between high contrast and low contrast in this study. The sharpness of the boundry between adjacent areas alters the perception of contrast, where sharper borders will give the appearance of greater contrast than diffuse ones. In addition the ability of the human eye to detect contrast differences is very dependent on the light intensity, for example in normal film viewing conditions a 2% difference in contrast is detectable, but in suboptimal viewing conditions a 20% difference in contrast may be required (Dendy & Heaton 1999).

The findings for inter-viewer reliability showed that for spatial resolution there was a difference between viewers ($p<0.05$) but for contrast there was no difference ($p>0.05$). For spatial resolution, viewer 2 scored higher for the hard copy images and soft copy images on the standard monitior compared to viewers 1 and 3, but that viewer 1 scored higher for the soft copy images on the mammography monitor. The variation in the findings may result from the different environments in which the images were viewed and the personal preference of the viewers. The mammography monitors are in a specially designed room with low ambient lighting and no disruptions. The standard monitors are in an open environment where the ambient lighting is not as low as recommended and there are constant interuptions. The hard copy images were viewed in good ambient light conditions but again there were constant distractions due to the working environment .

The importance of correct viewing conditions has been referred to in a number of articles. Skaane et al (2003) compared SFR for mammography to a full-field digital mammography system. Over a six month period women attending for breast screening were asked to participate in the study, that required them to undergo both conventional and digital mammography. Eight radiologists, all experienced in conventional mammography but with limited experience on digital mammography

reviewed the images. Detection rate for cancer on SFR was 0.76% and for digital it was 0.62%.

A follow up study by Skaane et al (2004) again compared cancer detection rates for SFR and full-field digital mammography. The images of women attending for breast screening over a 12 month period were reviewed by eight radiologists, seven of whom had participated in the original study in 2003. The cancer detection rates for the second study in 2004, were 0.54% for SFR and 0.86% for digital mammography. The authors concluded that the increased experience of the readers and the introduction of a dedictated reading room with improved lighting levels contributed to the improved the results.

Fuchsjäger et al (2003), investigated the impact of ambient lighting on the detectability of catheter fragments superimposed on adult chest radiographs, when using soft copy reading. Monitor display is more susceptible to differences in ambient light conditions compared to viewing boxes, particularly with regard to the reflection of light and a decrease in the displayed contrast ratio. Their results showed that under subdued ambient lighting (<10 lux) the mean detection rate for catheter fragments was higher ($p<0.05$) than that for bright ambient lighting (223 lux).

The results for inter-viewer reliability were then compared to other work to check the validity of the findings. Chotas et al (1997) designed a phantom aimed at replicating an adult chest for the assessment of a CR system. This phantom was constructed from copper, aluminium and acrylic to produce a phantom that mimicked the absorption in different areas of the chest. Also incorporated into the phantom were a contrast detail test object and a spatial resolution test object. 18 images of the phantom were acquired using exposure factors used in the adult ITU and processed using the "portable chest" algorithm. The contrast was assessed only on soft copy, by three radiographers where there was good agreement between observers 1 and 2 but observer 3 "deviated substantially", no statistical analysis was provided. For intra-observer variability the authors reported only a small difference.

The design of the phantom used by Chotas et al (1997) is far more complex than the one used in this study and would not be suitable for all Radiology departments. In addition copper is not a tissue equivalent material and produces beam hardening, also it has different characteristic radiation emission and also reabsorbed scattered photons. However as the authors noted the phantom was not designed to replicate a clinical situation but to provide a means of monitoring deterioration in the CR system as part of a QA programme.

The level of experience in radiology is important in viewing images as was demonstrated with the results of the pilot study where the least experienced viewer scored the poorest. Markus et al (1989) investigated the inter-observer variation in the interpretation of adult abdominal radiographs. 140 images were read by four viewers who were required to identify the pathology present. Agreement was excellent for high density findings such as renal calculi. For more subtle findings such as colitis the agreement was fair to poor. No statistical analysis of the results was done but the authors concluded that the variation was the result of different levels of experience. This highlights the difficulty of inter-viewer studies in radiology as it is difficult to get large numbers of experienced radiologists to participate.

Schaefer et al (1989) conducted a study that compared chest radiographs obtained of 32 patients in an ITU using CR and SFR. To ensure comparable images the imaging plate was loaded into the same cassette as the SFR. As it was behind the film it received a 44% reduced dose. A grid with a number of test objects was placed on the patient below the area of image acquisition, that is below the diaphragm. Nine readers reviewed the images on hard copy, and for four readers there was a statistically significant preference for hard copy CR ($p<0.05$). For the remaining five readers there was no difference in their performance for the two modalities ($p>0.05$). However one major issue with this study was the fact that the test grid was not over the area of clinical interest and therefore difficult to make a true assesment of the clinical implication.

The authors acknowledged that the SFR images were over exposed, and that 17 images were not diagnostic, this gives a good indication of the the wide latitude in

CR, but does raise concerns that unnecessary over exposure can occur when using CR. Seibert et al (1996) reported that six months after the introduction of CR, patient doses for adult mobile chest radiographs had increased. Introduction of a QA programme brought the exposures back to the original level.
From the limited literature published it is apparent that inter rater and intra rater variability in radiology has not been extensively investigated. From the findings available there appears to be consensus that inter-viewer variability does occur as was the case for this study.

5.3 Strengths of Study

5.3.1. *Novel area of research*

A strength of this study is that it aimed to address the lack of research into neonatal chest radiography, particularly work conducted by radiographers. Of the published literature cited in this study the majority, 11, were written by radiologists and four by medical physicists. As a result these articles relate more to measuring radiation dose and not to the acquisition of the images. For radiographers details of exposure factors and technique are of more relevance and are important in determining the final image quality.

Neonatal chest radiography is not a high profile area of radiology and there is a lack of research in this area. This is reflected in the number of publications identified on a Medline search in November 2006, using the combined key words, "neonatal" "chest" "imaging" only 1461articles were identified. Another search using the combined key words "breast" "imaging" resulted in 10440 articles. This is probably a result of the government initiatives directed into the breast screening programme and cancer treatment. In addition neonates form only a small part of the patient population when compared for example to the number of patients who attend for breast imaging.

5.3.2. *Survey into availability of CR*

From the literature only two studies into the availability of CR were identified. The study by Cohen (1992) only surveyed Children's hospitals in the US, and the survey by Bauman & Gell (2000) was world wide. However there has been no surveys conducted into the availability of CR in the UK, particularly those undertaking paediatirc radiology. The results of the survey indicated that CR was frequently introduced into NNU first and that the main reasons for selecting it was image quality and radiation dose. The results provided the direction for the study and identified an area that needed research.

5.3.3. *Phantom design*

The phantoms used in this study are unique in that there was a thicker middle section aimed at representing the higher absorption and scattering expected for the mediastinum. In studies by McPaland et al (1996) and Lowe et al (1999) the authors used a uniformly thick block of TE Perspex. Jones et al (2001) again used a uniform thickness of TE Perspex but created air pockets to represent the lungs. Chotas et al (1997) constructed a complex phantom from copper, aluminium and acrylic but this is not representative of the clinical situation as copper is not a tissue equivalent material.

Another crucial issue of this phantom design was the use of two different thicknesses of phantom to replicate the two weight categories most frequently found in NNU. Previous studies have only used the one thickness relating to 2.5Kg neonate, and have not taken account of lower weight neonates. With the increasing viability of VLBW neonates there is a need for more research in this area. In addition this phantom is inexpensive to construct as TE Perspex is readily available from Bio-medical Physics departments.

5.3.4 *Reproducible methodology*

A benefit of the methodology is the simplicity and reproducibility of it, and that it can be used in any size of Radiology department. It can be used with both static units and mobile units and for assessing any type of image acquisition modality. The materials used are easily accessed, TE Perspex is available from bio-medical Physics departments and the test object used is found in most Radiology departments. For dose measurement it was decided to use a dosemeter as these are simple to use and are avaiable in most Radiology departments. The use of TLDs was not considered as the aim was to produce a methodology that was simple to use and suitable for all sizes of Radiology departments. In addition, as reported by Armpilia et al (2002) TLDs will form an artefact on the image at the exposure factors used in neonatal chest radiography and therefore would not be of value in clinical trials.

Unlike animal studies there is no need for access to an animal research laboratories and the cooperation of an anaethetist. Clinical studies not only have ethical considerations but there is a wide range of variation in appearances of chest radiographs and the presence of pathology makes image interpretation more problematic.

5.3.5. *Use of hard copy and soft copy*

Of the studies cited, Cohen (1991), Broderick et al (1992 & 1993), Hufton et al (1998) and Rapp-Bernhardt (2005) all used hard copy only to assess the image quality, even where soft copy viewing facilities were available. In a study by Brill et al (1996) the images were compared on both hard copy and soft copy CR but not to SFR. This study is the only one into neonatal chest radiography that used both SFR and hard copy CR and soft copy CR. Use of soft copy reading enabled the digital system to be used to its full potential in terms of altering the contrast and use of edge enhancement, which reflects the true clinical situation. In addition this study was the only one that used two different types of monitors. The standard monitor was a LCD monitor and the mammography monitor a CRT. A further strength of this study was the use of half exposure SFR which provided better appreciation of the better image

quality obtained with half exposure CR. In all other studies only full exposure SFR were used.

5.3.6. *Selection of processing algorithms*

It could be argued that it would have been more appropriate to have selected the test algorithm provided by the manufacturer of the plate reader rather than the algorithm for neonatal chest radiography. However the phantom was designed to replicate the density differences found in the neonatal chests. The selection of the neonatal chest algorithm may have affected the appearance of the final images but as all the CR images were processed using the same protocol the impact on the final results was likely to have been negligible.

5.4 Weaknesses of Study

5.4.1 *Sample size*

A larger sample size for image assessment would have improved the statistical power to detect differences and the validity of the results. It would have been better to have acquired three images for each thickness of phantom and test pattern, to rule out the impact of any variation in the output of the x-ray unit.

5.4.2. *No intra-viewer comparison*

As part of the study it would have been of interest to analyse the intra-viewer variability, however, due to unforseen circumstances this was not done. One reason was that the light box used was removed and discarded, and the second problem was that two of the viewers left Norway, therefore no further image asssessment was possible. The results would have been of interest as this is a poorly researched field of radiology.

A medline search in November 2006, using the key words "intra viewer" "reliability" "radiology" elicited no articles. A second search with modified key words "intra rater" "reliability" "radiology" produced 21 results but only one was of relevance to this study. Elmore et al (1994) studied the inter and intra viewer variability between 10 radiologists reading screen film mammograms. The results of paired studies produced a kappa value 0.57. Sources of variability were considered to be due to differences in visual observation. A second source of variability was perceptual differences of the radiologists and how they classified lesions.

5.4.3 *Size of phantoms*

A weakness of the study was that the size of the phantom, 20x20cm was greater than the neonate that it represented. This was necessary in order to image the whole of the test object. However it was not considered to be a major weakness as all the images were acquired under the same conditions. A result of increasing the area irradiated was to increase the dose to the phantom. This confirms the findings of Cook (2001) who stated that "Appropriate collimation is the most important factor for improving image quality whilst also reducing dose..." (Cook 2001:232).

5.4.4.*No account of patient physiology*

The use of a phantom does not mimic the clinical situation as it does not take account of involuntary movements, for example heart beat and respiration, that can affect image quality. However this was not considered a major weakness as in neonatal chest radiography the exposure times used are very short and good radiographic technique can overcome the problem. In addition it is normal practice that neonates are supported in position during radiography therefore limiting voluntary movement.

5.4.5 *Use of static unit*

In general mobile x-ray units are used for image acquisition in NNU. However these units do not provide a stable output at the low exposures used. Static units provide a more constant output and also have a wider range of mAs values compared to mobile

units. For this study it was considered more important to reduce the number of variables involved to provide a base for comparing the images.

5.5 Meaning and Implications

The findings of this study indicate that soft copy images are as good as or better than SFR and hard copy CR, at the same exposure. When the exposure is reduced by half soft copy images are still comparable to full exposure SFR and hard copy CR. This could be of great benefit in the clinical situation, where initial radiographs could be acquired at full exposure and follow up radiographs to check the position of catheters and other support devices, at a reduced exposure. This policy has been advocated by Volk et al (2000) in the follow up of fractures to reduce patient's accumulated dose.

In addition the use of soft copy would enable images to be viewed at any number of locations at the same time. This would make clinical consultations easier and faster, increasing the efficiency of care of the neonate. The use of post processing and workstation tools to enhance the image quality is another benefit of soft copy reporting. Edge enhancement and grey scale reversal could be used to improve identification of pneumothoraces and of catheters, two frequently requested reasons for chest radiography in NNU.

Neonates are the most vulnerable patient group in terms of their susceptibility to the long term effects of radiaition exposure. Therefore a method of comparing the different imaging systems used in neonatal chest radiography that does not require a clinical study is of importance. The methodology described in this work is simple and can be undertaken by radiographers in any size of department without the need for specialist equipment. It can be used with both static and mobile units and both conventional and digital imaging modalities.

Phantom studies provide a good base from which to deveop a clinical study by providing data on the exposure level that produces a diagnostic image. In addition the

phanton can be used as part of a quality assurance programme to monitor changes in the imaging system over time and also to indicate the development of any problems.

5.6 Directions for Future Research

The availability of portable DDR is slowly increasing and it would be of value to assess the imaging characteristics and radiation dose requirements compared to SFR and CR.

It would also be worthwhile to audit the availability of CR in paediatric Radiology departments and to discover what effect the introduction has had in terms of exposure and image quality.

A future study on inter-observer reliability could be conducted using PACS where many experienced radiographers or radiologists could simultaneously review images. This would enable reliability studies to be larger and more meaningful.

It would be of interest to repeat the study but using a phantom that more closely represents the size of a neonate, to ascertain if this affects the spatial resolution and contrast.

Tele-medicine applications of these developments are a possible consequence of the rapidly evolving technology and a large geographical area. Tele-medicine can be defined as the investigation, monitoring and management of a patient regardless of the location of the patient. It enables clinicians to view patients on a video link and to consult with the staff treating the patient providing an expert opinion without physically being present.

In neonatal chest radiography this is an important development as it could allow doctors in remote locations, for example, The Shetland Islands, to treat a neonate without the need to transfer it to the NNU in Aberdeen. This is of particular importance as this patient group is very vulnerable and a transfer over long distances

could compromise their condition and therefore any development in the field of tele-medicine is a major advance in health care.

APPENDIX 1: Imaging Modalities

1.1 Screen Film Radiography (SFR)

In SFR, a light-tight cassette containing a pair of intensifying screens serves as the container for the radiographic film. The intensifying screens convert the x-ray photons into light which then forms the latent image in the film. This image only becomes visible after the film has been developed using an automatic film processor. The nominal speed of SFR systems is an indication of the exposure required to produce a diagnostic image and can range from 50 to 1000. The higher the nominal value, the faster the system, the less radiation required to produce a diagnostic image.

1.1.1. *Advantages of Screen Film Radiography*

SFR has been in use for a long time and is widely accepted in all areas of health care. Cassettes are resilient with a working life of up to 10 years, and three to five years for the intensifying screens, dependent on usage. SFR is a very flexible system enabling patients to be examined either in the Radiology department or on the NNU. There are a wide range of cassette sizes available so the cassette used can be tailored to the area under examination, limiting film wastage. In addition with SFR there is no need for expensive monitors for viewing the images, just simple light viewing boxes.

1.1.2. *Disadvantages of Screen Film Radiography*

SFR has a limited dynamic range and therefore any error in selection of exposure factors can result in an undiagnostic film and the need for a repeat, increasing the dose to the patient. Neonatal chest radiographs require a film/screen combination that has a high contrast and therefore a narrow latitude to visualise the anatomical structures, due to the low inherent contrast. Once a film has been developed it is not possible to alter the image to improve the visualisation of structures.

Intensifying screens are susceptible to damage and any damage will result in artefact formation on the final image each time the cassette is used. Film is also vulnerable to damage during the development process, with faults ranging from a film becoming jammed in the processor and being completely ruined, to scratch marks due to dirt in the processor. Incorrect storage of unexposed film can also result in the final image being undiagnostic due to an increase in the inherent contrast.

Another problem is incorrect identification of a film. Prior to processing the film is stamped with the patient's demographic data, if incorrectly marked it could be associated with the wrong patient. If any error is suspected the patient has to be re-x-rayed, an unnecessary overexposure.

A film is a unique record of an examination and must be carefully archived to avoid it being misplaced. Due to the working practices in Radiology departments a large demand is made on time and resources for film management. By its very nature a film can only be in one place at one time therefore staff need to be in the same place at the same time for consultation, a very time consuming process that is difficult to achieve in a busy hospital, particularly as NNU are frequently some distance for the Radiology department.

1.2 Computed Radiography (CR)

In CR, a cassette similar in appearance to that used for SFR is used but in this case it contains an IP. These IP "... consist of a thin protective layer, the phosphor layer, a reflective layer, support, light shield and backing layers." (Artz 1997:13). The phosphor layer is generally composed of barium fluorohalide crystals doped with Europium ($BaFX:Eu^{2+}$) where X is one of the halide group. Originally bromine was the halide of choice, but the development of new solid state lasers used in the IP readers, has resulted in iodine becoming the halide of choice (Weiser 1997; Cesar 1997 and Huda et al 1997). The $BaFX:Eu^{2+}$ is held in a binder in powder form and as a result diffusion of the light photons occurs resulting in Up, similar to the problems encountered with SFR.

Leblans et al (2000) described a needle imaging plate (NIP), that uses Caesium Bromide doped with Europium ($CsBr:Eu^{2+}$). The advantage of CsBr is that the crystals grow in a needle form allowing a higher density of phosphor packing, and as a result, the DQE has been reported as being 60%. However there are a number of problems with the NIP, in particular a greater number of artefacts are produced. In addition the phosphor crystals are not proving to be resilient and are sustaining damage during the reading process (Personal communication from Arve Sognen, Agfa Sales Manager, Norway).

For CR "The amount of energy stored at any point on the image receptor is directly proportional to the x-ray energy absorbed at that point..." (Weiser 1997:7). After exposure, the cassette is inserted into the plate reader where the IP is unloaded from the cassette and then scanned by laser. As the IP is scanned the stored energy is released in the form of light photons these are then converted to a digital signal by a photomultiplier tube, and an analogue to digital converter (ADC) from this data the final image is constructed. After reading, the IP is flooded with an intense fluorescent light to erase any residual image, then reloaded into the cassette for use again.

To ensure an optimal image, the correct processing algorithms must be applied. These are selected by the radiographer, prior to the plate being read from a series of set-ups provided by the manufacturer. The manufacturer's set-ups can be adapted to suit individual departments requirements. For departments involved in neonatal radiography "The manufacturer's default values need considerable adaptation in a pediatric environment, particularly to cater for very small and preterm infants" (de Silva 1997:57).

The images from the reader are checked on a quality control monitor for correct positioning and annotation. Images can then be post-processed to enhance detail and produce an optimal image. The images can be either printed out using a laser printer - hard copy, or sent to a network and displayed on a monitor- soft copy.

1.2.1 *Advantages of Computed Radiography*

A major advantage of CR is that it "...separates the production of a radiographic image into four separable parts: acquisition, image processing, storage and display" (Freedman & Artz 1997:25). The separation of each stage allows the correct optical density to be attained regardless of the exposure to the IP. In terms of image acquisition it is not necessary to alter existing x-ray equipment as the cassettes used for CR are the same size as those used for SFR.

CR has a much greater exposure latitude than SFR and "Because optical density is established by the software of the CR system, the density will be accurate regardless of the dose delivered to the imaging plate." (Cesar 1997:227). This has resulted in a reduction in retakes required due to incorrect exposure, as reported by number of authors (de Silva 1997; Weatherburn & Davies 1999). However, in neonatal chest radiography repeats are more frequently required for positional errors and therefore the wide latitude is of limited advantage (Arthur & Pease 1992).

Another major advantage of CR is that the image can be post- processed to produce an image of optimal quality. Post processing offers the possibility of changing the appearance of the image by altering the contrast and density. Inversion of the grey scale is helpful in checking line placement and diagnosing small pneumothoraces. This is of particular value in neonatal chest radiography, where the lines are very fine.

A particular advantage of CR that is important to neonatal radiography is that the plate readers can be situated in the NNU saving considerable time for the radiographer as there is no need to return to the department to process films. The reader can be connected to either a laser printer producing hard copy images or to a network for soft copy viewing which gives the clinicians rapid access to the images at their workplace.

Use of a network, as part of a PACS, allows images to be viewed in multiple locations at the same time, a distinct advantage over SFR. As there is no physical object, the

images cannot get lost therefore reducing the number of x-rays repeated because an image is missing.

1.2.2 *Disadvantages of Computed Radiography*

CR does have a number of disadvantages compared to SFR. The IP are expensive and easily damaged, particularly during the reading process. This can result in undiagnostic images due to the appearance of artefacts and therefore any damage means that the IP must be replaced.

Introduction of CR to a department requires a number of changes to existing working practices because "Although based on standard x-ray physics, CR is so different from traditional radiography that it can almost be considered a new modality" (Cesar 1997:231). In the case of radiographic technique it is of greater importance that the area under examination is correctly centred on the IP, if not, the ability of the plate reader to process the image correctly will be compromised (Artz 1997).

As mentioned in Section 1.2.1. CR has a wide exposure latitude therefore reduces retakes due to exposure errors. However this is a "double edged sword"

> "Because the appearance of an image is largely governed by the processing algorithms applied, there is no objective way or the technologist to assess level of exposure accurately if the "S" value is not a true indicator of exposure, with the potential that overexposures caused by poor technique or equipment faults may go undetected" (de Silva 1997: 59).

The "S" value is a numerical value assigned to the image by the plate reader. Individual manufacturers use different terminology and numerical scales to express this value. However, in general the "S" value is an indication of the degree of amplification the system had to apply to produce a diagnostic image. The "S" value is affected by a number of factors, including kVp, mAs, collimation, patient positioning

and any pathology present, as well as the algorithm selected. (Artz 1997; Cesar 1997; Hufton et al 1998 and Weatherburn & Davies 1999).

Another problem with CR is that of quantum noise in the image. The wide exposure latitude can allow exposure factors to be reduced to a point where the level of noise makes the image undiagnostic. This is a particular problem in neonatal radiography where exposure factors are very low (Cohen et al 1991).

A further concern with CR, is the issue of incorrect patient demographic data. This can result in images being lost, that is not recoverable when the correct patient data is used.

1.3 Direct Digital Radiography (DDR)

As implied by the name DDR "...does not use an intervening light stage as in an intensifying screen system (film screen radiography) or photostimulable phosphor (storage phosphor radiography system)" (Goo et al 2000:1016). There are three different systems for image acquisition currently available with the major difference between the systems the method by which the x-ray photons are converted into a digital signal.

1.3.1 *Digital Selenium Radiography (DSR)*

The DSR system (Thoravision, Philips Medical System, Hamburg, Germany) is a dedicated chest unit that came into clinical use in 1993. This is a static unit and is totally unsuitable for neonatal chest radiography.

1.4. Flat Panel Detectors (FPD)

FPD technology developed in the late 1990s when the initial 20x20 cm prototype described by Bury et al (1998) showed great promise. With a DQE approaching 60%, FPD were in theory three times more efficient than SFR or CR. By 1998, manufacturers had developed a 41x41 cm and 43x43 cm detector. These prototypes

again demonstrated a high DQE, with a spatial resolution of 3 lpmm^{-1} (Volk et al 2000). There are two different types of FPD, Direct Conversion and Indirect Conversion and these are discussed in the following sections.

1.4.1 *Direct Conversion*

As described by Chotas et al (1999) and Goo et al (2000), direct conversion systems are based on the use of amorphous selenium (a-Se) as a photoconductor. The photoconductor converts the incident x-ray quanta directly into an electrical charge. This charge is then drawn to a layer of thin film transistors (TFT) arrays, which in turn convert the charge to a digital signal. The digital signal is then displayed on a monitor for quality assurance checks and then sent to a workstation or printed out using a laser printer.The FPD is constructed in layers as shown in Figure 1. The first layer is a glass substrate onto which the TFT array is deposited. On to this a thin layer of a-Se is deposited using evaporation techniques. Finally the whole detector is encased in a protective coating to limit any physical damage (Chotas et al 1999).

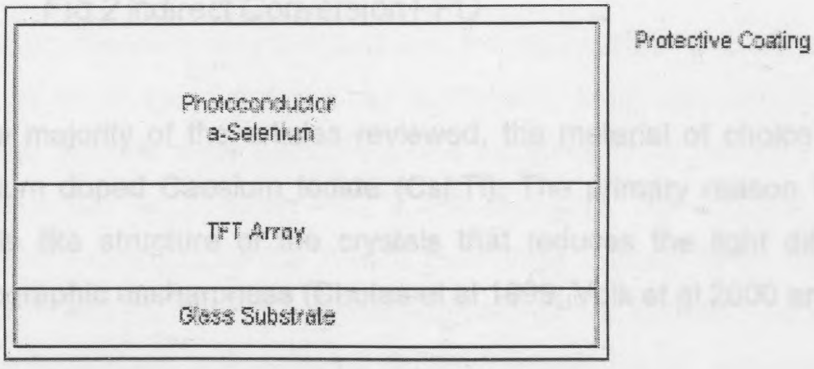


Fig. 1 Direct Conversion FPD

1.4.2 *Indirect Conversion*

The general construction of this FPD is similar to that described above with the TFT array deposited onto a glass substrate. The next layer consists of a layer of amorphous silicon (a-Si) that serves as a photodiode converting light photons into an electrical signal. Onto this layer there is deposited a scintillator material that converts the incident x-ray quanta into light photons. As with the direct conversion FPD there is a protective layer encasing the whole of the FPD to reduce any physical damage, Figure 2 (Volk et al 2000; Chotas & Ravin 2001; Floyd et al 2001).

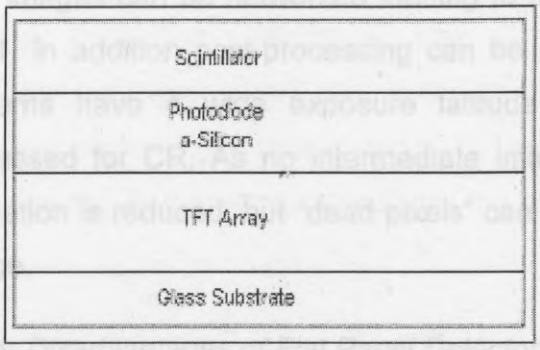


Fig.2 Indirect Conversion FPD

In the majority of the articles reviewed, the material of choice for the scintillator is Thallium doped Caesium Iodide (CsI:Tl). The primary reason for this choice is the needle like structure of the crystals that reduces the light diffusion and therefore photographic unsharpness (Chotas et al 1999; Volk et al 2000 and Floyd et al 2001).

Chotas et al (1999) states that the two types of detectors are not interchangeable and that indirect detectors appear to be the system of choice at present, an opinion reflected in the literature reviewed.

1.4.3 *Advantages of Flat Panel Detectors*

Despite the differences in construction both types of FPD have similar advantages and disadvantages. One of the main advantages is the higher DQE compared to that

for SFR and CR. In the literature a value of 60% is consistently quoted and exceeds the 25% and 20% values for SFR and CR respectively. This value of DQE is similar to that quoted for DSR systems (Bury et al 1998; Chotas et al 1999 and Floyd et al 2001).

The higher the DQE the greater the number of x-ray quanta that will be stopped by the imaging device, therefore the fewer the x-ray quanta required to produce the same density on an image. However, in neonatal chest radiography this can give rise to increased quantum mottle as so few quanta are required to produce the correct density on the image.

The images can be networked leading to the advantages discussed for CR, Section 1.2.1. In addition post-processing can be used to enhance the image quality. FPD systems have a wide exposure latitude with all the attendant advantages as discussed for CR. As no intermediate image recording device is required, artefact formation is reduced, but "dead pixels" can produce either black or white spots on an image.

1.4.4. *Disadvantages of Flat Panel Detectors*

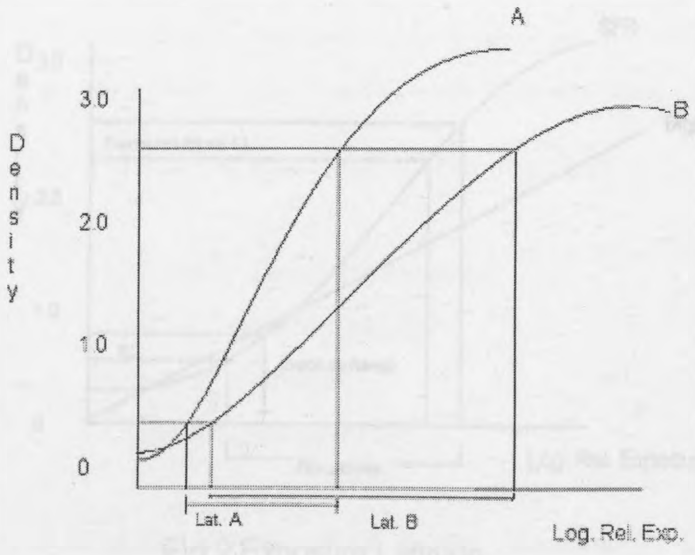
The major disadvantage is the cost of the new system and the need to replace either parts or all of the existing x-ray equipment. Until very recently all the FPD were installed in static x-ray equipment and therefore of no use for neonatal radiography. However, the first portable FPD is now available. The CXDI-31 (Canon Inc. Medical Equipment Group, Tochigi, Japan) resembles a cassette in appearance but uses a 24x30cm indirect conversion FPD. There is also a 35x43cm portable FPD, CXDI-50G (Canon Inc. Medical Equipment Group, Tochigi, Japan) now available. For neonatal chest radiographs, the CXDI-31 is the ideal size and is a very flexible system that can be used both in the department and in the NNU. However no reports have been published of its use in NNU.

APPENDIX 2: Latitude

The latitude of an imaging system is a combination of the film latitude and exposure latitude, and is a factor used to determine the type of film most suitable for a particular x-ray examination. In digital imaging this is referred to as the dynamic range and represents the range of exposures that can be displayed as differences in signal intensity. (Schaefer-Prokop & Prokop 1997).

2.1 Film latitude

Defined as the LRE that will produce a range of densities "...between 0.25-2.5" (Dendy & Heaton 1999:93) as this is the range of densities where information recorded is visible. Each type of film has a different film latitude, determined by the gradient of the characteristic curve. In Figure 1 the gradient of curve B is less than that of curve A, therefore curve B has the wider film latitude.



Film A has a narrow laitude so requires accurate exposure.

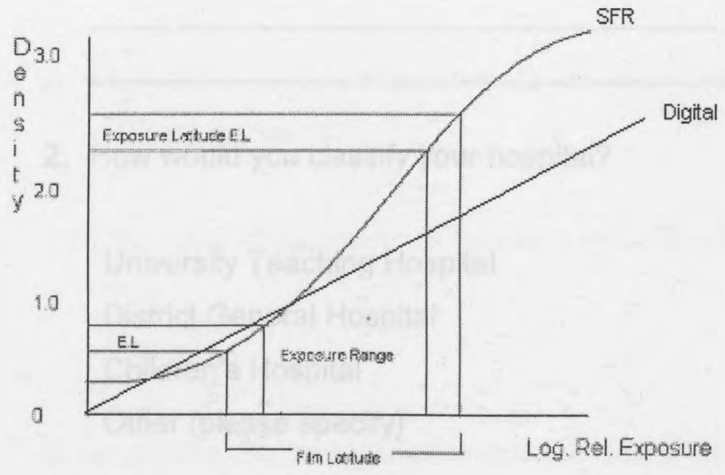
Film B has a wider latitude and so accomodates wider range of exposures

Fig.1 Film Latitude

2.2 Exposure latitude

Exposure latitude is dependent on the kVp selected and the anatomical area under examination. As the mAs is increased the exposure range moves to the right of the origin on the graph. Exposure latitude is obtained by subtracting the exposure range from the film latitude. The greater the exposure range the smaller the exposure latitude and vice versa at the same kVp and imaging the same anatomical area, Figure 2.

One significant difference between SFR and digital imaging systems is the greater exposure latitude of the digital systems. When using digital systems, areas that on SFR would be considered over or under-exposed contribute to the final image. The limiting factor in exposure selection for digital systems is the level of noise acceptable in the image (Cesar 1997).



Exposure latitude is degree of error in exposure that will still result in a diagnostic image.

For digital the exposure latitude is far greater due to the linear shape.

Fig.2 Exposure Latitude

APPENDIX 3: Pilot Questionnaire

A survey of the availability and use of Computed Radiography (CR), in hospitals that provide a paediatric radiology service.

Please answer the following questions by either ticking the appropriate box and/or writing comments in the space provided.

SECTION 1

These questions are designed to provide general information on the hospital and radiology department.

1. Please fill out the name and address of your hospital in the space provided below

   _____

   _____

   _____

   _____

2. How would you classify your hospital?

   University Teaching Hospital ☐
   District General Hospital ☐
   Children's Hospital ☐
   Other (please specify) ☐

3. How many x-ray rooms in your department?

   Less than 5 ☐ 10-14 ☐ 20 or over (specify) ☐
   5-9 ☐ 15-19 ☐

4.Please indicate the number of each of the following modalities in your department and if they are DICOM compliant?

Modality	Number of each	DICOM compliant Y/N
CT		
MRI		
Ulatrsound		
Fluoroscopy		
General		

SECTION 2

This section is looking at staffing levels and departmental workload

5. How many Whole Time Equivalent (WTE) radiographers in your department?

___

6. How many general examinations are performed per annum, to the nearest thousand?

___

7. Does your department undertake paediatric radiography?

Yes ☐

No ☐

If no paediatric work undertaken, I would like to thank you for taking the time to fill out this questionnaire.

8. How many paediatric general examinations are performed per annum to the nearest thousand?

___

9. How many WTE radiographers, if any solely undertake paediatric radiography?

___

10. Does your department have dedicated rooms for paediatric examinations?

Yes (please specify) ☐

No ☐

11. Does your department use Film Screen radiography for paediatrics?

Yes ☐

No (go to section 3) ☐

12. Which Film/screen combination do you use for paediatric work? ___

13. In the table below please indicate the nominal speed class used for the examinations listed, and if Automatic Exposure Control (AEC) is used?

Examination	Nominal speed	AEC Y/N
Skull		
Chest		
Abdomen		
Pelvis		
Extremities		

SECTION 3

This section looks at the availability of CR in paediatric radiography.

Please complete this section only if CR is available, if not, please go to Section 4.

14. When was the CR system installed? ___

15. Is your CR vendor the same as the principal vendor of Film/Screen system?

Yes ☐
No ☐

16. Did the installation of CR take place in

Yes ☐
No ☐

17. Who was the principal decision maker on going over to CR?

Please tick one box only

Hospital Administration ☐
Radiographers ☐
Radiologists ☐
Other Clinical Staff ☐

18. Below are a number of reasons for moving to CR, please rate them as to their importance?

1 being the most important and 6 the least

Financial savings ___
Radiation dose reduction ___
Image quality ___
Increased patient throughput ___
Pressure from extra-departmental sources ___
Building and/or equipping new department ___
Other (please specify) ___

19.Is CR used for all general paediatric radiography?

Yes	☐
No	☐
If No, what percentage of examinations done on CR	☐

20. Please indicate which examinations are not done on CR and why?

_____

21. What type of imaging plates are used in your department?

Rigid	☐
Flexible	☐

22. Please indicate if you have altered the number of cassettes since changing to CR?

More cassettes	☐
Same	☐
Fewer cassettes	☐

23. What percentage of the Imaging Plates are high resolution? ___

24. What appears to be the working life of the Imaging Plates?

12-23 months	☐	48-59 months	☐
24-35 months	☐	Over 60 months	☐
36-47 months	☐	Too early to know	☐

25. Did the paediatric algorithms, as programmed by the vendor, require modification?

Yes	☐
No	☐
If Yes, what modifications	☐

26. Does your department have an integrated RIS/HIS?

Yes	☐
No	☐

27. How are the images displayed for reporting?

Soft copy (go to question 29)	☐
Hard copy	☐
If Hard copy (please specify film format)	☐

28. Are all the acquired images printed?

Yes	☐
No	☐

29. Please indicate specifications of monitors used for reporting?

Specification	☐
Black and white	☐
General purpose colour	☐
1K resolution	☐
2K resolution	☐
Landscape	☐
Portrait	☐

30. What type of archive do you use for digital images? ___

30. If a network is in use, is it

Radiology department only ☐
Limited to certain clinical areas (please specify eg. NNU) ☐
Hospital wide ☐

32. What type of network is it?

10B Ethernet ☐
100B Ethernet ☐
Other (please specify) ☐

SECTION 4

This section is looking at future development

33. Is your department planning to install CR?

Yes ☐
No ☐
If Yes, projected date ☐

34. Are there plans to introduce a PACS?

Yes ☐
No ☐
If Yes, will it be hospital wide? ☐

Thank you for your time and patience

APPENDIX 4: Final Questionnaire

A survey of the availability and use of Computed Radiography (CR), in hospitals that provide a paediatric radiology service.

Please answer the following questions by either ticking the appropriate box and/or writing comments in the space provided.

SECTION 1

These questions are designed to provide general information on the hospital and radiology department.

1. Please fill out the name and address of your hospital in the space below.

   _____
   _____
   _____
   _____

2. How would you classify your hospital?

NHS University Teaching Hospital	☐
NHS District General Hospital	☐
NHS Children's Hospital	☐
NHS Other (please specify)	☐

3. How many general X-ray rooms does your department have?

Less than 5	☐	15-19	☐
5-9	☐	Over 20 (please specify)	☐
10-14	☐		

4. Does your department carry out paediatric radiography?

Yes	☐
No	☐

If no paediatric radiography is undertaken in your department, thank you for completing this questionnaire. Please return using the SAE enclosed.

SECTION 2

This section is aimed at ascertaining your department protocols for paediatric radiography.

5. How many general examinations are performed per annum? ___

6. How many radiographers, if any, solely undertake paediatric radiography?

   Please specify number ___

7. Does your department have any dedicated x-rooms for paediatrics radiography?

   Yes (please specify) ☐
   No ☐

8. Does your department use film-screen radiography and /or computed radiography for paediatric work?

   Film screen radiography ☐
   CR ☐
   Both ☐

9. What film-screen combinations are used for paediatric radiography?

   Please specify ___

10. In the table below, please indicate the nominal speed of film-screen combination used for the examinations listed and if AECs are used?

Anatomical area	Nominal speed	AEC Y/N
Skull		
Chest		
Abdomen		
Pelvis		
Extremities		

SECTION 3

Only complete this section if CR is available in your department.

11. When was the CR system installed?

Please specify _____

12. Is the CR vendor the same as that supplying other radiographic equipment?

Yes (please specify) ☐
No ☐

13. How did the transition take place?

Stages ☐
In one step ☐
If stages please specify time scale ☐

14. Which of the following groups provided the main impetus for the transition to CR?

Please tick one box only.

Hospital Administration ☐
Radiographers ☐
Radiologists ☐
Other medical staff (eg NNU) ☐

15. Below are a number of reasons for moving to CR. Please rate them as to their importance to your decision to opt for CR?

1 being the most important and 6 the least

Financial savings ☐
Radiation dose reduction ☐
Image quality ☐
Increased patient throughput ☐
Building and/or equipping new department ☐
Other (please sprecify) ☐

16. Is CR used for all general paediatric radiography?

Yes ☐
No ☐
If No, what percentage of examinations done on CR ☐

17. What examinations are not done on CR? ___

18. What type of imaging plate does your department use?

Rigid ☐
Flexible ☐

19. Please indicate if the number of cassettes has altered with the introduction of CR?

More cassettes ☐
Same ☐
Fewer cassettes ☐

20. What percentage of the imaging plates are high resolution plates? ___

21. What is the working life of the imaging plates?

12-23 months ☐
24-35 months ☐
36-47 months ☐
48-59 months ☐
Over 60 months ☐
Too early to know ☐

22. Did the vendor's default algorithms for paediatrics require modification?

Yes	☐
No	☐
If Yes, what modifications	☐

23. What type of archive does your department have?

Short term	☐
Long term	☐

If you would be willing to possibly answer a further questionnaire at a late date please indicate below.

Yes	☐
No	☐

Thank you for your time and patience in completing this questionnaire.

Please return the questionnaire in the SAE provided.

APPENDIX 5: Cover Letter

In-Patient X-Ray Department,
Aberdeen Royal Infirmary,
Foresterhill,
Aberdeen

1st December 2000

Dear Superintendent,

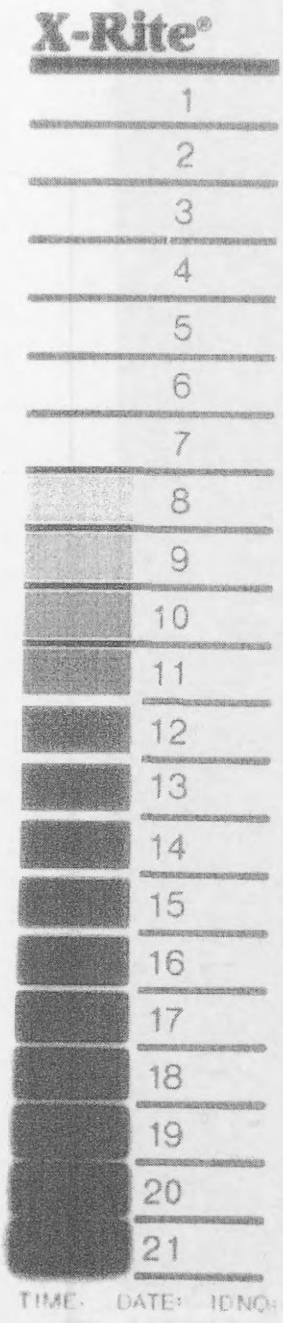
I am a Senior Radiographer at Aberdeen Royal Infirmary, currently working towards gaining an MPhil in Radiography. As part of my research I am interested in the availability of CR in hospitals doing paediatric radiography. I would therefore be grateful if you could take the time to fill out the enclosed questionnaire and to return it in the SAE provided.

Thank you for your help.

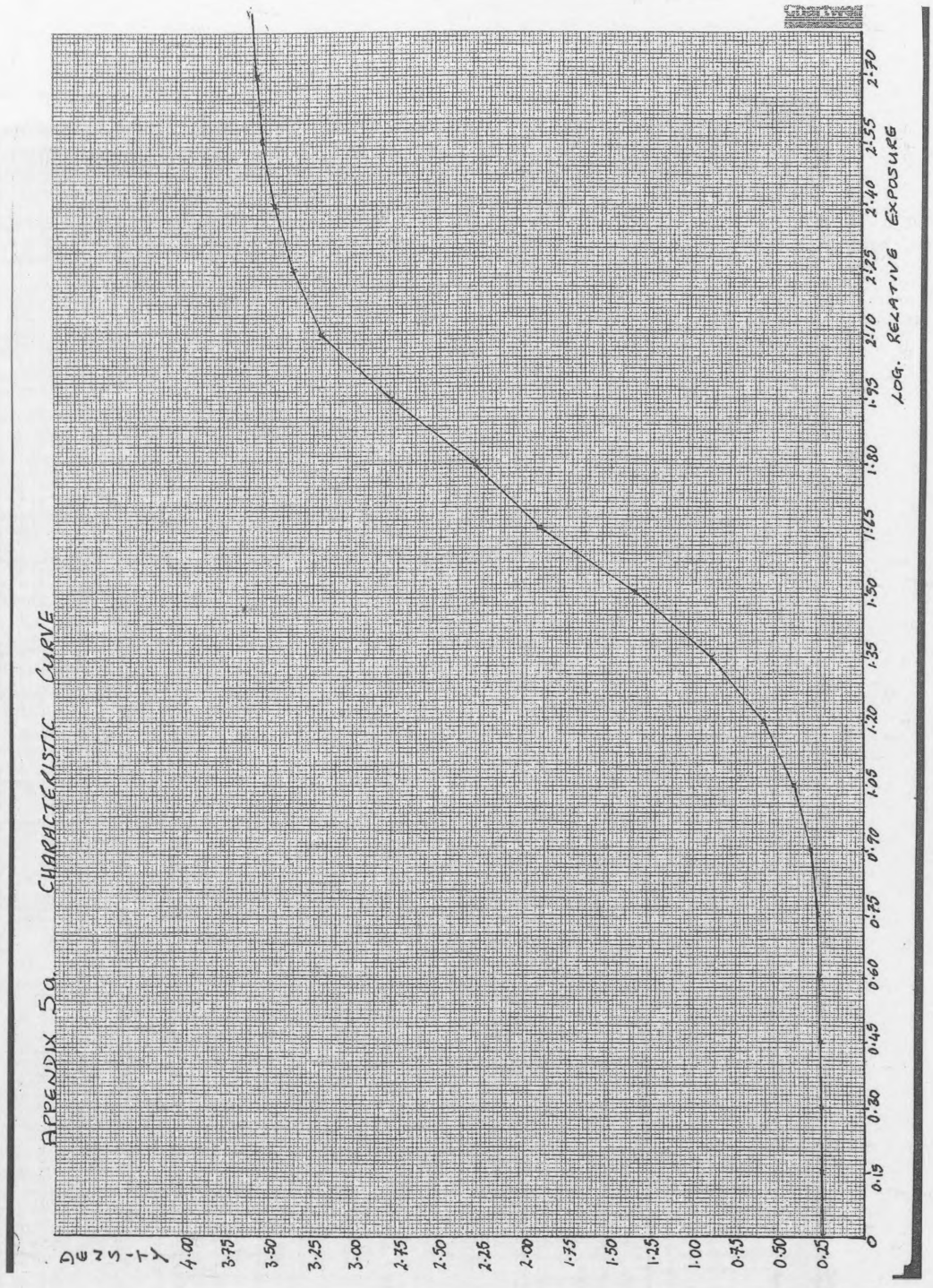
Yours sincerely

Katrina E Borthwick

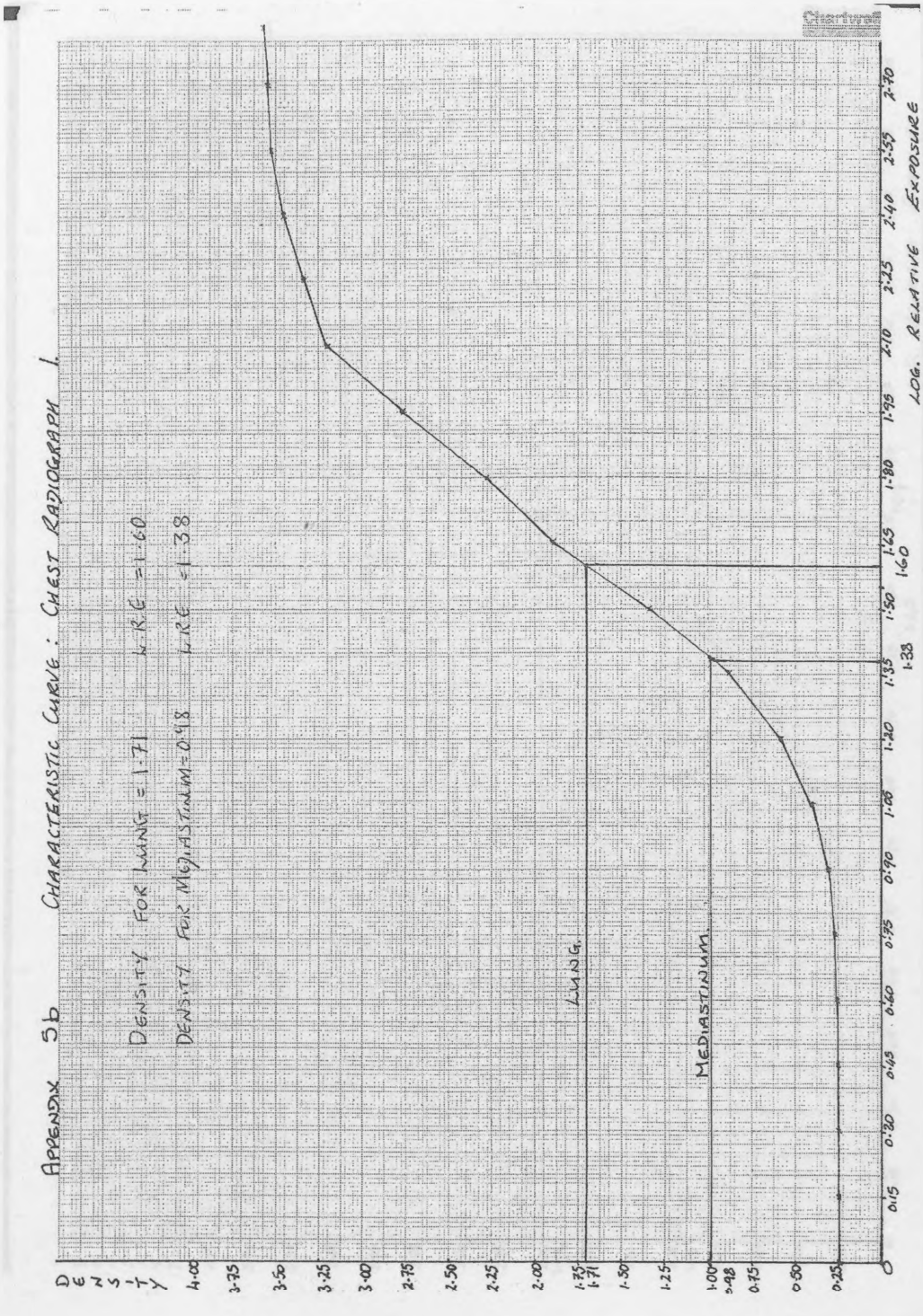
APPENDIX 6: Image of sensitometric strip



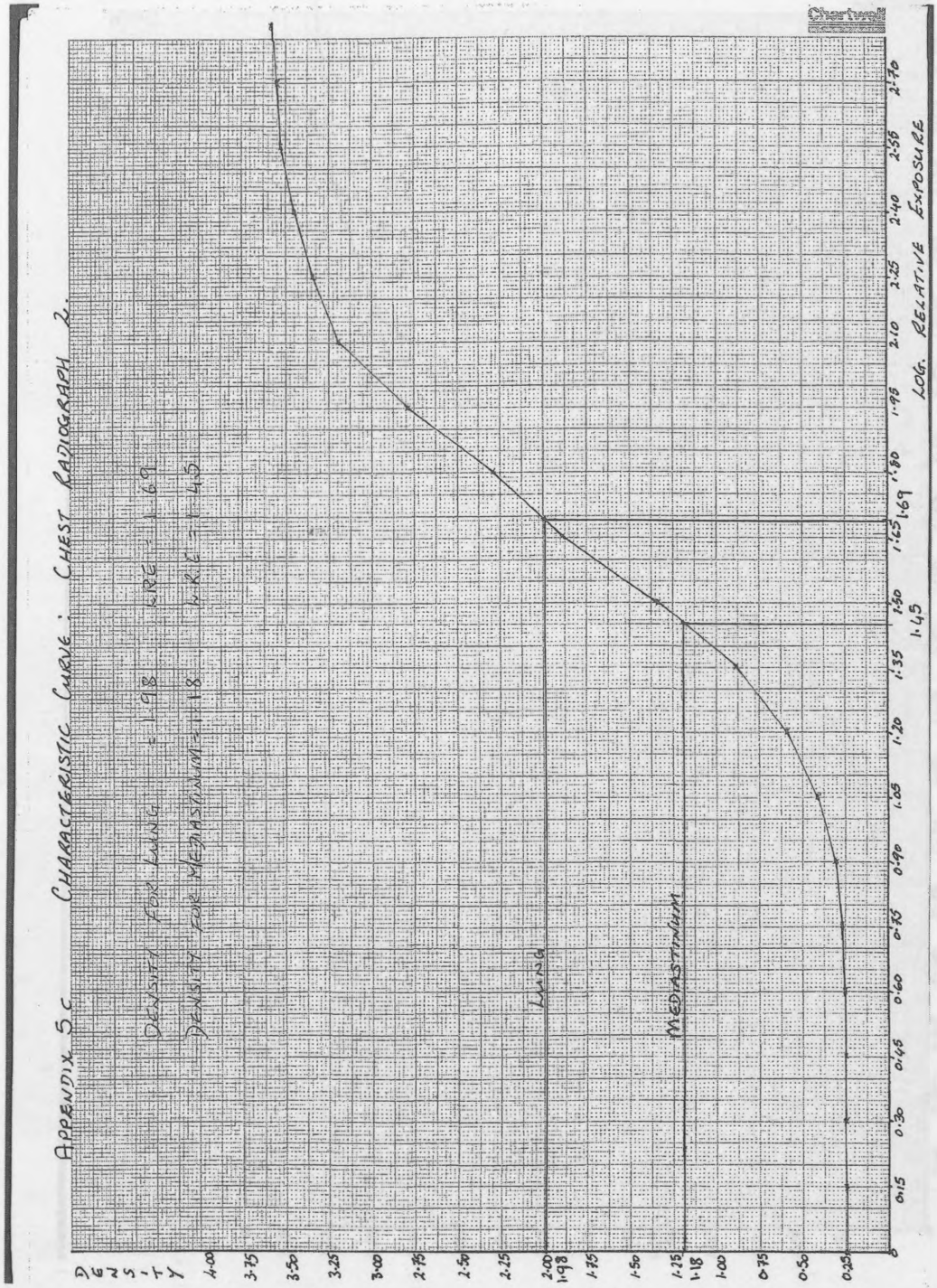
APPENDIX 7a: Characteristic curve



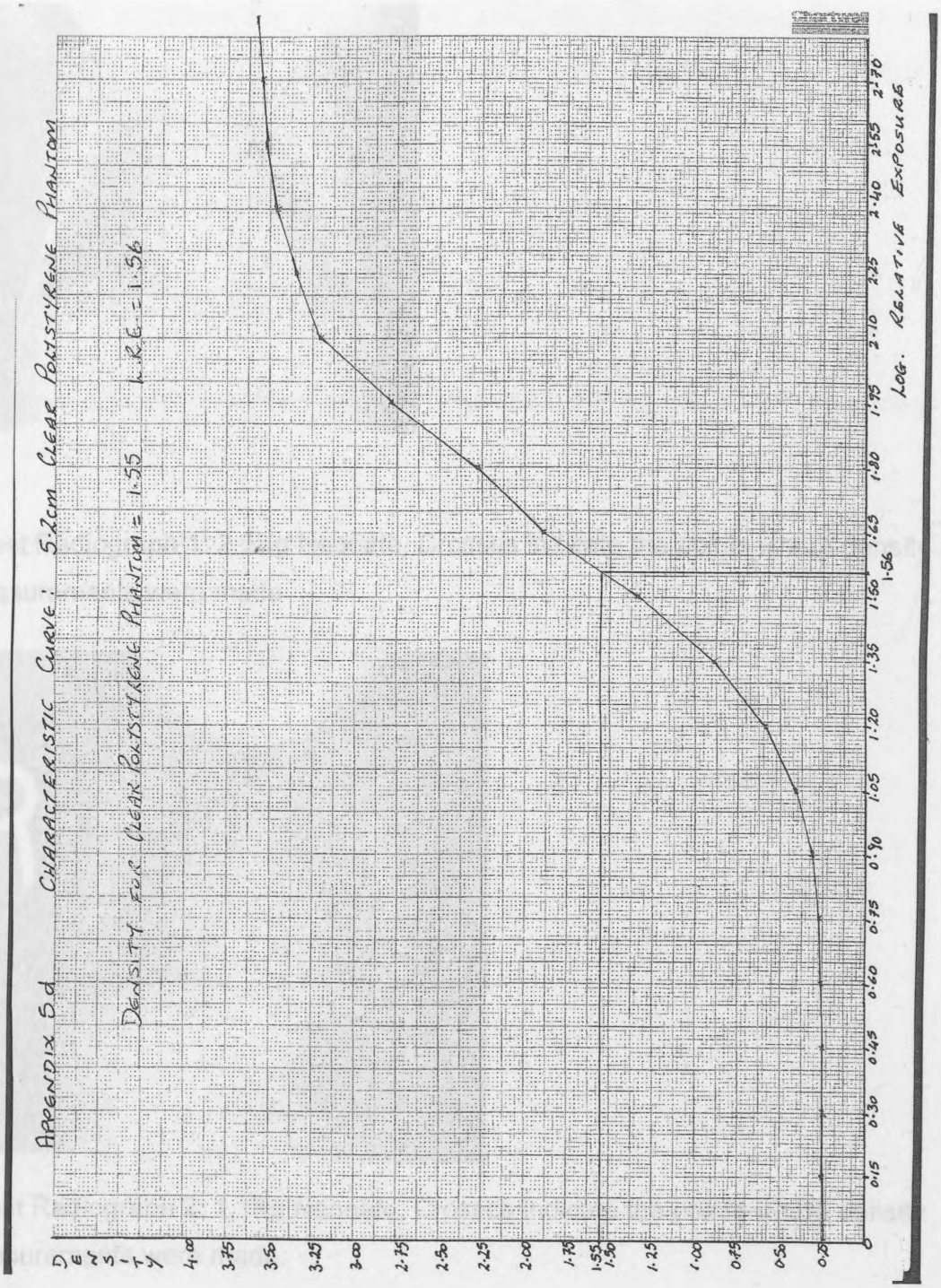
APPENDIX 7b:Characteristic curve: Chest radiograph 1



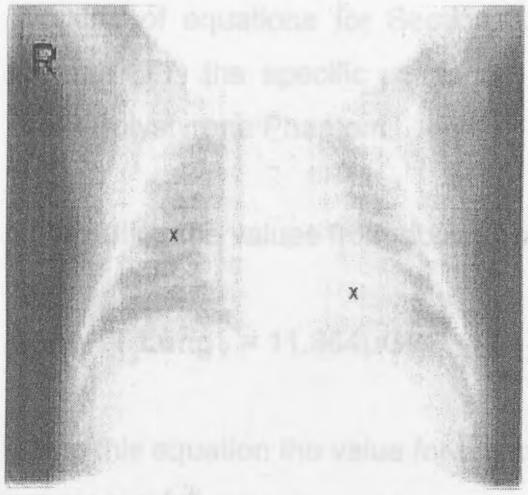
APPENDIX 7c:Characteristic curve: Chest radiograph 2



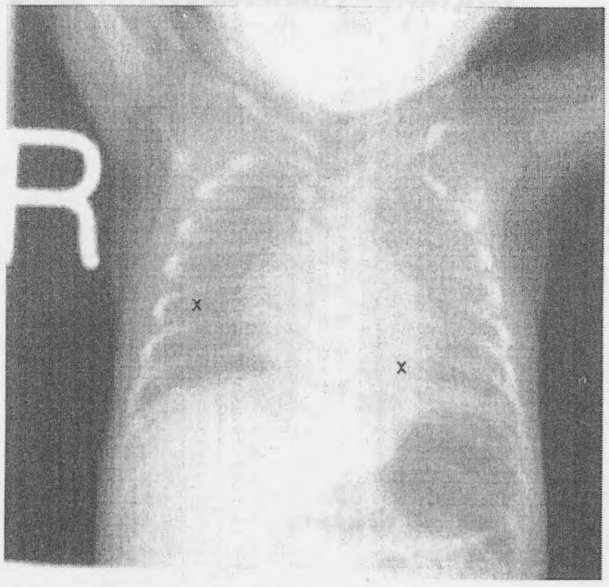
APPENDIX 7d: 5.2cm Clear Polystyrene Phantom



APPENDIX 8: Images of Chest Radiographs



Chest Radiograph 1: 2.5Kg Neonate, Crosses indicate the points where density measurements were made



Chest Radiograph 2: 1.1Kg Neonate, Crosses indicate the points where density measurements were made.

APPENDIX 9: Calculations from Chapter 3

Working of equations for Section 3.10, calculating the radiation dose transmitted through (TT) the specific points on neonatal chest radiograph 2, using the 5.2cm Clear Polystyrene Phantom.

Substituting the values from above gives the following

Dose TT Lung $_2$ = 11.864µGy

Using this equation the value for the mediastinum can be calculated in the same manner as follows:

Substituting the values from above gives the following

Dose TT Mediastinum $_2$ = 6.827µGy

APPENDIX 10: Illustration of TOR (CDR) Test Object

(Courtesy of Leeds Test Objects Ltd. Boroughbridge, UK)

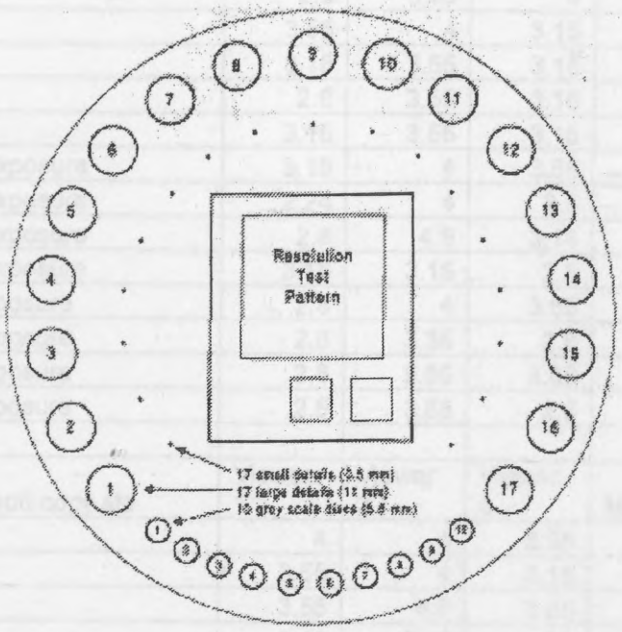


Figure 1: Layout of test details (not to scale)

APPENDIX 11: Results tables

Spatial resolution hard copy					
Image	Viewer 1	Viewer 2	Viewer 3	Mean	SD
2.0cm SFR	3.55	4	4	3.85	0.21
4.2cm SFR	3.15	3.55	3.55	3.42	0.19
3.0cm SFR	3.15	4	4	3.71	0.4
5.2cm SFR	2.8	3.55	4	3.45	0.49
2.0cm CR	3.55	4	3.15	3.57	0.35
4.2cm CR	3.15	3.55	3.15	3.28	0.19
3.0cm CR	2.8	3.55	3.15	3.17	0.3
5.2cm CR	3.15	3.55	3.15	3.28	0.19
2.0cm SFR Half Exposure	3.15	4	3.55	3.57	0.35
4.2cm SFR Half Exposure	2.24	4	2.5	2.91	0.77
3.0cm SFR Half Exposure	2.8	4.5	3.15	3.48	0.73
5.2cm SFR Half Exposure	3.15	3.15	2.5	2.93	0.3
2.0cm CR Half Exposure	2.8	4	3.55	3.45	0.5
4.2cm CR Half Exposure	2.8	3.55	2.8	3.05	0.35
3.0cm CR Half Exposure	2.8	3.55	3.55	3.3	0.35
5.2cm CR Half Exposure	2.5	3.55	2.8	2.95	0.44
Spatial resolution soft copy std	Viewer 1	Viewer 2	Viewer 3	Mean	SD
2.0cm CR	4	4	3.55	3.85	0.21
4.2cm CR	3.55	4	3.15	3.57	0.35
3.0cm CR	3.55	4.5	3.55	3.87	0.45
5.2cm CR	3.15	3.15	2.8	3.03	0.16
2.0cm CR Half Exposure	3.55	4.5	3.55	3.87	0.45
4.2cm CR Half Exposure	3.15	4	3.15	3.43	0.4
3.0cm CR Half Exposure	3.55	4.5	3.15	3.73	0.57
5.2cm CR Half Exposure	3.55	4	2.8	3.45	0.49
Spatial resolution soft copy mammo	Viewer 1	Viewer 2	Viewer 3	Mean	SD
2.0cm CR	4.5	3.15	3.55	3.73	0.57
4.2cm CR	4	3.55	3.55	3.7	0.21
3.0cm CR	4.5	3.55	3.55	3.86	0.48
5.2cm CR	3.55	2.5	3.15	3.07	0.43
2.0cm CR Half Exposure	4	3.15	3.55	3.57	0.35
4.2cm CR Half Exposure	4	2.8	3.15	3.32	0.5
3.0cm CR Half Exposure	4	3.15	3.15	3.43	0.4
5.2cm CR Half Exposure	3.15	4	3.15	3.43	0.4

High Contrast hard copy					
Image	Viewer 1	Viewer 2	Viewer 3	Median	SD
2.0cm SFR	16	17	16	16	0.5
4.2cm SFR	14	16	16	16	1
3.0cm SFR	15	14	15	15	0.5
5.2cm SFR	16	16	16	16	0
2.0cm CR	16	17	17	17	0.5
4.2cm CR	15	15	15	15	0
3.0cm CR	15	17	16	16	0.816497
5.2cm CR	15	15	15	15	0
2.0cm SFR Half Exposure	16	17	16	16	0.5
4.2cm SFR Half Exposure	12	14	14	14	0.5
3.0cm SFR Half Exposure	15	15	15	15	0
5.2cm SFR Half Exposure	12	13	13	13	0.5
2.0cm CR Half Exposure	16	17	16	16	0.5
4.2cm CR Half Exposure	14	15	15	15	0.5
3.0cm CR Half Exposure	16	17	16	16	0.5
5.2cm CR Half Exposure	12	13	14	13	0.816497
High Contrast soft copy std	Viewer 1	Viewer 2	Viewer 3	Median	SD
2.0cm CR	17	17	16	17	0.5
4.2cm CR	12	16	15	15	1.732051
3.0cm CR	15	17	16	16	0.816497
5.2cm CR	11	14	14	14	1.5
2.0cm CR Half Exposure	15	17	16	16	0.816497
4.2cm CR Half Exposure	13	15	15	15	1
3.0cm CR Half Exposure	15	16	16	16	0.5
5.2cm CR Half Exposure	12	12	13	12	0.5
High Contrast soft copy mammo	Viewer 1	Viewer 2	Viewer 3	Median	SD
2.0cm CR	15	17	17	17	1
4.2cm CR	15	16	16	16	0.5
3.0cm CR	15	17	17	17	1
5.2cm CR	14	15	15	15	0.5
2.0cm CR Half Exposure	16	17	16	16	0.5
4.2cm CR Half Exposure	14	15	15	15	0.5
3.0cm CR Half Exposure	15	16	16	16	0.5
5.2cm CR Half Exposure	12	12	15	12	1.5

Low Contrast hard copy					
Image	Viewer 1	Viewer 2	Viewer 3	Median	SD
2.0cm SFR	14	14	15	14	0.5
4.2cm SFR	14	14	15	14	0.5
3.0cm SFR	14	14	15	14	0.5
5.2cm SFR	14	13	14	14	0.5
2.0cm CR	16	16	16	16	0
4.2cm CR	15	14	15	15	0.5
3.0cm CR	16	16	16	16	0
5.2cm CR	14	12	14	14	1
2.0cm SFR Half Exposure	15	15	15	15	0
4.2cm SFR Half Exposure	12	13	13	13	0.5
3.0cm SFR Half Exposure	12	14	14	14	1
5.2cm SFR Half Exposure	12	12	12	12	0
2.0cm CR Half Exposure	15	16	16	16	0.5
4.2cm CR Half Exposure	14	14	15	14	0.5
3.0cm CR Half Exposure	16	15	15	15	0.5
5.2cm CR Half Exposure	13	12	14	13	0.816497
Low Contrast soft copy std	Viewer 1	Viewer 2	Viewer 3	Median	SD
2.0cm CR	17	16	16	16	0.5
4.2cm CR	12	14	14	14	1
3.0cm CR	15	16	16	16	0.5
5.2cm CR	12	12	14	12	1
2.0cm CR Half Exposure	15	17	15	15	1
4.2cm CR Half Exposure	13	14	15	14	0.816497
3.0cm CR Half Exposure	16	15	15	15	0.5
5.2cm CR Half Exposure	13	13	14	13	0.5
Low Contrast soft copy mammo	Viewer 1	Viewer 2	Viewer 3	Median	SD
2.0cm CR	16	16	16	16	0
4.2cm CR	12	15	15	15	0.5
3.0cm CR	16	16	16	16	0
5.2cm CR	12	12	14	12	1
2.0cm CR Half Exposure	13	16	16	16	1.5
4.2cm CR Half Exposure	13	14	14	14	0.5
3.0cm CR Half Exposure	15	15	15	15	0
5.2cm CR Half Exposure	13	13	14	13	0.5

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