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Optimisation of the Digital Radiographic Imaging of Suspected Non-Accidental Injury

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A thesis submitted to the University of London
For the Degree of Doctor of Philosophy
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Abstract

Aim: To optimise the digital (radiographic) imaging of children presenting with suspected non-accidental injury (NAI).

Objectives: (i) To evaluate existing radiographic quality criteria, and to develop a more suitable system if these are found to be inapplicable to skeletal surveys obtained in suspected NAI. (ii) To document differences in image quality between conventional film-screen and the recently installed Fuji5000R computed radiography (CR) system at Great Ormond Street Hospital for Children. (iii) To document the extent of variability in the standard of skeletal surveys obtained in the UK for suspected NAI. (iv) To determine those radiographic parameters which yield the highest diagnostic accuracy, while still maintaining acceptable radiation dose to the child. (v) To determine how varying degrees of edge-enhancement affect diagnostic accuracy. (vi) To establish the accuracy of soft compared to hard copy interpretation of images in suspected NAI.

Materials and Methods: (i) and (ii) Retrospective analysis of 286 paediatric lateral spine radiographs by two observers based on the Commission of European Communities (CEC) quality criteria. (iii) Review of the skeletal surveys of 50 consecutive infants referred from hospitals throughout the United Kingdom (UK) with suspected NAI. (iv) Phantom studies. Leeds TO.10 and TO.16 test objects were used to compare the relationship between film density, exposure parameters and visualisation of object details. (iv) Clinical study. Anteroposterior and lateral post mortem skull radiographs of six consecutive infants were obtained at various exposures. Six observers independently scored the images based on visualisation of five criteria. (v) and (vi) A study of diagnostic accuracy in which six observers independently interpreted 50 radiographs from printed copies (with varying degrees of edge-enhancement) and from a monitor.

Results: The CEC criteria are useful for optimisation of imaging parameters and allow the detection of differences in quality of film-screen and digital images. There is much variability in the quality and number of radiographs performed as part of skeletal surveys in the UK for suspected NAI. The Leeds test objects are either not sensitive enough (TO.10) or perhaps over sensitive (TO.16) for the purposes of this project. Furthermore, the minimum spatial resolution required for digital imaging in NAI has not been established. Therefore the objective interpretation of phantom studies is difficult. There is scope for reduction of radiation dose to children with no effect on image quality. Diagnostic accuracy (fracture detection) in suspected NAI is generally low, and is not affected by image display modality.

Conclusions: The CEC quality criteria are not applicable to the assessment of clinical image quality. A national protocol for skeletal surveys in NAI is required. Dedicated training, close supervision, collaboration and consistent exposure of radiologists to cases of NAI should improve diagnostic accuracy. The potential exists for dose reduction when performing skeletal surveys in children and infants with suspected NAI. Future studies should address this issue.

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Dedication

To my family.

My husband – Edward. Our children – Golibe and Luka;
For their love. For keeping my head up in the clouds.

My brothers and sisters – Obi, Enuma, Nkechi, Kushey and Chike;
For their humour. For keeping my feet firmly on the ground.

My mother – Gladys, and in memory of my Father – Ernest “Ati” Mbamali;
For teaching me that, “A job worth doing, is worth doing well.” I try.

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List of Abbreviations

A	Detail area (Leeds test objects)
ACR	American College of Radiology
Al	Aluminium
ALARA	As low as reasonably achievable
ANOVA	Analysis of variance
AP	Anteroposterior
A_z	Area under the receiver operating characteristic (ROC) curve
BIB	Bibliography
BSPR	British Society of Paediatric Radiology
CCJ	Costochondral junction
CEC	Commission of European Communities
CML	Classical metaphyseal lesion
CPR	Child protection register
CPR*	Cardiopulmonary resuscitation
CR	Computed radiography
CT	Computed tomography
C_T	Minimum contrast required for detail detection (Leeds test objects)
Cu	Copper
CVJ	Costovertebral junction
DP	Dorsoplantar
DQE	Detector/Detective quantum efficiency
DR	Digital radiographs
FNF	False negative fraction
FPF	False positive fraction
FRCR	Fellow of the Royal College of Radiology
FRM	Fixed read mode
FS	Film-screen
GOSH	Great Ormond Street Hospital for Children, London, United Kingdom
HR	High resolution
H_T	Detection index (Leeds test objects)
HTA	Health technology assessment

List of Abbreviations

ICH	Institute of Child Health
ID	Identification
IP	Imaging plate
ICS	Image criteria score
KV(p)	Kilovoltage (peak)
Lat	Lateral
lp/mm	Line pairs/mm
LUT	Look up table
mAs	Milliampere second
MRI	Magnetic resonance imaging
MTF	Modulation transfer function
NAI	Non-accidental injury
NEQ	Noise equivalent quanta
NRPB	National Radiological Protection Board
OI	Osteogenesis imperfecta
PACS	Picture archiving and communications system
PMT	Photomultiplier tube
QoL	Quality of life
RCR	Royal College of Radiologists
ROC	Receiver operating characteristic
RSNA	Radiological Society of North America
S	Sensitivity value (Fuji Ltd)
S-ARM	Semi-auto read mode
SNR	Signal to noise ratio
SPNBF	Subperiosteal new bone formation
TCDD	Threshold contrast detail detectability
TNF	True negative fraction
TPF	True positive fraction
UK	United Kingdom
UKRC	United Kingdom Radiological Congress
US	Ultrasound
USA	United States of America
VGAS	Visual grading analysis score
WS	Wiener spectrum

Dissemination of Results

Publications

- *Diagnostic accuracy of fracture detection in suspected non-accidental injury: Effect of edge-enhancement and digital display on observer performance*
Offiah AC, Moon L, Hall CM, Todd-Pokropek A
Accepted Clinical Radiology August 2005
- *Optimal exposure parameters for digital radiography of the infant skull: A pilot study*
Offiah AC, Grehan J, Hall CM, Todd-Pokropek A
Accepted Clinical Radiology July 2005
- *Observational study of skeletal surveys in suspected non-accidental injury*
Offiah AC, Hall CM Clin Radiol 2003;58:702 – 705
- *Evaluation of the Commission of European Communities quality criteria for the paediatric lateral spine*
Offiah AC, Hall CM Br J Radiol 2003;76:885 – 890

Oral Presentations

- *Safety issues in digital imaging in paediatric work*
UKRC, Manchester, June 2005
- *Digital imaging in NAI: A ROC study*
RSNA Annual Conference, Chicago, December 2004
- *Digital image display in NAI: A ROC study*
BSPR Annual Conference, Leicester, November 2004
- *Optimal exposure parameters for digital radiography of the infant skull: A pilot study*
BSPR Annual Conference, Leicester, November 2004
- *Optimisation of image quality in NAI*
ICH / GOSH Grand Round, March 2003
- *The sensitivity value "S" is an insensitive measure of digital image quality*
RSNA Annual Conference, Chicago, December 2002

Section A – Literature Review

- *Variability in quality of NAI imaging in the UK*
BSPR Annual Conference, Sheffield, November 2002
- *Evaluation of the CEC criteria for paediatric lateral spine radiographs*
ESPR Annual Conference, Bergen, June 2002
- *Image quality, the CEC and “S”*
North Thames (East) Academic Meeting, London, March 2002

Poster Presentations

- *Image quality of film-screen Vs digital radiographs*
RCR Annual Conference, London, September 2002
- *Image quality, the CEC and “S”*
UKRC Radiological Conference, Birmingham, June 2002

Section A

Literature Review

Chapter 1

Introduction and rationale for the research

The vast majority of studies performed to assess the quality of images obtained using computed radiographic techniques have concentrated on chest imaging. Of those in which the musculoskeletal system has been studied, only a very few have touched on images obtained for the diagnosis of non-accidental injury (NAI).

Studies on the musculoskeletal system have compared images obtained with digital against those obtained with conventional film-screen techniques using fixed radiographic parameters (kVp, mAs). The few studies in which radiographic parameters were altered have been performed on phantoms due to the restrictions imposed by the need to limit radiation dose in children (and adults).

Anecdotal evidence exists supporting the view that computed radiography (CR) does not produce images of sufficiently high quality for the diagnosis of NAI. However this has not prevented paediatric departments (including the radiology department at Great Ormond Street Hospital for Children) from installing digital systems.

The aim of this study is to optimise CR imaging of suspected NAI such that images of the highest quality are produced and displayed to maximum diagnostic effect.

A study on human subjects concentrating on the digital imaging of NAI has not previously been performed.

1.1 Child Abuse

Ambroise Tardieu, a physician in France is credited with the first description of the manifestations of inflicted injury in children [SILV1972]. This description was presented in 1860, 35 years before the discovery of x-rays by Wilhelm Conrad Roentgen, and was based on pathological findings. John Caffey in 1946 gave the first radiological description [CAFF1946]. In this seminal paper, Caffey noted the association of multiple long bone fractures in infants with chronic subdural haematoma. Although there has since been much work in this field, there is still no universal definition of the term child abuse. This is largely due to the differences in acceptable levels of parental (carer) control and discipline amongst various communities [MAIT1996], and within the same community with the passage of time. In the past, no clear distinction was made between the different forms of abuse, thus the following quotation attributed to Henry Kempe

“Child abuse is the difference between a hand on the bottom and a fist in the face.” [SPEI1989]

Although graphic, this definition does not reflect the existence of the non-physical forms of abuse, namely emotional abuse and neglect. These days the definition has been broadened to take cognisance of the varying ways child abuse may manifest. In America, the Child Abuse Prevention and Treatment Act states

“Child abuse and neglect means the physical or mental injury, sexual abuse, negligent treatment, or maltreatment of a child under the age of 18 by a person who is responsible for the child’s welfare under circumstances which indicate the child’s health or welfare is harmed or threatened thereby”. [RICH2000]

There are four major types of abuse: neglect, physical abuse, sexual abuse and emotional abuse. The breakdown of children and young people (in England) on the child protection register (CPR) by age, gender and category of abuse for the years ending 31 March 2000 to 2004 [DOH2005] is shown in *Table 1.1-1* (next page).

Table 1.1-1: Registrations¹ to child protection registers during the years ending 31 March 2000 to 2004, by category of abuse [DOH2005]

England	numbers and percentages									
Category of abuse	numbers ¹					percentages				
	2000	2001	2002	2003	2004	2000	2001	2002	2003	2004
Neglect ²	12,900	12,400	10,800	11,700	12,600	44	46	39	39	41
Physical abuse ²	9,500	8,000	5,300	5,700	5,700	32	30	19	19	19
Sexual abuse ²	5,100	4,300	2,800	3,000	2,800	17	16	10	10	9
Emotional abuse	4,800	4,600	4,700	5,400	5,600	17	17	17	18	18
Categories not recommended by 'Working Together' ³	310	420	.	.	.	1	2	.	.	.
No category available (transfer pending conferencing) ³	320	180	.	.	.	1	1	.	.	.
Mixed / not recommended by 'Working Together' ⁴	.	.	4,100	4,400	4,300	.	.	15	15	14

NOTES

- 1 Where a child was registered more than once in the year, each registration has been counted. Registrations include unborn children.
- 2 These three main categories also featured in the 'mixed' categories from 1998 to 2001 only. This table incorporates these 'mixed' categories with the main categories in order to show the total numbers of children for whom each category of abuse was cited on the register. The total of the percentages will exceed 100 for these years because children in the "mixed" categories are counted more than once.
- 3 These categories were discontinued from 1 April 2001.
- 4 This category was introduced from 1 April 2001.

The diagnosis of child abuse is a difficult one; thus the subtlest forms, neglect and emotional abuse, together constitute about 60% of cases. It is likely that the incidence of emotional abuse is underestimated. In the absence of physical signs, it is often very difficult to prove a case of sexual abuse, particularly in the younger child or infant who has not yet begun to speak. The presence of physical abuse on the other hand is more easily established, and furthermore can be permanently documented by means of clinical photographs, x-rays, ultrasound, computed tomography (CT) and magnetic resonance imaging (MRI). It is with this, the most diagnostically concrete form of child abuse that the radiologist deals, and when the radiologist has confirmed the presence of physical injury, he/she must then attempt to establish if the injuries were sustained through accidental or non-accidental mechanisms in order to make a diagnosis of physical abuse i.e. non-accidental injury.

1.2 *Diagnosis of Non-Accidental Injury*

Infants and young children are said to be the most vulnerable in terms of fatal injuries as a result of abuse – 90% of child abuse and neglect fatalities are less than five years old, and 41% less than a year old [MCCL1993]. Although rarely lethal themselves, it has been said that most infants who die following abuse have associated skeletal injuries, usually in the healing phase at the time of their death [KLE1995A]. Severe skeletal, neurological and organ damage may be present in the absence of significant clinical signs. Furthermore, child abuse is one of only a few medical situations in which the paediatric doctor cannot take for granted the truth of the explanations given by the parent(s)/carer(s). The radiologist therefore plays a crucial role in the diagnosis of NAI. Once the presence of skeletal injuries has been confirmed, it is often difficult to reach a firm conclusion as to the mechanisms involved in a particular pattern of injury. This is especially true when an injury occurs in isolation. There are several confounding issues

- What degree of force was required to produce the injury?
- Could the injuries identified have all been sustained on one occasion?
- Is the mechanism of injury put forward by the carer(s) likely to have resulted in that particular injury or pattern of injuries?
- What age is the injury i.e. could it have occurred within the time span given by the carer(s)? (In whose custody was the child at that time?)
- Is the underlying bony structure abnormal? For instance a child with osteogenesis imperfecta has fragile bones that may fracture in the course of normal day-to-day handling
- Are there other features to support the presence of an underlying skeletal or metabolic disease?
- Has this child with underlying bony abnormality been physically abused?

It is important that these questions are answered to the best of the radiologist's capabilities; an incorrect diagnosis may mean that the child is taken away from loving parents causing great damage to the entire family unit. A missed diagnosis exposes

the child to further abusive episodes, which tend to increase in severity and may culminate in the child's death [ALEX1990, KLEI1995A, CHAP1997].

Generally speaking, there are several important patterns of injury that may lead a clinician/radiologist to suspect NAI in any given case. These are a single fracture with multiple bruises, multiple fractures in different stages of healing, with or without soft tissue injury, single or multiple metaphyseal-epiphyseal fractures, rib fractures, subperiosteal new bone formation (SPNBF), and a skull fracture associated with intracranial injury [HOBB1989]. Because of the multiplicity of fractures that may occur (clinically suspected or quiescent) it is imperative that high quality radiographs of all bones are obtained. These radiographs are known collectively as a skeletal survey.

1.3 The Skeletal Survey

The physically abused child may come to the physician's attention directly through presentation in casualty with an obvious injury, or indirectly when a radiologist notices (for example) occult rib fractures on a chest radiograph taken for a suspected chest infection. In either case, a series of radiographs will then usually be performed to exclude further injuries. This series of radiographs is known as the skeletal survey.

The standard skeletal survey performed at GOSH is shown in *Box 1.3-1*.

Box 1.3-1

THE STANDARD SKELETAL SURVEY AT GREAT ORMOND STREET HOSPITAL *

AP skull	Lat lumbar spine
Lat skull	AP upper limbs including shoulders and wrists
AP chest	AP lower limbs including hips and ankles
AP abdomen and pelvis	DP hands
Lat thoracic spine	DP feet

AP = anteroposterior

Lat = lateral

DP = dorsopalmer/plantar

** In November 2003, left and right oblique chest radiographs were added as routine. The benefits of these additional radiographs is currently being assessed*

Although the views taken in a skeletal survey may vary from institution to institution, some general rules apply

- The imaging system should be of high quality
- The American College of Radiology (ACR) standards suggest that the imaging system has a limiting resolution of at least ten line pairs per mm (lp/mm), and a maximum speed of 200 [ACR1997]
- There should be tight collimation of each anatomical area
- Additional views should be taken of any known sites of injury, and of clinically suspicious sites and abnormal sites identified on the radiographs

In one series, additional radiographs following a two-week interval increased the detection rate of fractures by 27% [KLEI1996A]. Additional (delayed) radiographs are also of benefit in the difficult task of dating fractures, an aspect of the diagnosis that is inevitably raised by the courts.

1.4 *Legal Issues*

Workers in the United Kingdom have expressed their belief that the Children Act of 1990 is failing severely abused and neglected children due to the interpretation of this act by social workers, guardians ad litem, and the courts. It is felt that too much emphasis is placed on keeping these children within their natural families, an environment within which they were possibly harmed in the first place [SPEI2000].

The difficulties associated with establishing a legal diagnosis of NAI are well illustrated by the fact that in America, of the 3,195,000 reports of suspected abuse of all types investigated in 1997, 60% to 65% were unsubstantiated [RICH2000]. The cost in economic terms and psychological trauma to the involved families is enormous. To facilitate the courts as they attempt to reach a conclusion in individual cases, be they care proceedings or criminal cases, “expert witnesses” are instructed both by the defence and the prosecution to give their opinions as regards number, site and mechanism of causation of each fracture/injury identified. The expert witness is expected to give an objective opinion, and (particularly since the publication of the Woolf Report [HMSO1996]) owes his/her principal allegiance to the court, not to the party instructing them. Berlin and Williams in their paper on malpractice issues in radiology, outline the qualities that should be found in the medical expert witness

“The radiologist who assumes the role of expert witness in medical malpractice litigation should have substantive training, knowledge, and experience in the specific radiologic (sic) practice that is the focus of the lawsuit. The radiologist should be adequately informed about the facts of the case, should review the American College of Radiology Standards of Practice prevailing at the time of the occurrence, and should testify fairly and impartially. Failure to conform to any or all of these admonitions may result in the expert’s disqualification. A disqualification by a judge because of lack of credentials or credibility in one case may seriously impair the effectiveness of the potential expert witness in future cases” [BERL2000]

Similarly, in the British courts, the expert should (a) provide a straightforward, not a misleading opinion; (b) be objective and not omit factors which do not support their opinion; and (c) have researched the case thoroughly [RER1991].

Given the above, it can (perhaps somewhat naively) be assumed that differences amongst expert witnesses (for defence and/or prosecution) in non-accidental injury

cases in the UK are purely as a result of honest differences in professional opinion. The opinion given will depend on the quality of the diagnostic images obtained. In other words the same radiologist may detect a fracture or soft tissue injury on one set of images not seen on another set taken on the same child at the same time, but of inferior radiological quality. It is therefore imperative that images taken for the diagnosis of non-accidental injury are of the highest quality obtainable, even if this means an increased radiation dose to the child [ACR1997].

1.5 Computed Radiography

Computed radiography (CR), also known as storage phosphor radiography was first introduced in the early 1980's [SONA1983]. It is a form of digital imaging increasing in popularity because of advances in technology (picture archiving and communication systems – PACS) allowing for “filmless” departments and because of its easy integration with conventional x-ray machines. In comparison to conventional radiology there is uncoupling of the imaging and storage systems.

In brief the system consists of two major components: (1) a reusable laser-stimulated luminescent phosphor imaging plate and (2) a scanning and recording mechanism [KANG1988]. The phosphor plate is sensitive to x-rays but relatively insensitive to light. While expensive, it can be reused several thousand times [SHAW2001].

The technique has several practical advantages over conventional film-screen radiography, including economic and ergonomic [SCHA1997]. In terms of technical efficacy, it has reduced spatial, but increased contrast resolution [COWE1993]. In paediatric imaging, relevant to its reduced spatial resolution of two to five line pairs/mm (lp/mm)* is the fact that the ACR standards suggest a minimum resolution of 10lp/mm for all radiographs in a skeletal survey performed for suspected NAI [ACR1997]. A recent study led to the conclusion that although technically CR does not meet the ACR standards, when images were viewed under conditions equivalent to the authors' clinical practice (2K monitor and magnification capabilities), the limiting spatial resolution of CR (4.3lp/mm) approached that of conventional film-screen (3.7 – 5.2lp/mm) [BROW2001]. It should be noted that at GOSH, when interpreting traditional film-screen radiographs in cases of suspected NAI, it has always been routine practise to use a magnifying lens. Under these conditions, Brown et al showed that film-screen achieved a limiting spatial resolution of 11.8lp/mm. Their results highlight the need to assess the diagnostic as well as the technical efficacy of imaging systems with particular reference to situations requiring high resolution images. It also highlights the need for departments to optimise their imaging parameters.

* High resolution and mammographic plates have spatial resolutions of $\cong 10$ and 20lp/mm respectively

Unlike film-screen, with computed radiography it is not possible to make a direct correlation between film density and exposure. In summary, with CR systems, when (as in usual practice) the system's read mode is set at "auto", the system reader adjusts system parameters such that radiographs of almost constant density are produced regardless of plate exposure [COWE1993].

To give some idea of the exposure to the patient, manufacturers have defined "exposure indices" and their relationship to plate exposure [BIR2001]. The latitude and more significantly the exposure index appear on both hard and soft copy images of the radiograph. Manufacturers suggest reference ranges for exposure indices for each examination. Fuji Co Ltd. has called their exposure index "Sensitivity" (S). S is inversely related to exposure.

Although film density remains constant, in clinical practice dose reduction (increasing S value) is limited by an increase in quantum mottle. Conversely, because signal to noise ratio increases with radiation dose (decreasing S), the danger with CR is that patient exposure may unwittingly be increased. For practical purposes, it has been said that it is sufficient to determine a "target value" for S for different examinations [SCHA1997]. Perhaps "target ranges" are more realistic. As the image quality required varies for different clinical indications, it would seem prudent to determine target ranges based not just on the examination (e.g. chest radiograph) but also (occasionally) on the indication (e.g. to exclude rib fractures in suspected NAI).

Having accepted the need to optimise image quality, there is an obvious question that needs to be answered. Namely, "How is the quality of a radiograph to be assessed?"

1.6 Image Quality

When we ask, “What is the quality of a radiograph?” we are asking what degree of excellence that radiograph has attained. In this regard there are a number of questions to be answered.

HOW WELL DOES THE IMAGING SYSTEM PERFORM? Answers to this question concern measures of the objective physical performance of an imaging system (see *Section 4.2*, page 85), and are usually sought under standardised experimental conditions. They assess the technical efficacy of an imaging system. Quality in this case might be expressed, for example, in terms of spatial resolution, modulation transfer function (MTF), grey-scale bit resolution, dynamic range, signal-to-noise ratio or detector quantum efficiency (DQE) [THOR1994, JAME2001].

HOW EXCELLENT IS THE RADIOGRAPH THAT IS PRODUCED? This is dependent on the answers to the first question. However in the clinical setting it is also dependent on radiographic technique. Radiation exposure, patient positioning, collimation and presence of artefact all contribute to clinical image quality. In the paediatric population patient movement also contributes significantly to image quality. When performed for the exclusion of NAI, another aspect of image quality needs to be addressed. Namely, **WHAT IS THE OVERALL QUALITY OF THE SKELETAL SURVEY?** In this regard the number and projection of radiographs obtained is important (see *Section 1.3*, page 26).

Questions two and three above address the diagnostic efficacy of the imaging system [THOR1994]. They are measured in the clinical setting, are the most common to be researched, and may be expressed in terms of accuracy, sensitivity, specificity, area under the receiver operating characteristic (ROC) curve (A_z) etc.

The obvious pitfall in the assessment of image quality is its reliance on observers, which introduces an element of subjectivity. This is particularly so in the case of NAI, when not only must the fracture(s) be detected, but following this, a decision on the mechanism, age and cause (accidental/inflicted) of each identified injury must also be reached. Furthermore an image deemed of sufficient quality for the diagnosis to be made by one observer may not necessarily allow the diagnosis to be reached by a second, less experienced observer. This failure by the second observer might be totally unrelated to image quality, but rather, related to observer capability or confidence level. It is for this reason that the ROC curve is an advantageous method of

statistical analysis, being independent of the individual decision threshold of each reader [SCHA1997].

Viewing conditions are also contributory. What is the level of ambient light? What are the conditions of the light boxes? What is the colour of the light illumination – does this have any effect on the visualisation of subtle abnormalities? Has a magnifying glass been used? What is the visual acuity of the observer? Are the observer's glasses clean? (!) Are hard or soft copy images being reviewed? If the latter is the case, what is the matrix size of the monitor? It can be seen that when expressing the diagnostic efficacy of a system, mention must be made of the level of experience of the observer(s) and of the viewing conditions, in order to allow comparison of results of different workers.

The Commission of European Communities (CEC) has published guidelines for adult [CEC1996] and paediatric [EUR1996] practice. These guidelines are intended to allow departments to optimise their imaging systems. Technical parameters (including optimal viewing conditions and exposure factors) are listed. The guidelines also indicate anatomical features that should be visualised, as well as the appropriate degree of visualisation for common radiographic projections. They have been shown to be a useful tool for optimising radiographic technique and reducing patient dose [MOON1998]. Parameters for the paediatric lateral segmental spine radiograph are summarised in *Table 7.6-2* (page 151) and *Appendix II* (page 270), and for the skull in *Table 11.6-7* (page 206).

Although having no impact on the image, there are other important quality parameters, particularly from the medico-legal point of view. These include patient details (such as age, name, date of birth and hospital number), examination details (such as place, date and time of examination), and finally, in the case of NAI, radiographer's identification (ID). These factors are not usually taken into consideration when reporting on image quality. However both the ACR standards [ACR1997] and the draft British Society of Paediatric Radiology (BSPR) standard for skeletal surveys for NAI [BSPR2003], mention them as essential parameters for an acceptable study.

There is a trade-off between image quality and radiation dose [VANO1995A, JONS1996, ALME1996, and HUFT1998]. It is recognised that images of the highest quality are required for detection of the subtle fractures of NAI, even if this means increased radiation dose to the patient [ACR1997]. However dose cannot be increased indefinitely. There will come a point beyond which there will be no diagnostic benefit

from further increases in exposure. This point varies with the clinical indication, and must be determined. The optimisation of radiographic parameters is thus an essential aspect of the practise of all radiology departments, particularly those that image children (because of the detrimental effects of radiation).

1.7 Summary

There is conflicting evidence as regards the use of digital radiographs for the diagnosis of subtle abnormalities such as undisplaced wrist fractures or the fractures of NAI [YOUM1998, PEER2002]. This is largely due to the limitation in spatial resolution (typically approximately 5lp/mm) of digital systems. Although there are many studies comparing clinical efficacy of CR to conventional film-screen systems, the majority have concentrated on the chest radiograph. Studies relevant to the musculoskeletal system are discussed in *Section 4.6* (page 97). While it is agreed that departments need to optimise the imaging parameters that they use when a new (digital) system is installed, there are no published studies on the optimum parameters for digital radiographs in suspected NAI. This is of importance, as the diagnosis of NAI depends to a large extent on the detection of subtle, clinically unsuspected fractures. Image quality obviously depends on the radiographic parameters employed, and in the case of NAI, the number and projection of radiographs is also crucial.

Radiation dose must also be considered. With CR, there is no direct correlation between exposure and film density. Rather, note must be taken of the exposure index which appears on the radiograph. Fuji has called their index “S” or “sensitivity”. S has a constant relationship to exposure. It is recommended that departments set target values (ranges are more practical) for each examination. Perhaps target ranges should also reflect the clinical indication. Thus lower S values (higher radiation dose) would be more acceptable for NAI than for the diagnosis of a skeletal dysplasia (for example). This higher dose would have to be justified by increased fracture detection.

There is a complex relationship between technical efficacy, clinical efficacy, digital image quality, and the radiologist's confidence in making a diagnosis of NAI. The situation is further confounded by the lack of a gold standard for NAI. Emphasis should be placed purely on the detection of fractures (and other radiographic parameters such as periosteal reaction and soft tissue swelling) rather than on their overall interpretation. In this way, it is possible to perform studies of diagnostic accuracy designed to optimise radiographic parameters for the digital imaging of suspected NAI. This summarises the aim of the present thesis.

Chapter 2

Bones

This chapter is divided into four sections. The first is an overview of the anatomy and structure of bone. The second summarises the process of bone growth. A section then follows on the significance of skeletal anatomy to the tendency to injury and types of injury seen in the growing child. The fourth and final section is a discussion on the mechanism of fracture healing.

2.1 ***The Anatomy and Structure of Bone***

GROSS ANATOMY Bone is a complex tissue with a matrix consisting of organic and inorganic components. The skeleton provides internal support, sites of muscle attachment, and in the case of the skull, protection to the brain. Bone has a tensile strength approaching that of cast iron, while being three times lighter and ten times more flexible [BUCK1995A]. Bone is formed throughout life in the processes of growth, maintenance (changes in response to mechanical and hormonal signals), modelling, remodelling, and healing.

The bones in the body are classified into three large groups based on their shape

SHORT BONES measure approximately the same in all directions. Examples include the vertebral bodies, the bones of the ankle (tarsal bones) and those of the wrists (carpals). They have relatively thin cortices and may be irregular, cuneiform, cuboidal or trapezoidal in shape.

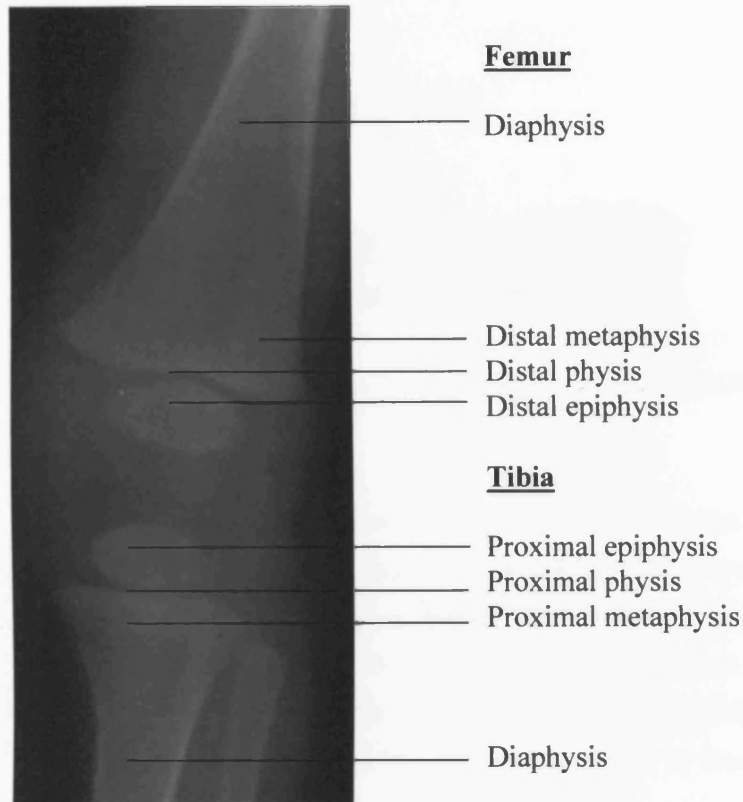
FLAT BONES have one diameter (width or depth) significantly greater than the other two. They may vary in size from the relatively large iliac wing to the much smaller vertebral lamina.

TUBULAR BONES like flat bones have one diameter significantly greater than the other two – tubular bones are significantly longer than they are wide or deep. Long tubular bones include the femur, tibia, humerus and radius. Shorter tubular bones include the metacarpals, metatarsals and phalanges of the fingers and toes.

Tubular bones of the growing child are divided into distinct zones – the shaft or *diaphysis*, which is continuous with the flared *metaphysis*. The latter is separated from the *epiphysis* by the growth plate or *physis*. The long tubular bones have a metaphysis, physis and epiphysis at either end of their diaphyses, while the shorter bones have only one physis and epiphysis. Occasionally, a short tubular bone such as a metacarpal may have a second epiphysis at its proximal end known as a “pseudoepiphysis”. Pseudoepiphyses occur as normal variants or in association with various skeletal dysplasias – radiological confusion with fractures by a trained radiologist is unlikely.

Figure 2.1-1 (next page) illustrates the various zones of growing bones.

Figure 2.1-1: The growing bone

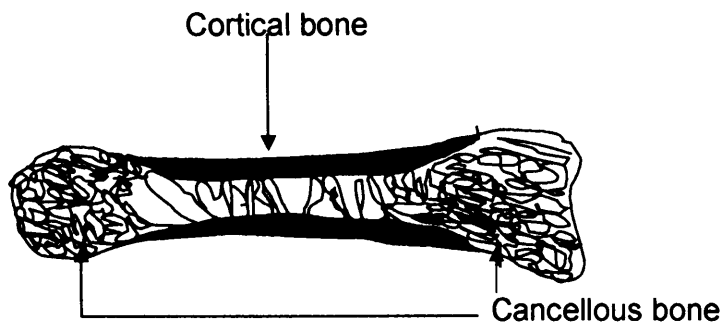


The physis (or growth plate) is cartilaginous in nature, and is seen on radiographs as a radiolucent (wavy) line in contrast to the radiodensity of the adjacent bones. Different disease entities (particularly neoplastic diseases), and in the case of trauma, (particularly non-accidental trauma,) different mechanisms of injury will target the various zones to a greater or lesser degree. Knowledge of this assists the radiologist in reaching a diagnosis. With skeletal maturity and fusion (ossification) of the physis, classification into the different zones is of reduced significance.

CORTICAL AND CANCELLOUS/MEDULLARY BONE Examination of a cross-section of bone with the naked eye reveals two types, cortical and cancellous [MART1989BIB*] and *Figure 2.1-2* (next page).

* BIB = bibliography

Fig 2.1-2: Diagrammatic representation of longitudinal section of bone
Adapted from [BUCK1995A]



Matrix composition and structure is identical in both types. However cortical bone has an increased mass of bone matrix per unit volume when compared to cancellous bone. In other words cortical bone is denser than cancellous bone; with a porosity of 10% compared to the 50% - 90% porosity of cancellous bone [BUCK1995A]. The compressive strength of bone is proportional to the square of its density. Therefore the compressive strength of cortical bone may be up to ten times more than that of a similar volume of cancellous bone [RUBI1990BIB].

Approximately 80% of the mature skeleton consists of cortical bone [RECK1992BIB]. Cortical bone is found mainly in the diaphyses of long bones, while cancellous bone is mainly found in the vertebral bodies, pelvic bones and the metaphyses of long bones. In areas where cancellous bone predominates, a relatively thin shell of cortical bone surrounds it.

Because of its less compact nature, the surface area of cancellous bone is approximately twenty times that of cortical bone. The proportion of bone cells in contact with bone marrow cells is therefore significantly greater in cancellous bone. In cortical bone there are a higher proportion of bone cells completely surrounded by bone matrix [MART1989BIB]. This increased proximity to blood vessels in the bone marrow is thought to explain the increased metabolic activity and remodelling that is seen in cancellous bone, and why it appears to change more rapidly to mechanical loads than cortical bone [BUCK1995A]. This is demonstrated radiographically by the observation that following immobility, disuse osteopaenia is seen earlier in the periarticular and metaphyseal cancellous bone (resorption of trabeculae) than in the

cortical bone of the diaphyses of long bones (formation of resorption cavities) [BUCK1995A].

Woven and Lamellar Bone As the skeleton matures, woven (fibre/primary) bone is resorbed and replaced by lamellar (secondary) bone. This is true of both cortical and cancellous bone, and also occurs during fracture healing [SEVI1981BIB] (see *Section 2.3* page 48). The replacement of woven with lamellar bone is normally complete by the age of 5 years, with the exception of the growth plates, the ossicles of the middle ear, the suture margins of the cranial bones and tendon and ligament attachments where woven bone may persist [BUCK1995A].

The differences between woven and lamellar bone are summarised in *Table 2.1-1*.

Table 2.1-1: Differences between woven and lamellar bone

Feature	Woven	Lamellar
Turnover rate	Rapid	Less active
Deposition rate	Rapid	Less active
Distribution of collagen fibrils	Irregular/random	Regular
Osteocyte ratio	4 : 1	1 : 4
Size, orientation and distribution of osteocytes	Variable	Uniform, parallel to each other and to collagen fibrils
Water content	High	Relatively low
Mineralisation	Irregular	Regular
Flexibility	High	Low
Deformity	Easily deformed	Less deformable
Strength	Low	High
Response to applied force	Isotropic	Anisotropic
Radiographic appearance	Irregular	Homogeneous

Woven bone is more easily deformed than lamellar bone and its mechanical response to an applied force is constant regardless of the orientation of the applied force (isotropic). This means that in the process of fracture healing, the normal mechanical properties of the affected bone are not restored until the woven bone of the fracture callus has been replaced by mature lamellar bone [BUCK1991BIB, BUCK1995A].

BONE CELLS Various bone cells, distinguished by their morphology and location carry out the functions of bone formation, mineralisation, resorption and repair. *Box 2.1-1* (next page) summarises the origin of the various bone cells.

Box 2.1-1

CELL LINE ORIGIN OF BONE CELLS

MESENCHYMAL STEM CELLS

Preosteoblasts
Osteoblasts
Bone lining cells
Osteocytes

HAEMATOPOIETIC STEM CELLS

Monocytes
Preosteoclasts
Osteoclasts

Adapted from [BUCK1995A]

PREOSTEOBLASTS Given the correct stimulus (e.g. following a fracture) these undifferentiated mesenchymal cells have the ability to proliferate and differentiate into osteoblasts. They are generally located in the bone canals, endosteum, periosteum and marrow, although they may also migrate into bone from the bloodstream or surrounding tissues [BUCK1995A].

OSTEOBLASTS The primary role of active osteoblasts is the synthesis and secretion of organic bone matrix. It is thought that osteoblasts respond to hormones such as parathyroid hormone and local cytokines by releasing mediators that stimulate osteoclast activity [RODA1981]. Additional functions attributed to osteoblasts include the control of electrolyte fluxes between osseous and extracellular fluids and a role in the control of bone matrix mineralisation by the synthesis of organic matrix components of bone and the production of matrix vesicles [RAIS1983]. The activities of osteoblasts and osteocytes are co-ordinated by means of cytoplasmic processes via which the two types of cell are in contact. Following the production of bone matrix, active osteoblasts may develop along one of three pathways; they may become bone-lining cells, they may become osteocytes by completely surrounding themselves with bone matrix, or they may disappear from sites of bone formation [BUCK1995A].

BONE LINING CELLS are also known as resting osteoblasts or surface osteocytes. They lie directly against the bone matrix. In response to parathormone, they secrete lytic

enzymes that break down the thin osteoid layer that covers the mineralised bone matrix, as a first step in the process of bone resorption.

OSTEOCYTES make up more than 90% of the bone cells found in the mature skeleton [BUCK1995A]. Through cytoplasmic extensions, they contact and form a complex network with each other, and with osteoblasts and bone-lining cells. This contact allows the cell-mediated exchange of minerals to take place between osseous fluid and blood.

OSTEOCLASTS The stimulation of haematopoietic mononuclear stem cell precursors (in the blood stream or bone marrow) by specific hormones and growth factors leads to the formation of these large multinucleated cells. Osteoclasts are capable of dividing into mononuclear cells that can be reactivated to form new osteoclasts. Osteoclasts perform the function of bone resorption via three mechanisms, all of which commence with the migration and attachment of the stimulated osteoclast to the surface of the bone.

- In the major process by which bone resorption occurs, brush border and proton pumps are then formed at the border of the cell closest to the bone. The bone mineral is solubilised in the acid environment created through the transport of protons by proton pumps. This process reduces the pH from around seven to around four [BUCK1995A].
- In a second mechanism, osteoclasts secrete acid proteases that degrade any remaining organic matrix.
- Finally, an intracellular process also exists whereby osteoclasts ingest matrix fragments by phagocytosis. The fragments are then degraded within cytoplasmic vacuoles.

Osteopetrosis is a disease that illustrates the effects of deficient osteoclast activity. In osteopetrosis the marrow contains an excess of cartilage, bone and fibrous tissue as a result of failure of bone resorption by poorly functioning osteoclasts. Affected patients may be severely anaemic, prone to infection and susceptible to early death. However, bone marrow transplantation may be curative, by providing monocytes capable of differentiating into functional bone resorbing osteoclasts.

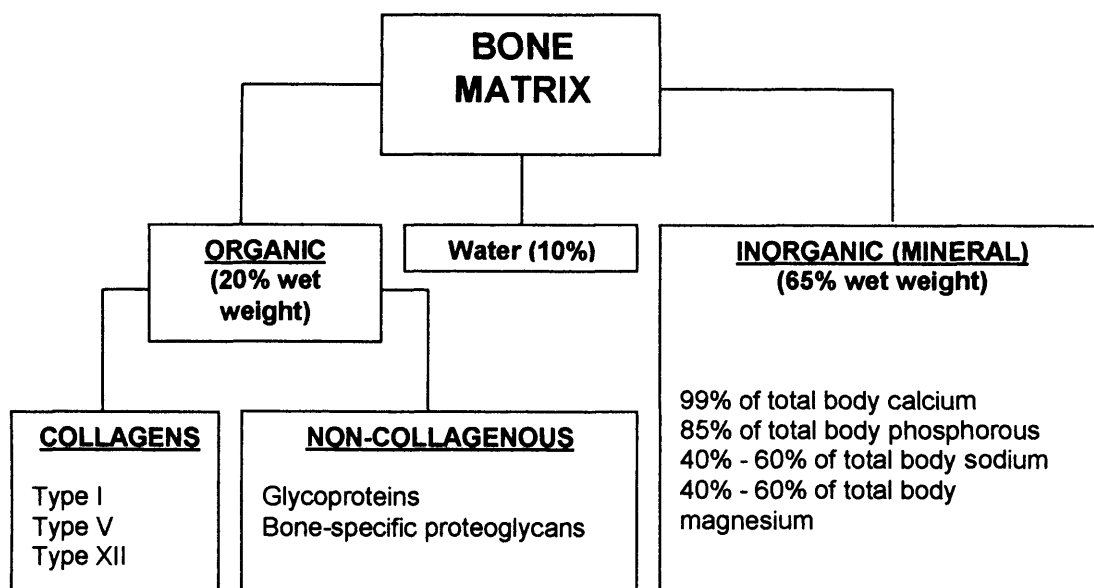
THE PERIOSTEUM covers the outer surface of bones except at sites of tendinous, ligamentous and interosseous membrane insertion, and immediately around or within synovial joints (such as the femoral neck). It consists of two layers, a relatively thick inner osteogenic or cambium layer, and a thin outer layer that is more dense and

fibrous. The two layers are connected by Sharpey's fibres, and the outer fibrous layer is firmly attached to, and difficult to separate from the insertion sites of muscle, tendons and interosseous membrane [KLEI1998A, RECK1992BIB]. The cells of the osteogenic layer contribute to various functions; they are able to become osteoblasts, form hyaline cartilage, play a role in fracture healing by forming extraosseous callus [BUCK1991BIB], and during bone growth secrete the organic matrix that enlarges the diameter of the bone. The periosteum contributes significantly to the blood supply of bone, and periosteal cells can resorb and form bone in response to local or systemic stimuli [BUCK1995A].

BONE MATRIX It has been said that the stability of bone matrix is such that it can remain essentially unchanged, retaining much of its strength for centuries after death [SCHA1992].

The composition of bone matrix is summarised in *Figure 2.1-3*.

Figure 2.1-3: The composition of bone matrix



The organic component gives bone its form and plays a role in allowing bone to resist tension. Removal of the organic matrix of bone renders the bone rigid and brittle, minor deformation causes it to fracture; sharp blows will shatter it. In contrast, demineralised bone, like tendons and ligaments, is flexible and pliable and can even be tied into a knot without fracturing [BUCK1995A].

MINERALISATION Rather like the transformation of water into ice, bone mineralisation is a phase transformation in which soluble calcium and phosphate become solid calcium phosphate [GLIM1992BIB]. Once begun, the process of mineralisation is fairly rapid, with 60% of the ultimate mineral being formed within hours. Following the initial phase, mineralisation continues over a prolonged period, with a resultant gradual increase in bone density [BUCK1995A].

With increasing maturation from childhood to adulthood, and also in the process of fracture healing, there is increasing mineralisation and organisation of bone matrix, maturation of bone crystals and replacement of woven by lamellar bone, all of which result in an increase in bone stiffness [TORZ1981BIB].

BLOOD SUPPLY TO BONE There is a complex network of blood vessels supplying blood to the bone marrow, bone tissue and periosteum. The blood supply to bones can be divided into two major systems, the periosteal-diaphyseal-metaphyseal blood supply, and the epiphyseal blood supply.

THE PERIOSTEAL-DIAPHYSEAL-METAPHYSEAL BLOOD SUPPLY There are three sources of blood supply to the diaphyses and metaphyses of bones. These are a) nutrient arteries b) penetrating epiphyseal and metaphyseal arteries and c) periosteal arteries. Branches of these arteries join to form the medullary vascular system. The vascular network on the surface of the fibrous periosteum anastomoses with the medullary vascular system, the vessels within skeletal muscle, and with vessels in the osteogenic periosteal layer. The diaphyses and metaphyses therefore receive blood from two sources – the medullary vascular system and the periosteal system [BROO1971BIB]. This explains why metaphyseal and diaphyseal fractures can heal following either medullary reaming or periosteal stripping [BUCK1995A]. However, blood supply to both osteogenic and fibrous periosteal layers is dependent on anastomoses with vessels supplying skeletal muscle. After it has been stripped from the underlying bone, periosteum can only remain viable and form new bone if the vascular connections between muscle and periosteum remain intact [KING1976].

THE EPIPHYSEAL BLOOD SUPPLY The epiphysis is dependent for its blood supply on vessels that penetrate it. This is because very few if any vessels are capable of penetrating the cartilaginous physis. With maturity and fusion of the growth plate, vascular channels do penetrate the physeal scar, but their functional significance is uncertain [TRUE1957, TRUE1963, BUCK1995A]. This dependence on a solitary system explains the increased tendency of some epiphyses (e.g. the proximal femoral) to avascular necrosis.

2.2 *The Production of Bone*

Bone is produced throughout life in the processes of formation, growth, maintenance and healing. The well co-ordinated processes of modelling and remodelling maintain the characteristic shapes and sizes of individual bones. Modelling implies alteration in the shape of the bone. Remodelling refers to bone turnover with no alteration in shape [BUCK1995B]. The rate of bone turnover has been estimated at about 100% per year at one year of age. This declines to about 10% per year in late childhood, a rate that is maintained (or slowly reduced) throughout life [AVIO1990BIB]. Bone formation may occur within cartilage (enchondral), within an organic matrix membrane (intramembranous) or by deposition of new bone on existing bone (appositional). The actual mechanism of bone formation is identical in all three processes [BUCK1995B].

ENCHONDRAL BONE FORMATION The bones of the vertebral column, skull base and appendicular skeleton (except the central region of the clavicle) are formed through enchondral ossification. Undifferentiated cells aggregate, secrete a cartilaginous matrix, and differentiate into chondrocytes that form a hyaline or hyaline-like cartilaginous template [CAPL1990]. In the diaphyseal region, a periosteal lining is formed which produces a thin bony collar. Some regions of the cartilage matrix mineralise, the chondrocytes enlarge, and invading vascular buds cause resorption of the central cartilage with the ultimate formation of a marrow cavity. Osteoprogenitor cells (that differentiate into osteoblasts and form a bone matrix on the mineralised cartilage) accompany the vascular buds. The immature bone and calcified cartilage is resorbed by osteoclasts, and replaced with mature lamellar bone by osteoblasts.

After the embryonic formation of the long and short bones and epiphyseal centres, enchondral ossification continues in the physes and epiphyses until skeletal maturity, and also occurs in the healing of some fractures, particularly if these fractures are not immobilised [BUCK1995B].

INTRAMEMBRANOUS BONE FORMATION The facial bones, skull vault, pelvic bones and middle portion of the clavicle are formed by intramembranous ossification. The bone that is formed during limb lengthening also forms by intramembranous ossification [ARON1990, SHEA1992]. This differs from enchondral ossification in that there is no prior formation of a cartilaginous template. The process is initiated by the aggregation of undifferentiated mesenchymal cells into layers or membranes. A loose organic

matrix containing blood vessels, fibroblasts and osteoprogenitor cells is formed. The progenitor cells differentiate into osteoblasts that form spicules and islands of organic matrix. The organic bone matrix is subsequently mineralised, and the spicules and islands covered by more osteoblasts that lay down more organic matrix. Those osteoblasts that are surrounded by matrix become osteocytes, and develop long cytoplasmic extensions that allow them to establish and maintain contact with other osteocytes [BUCK1995B].

APPOSITIONAL BONE FORMATION occurs during modelling, remodelling and periosteal bone growth. The initial process is the alignment of osteoblasts on an already existing bone surface. The osteoblasts then secrete osteoid, successive layers of which form bone lamellae. During bone remodelling this process occurs at sites of osteoclastic resorption of bone. During periosteal bone growth, new layers of bone are produced by periosteal osteoblasts secreting osteoid onto the outer surface of existing bone [BUCK1995B].

2.3 *Significance of Anatomy to Trauma in Growing Bones*

THE GROWTH PLATE The presence of a cartilaginous growth plate (physis) in the immature skeleton exposes children to epiphyseal injuries not seen once skeletal maturation and physal fusion have occurred. Salter and Harris first classified these injuries [SALT1963]. Although they have been reported, their occurrence is relatively infrequent in NAI [MERT1981, THOM1984, TRED1984].

THE CHONDRO-OSSEOUS JUNCTION Planar metaphyseal fractures are relatively common in physically abused children [KLEI1986]. This has been explained by the observation that in a young infant, the primary spongiosa (metaphysis adjacent to the cartilaginous growth plate) is the weakest part of the growing bone. This is by virtue of the fact that it contains only a few mineralised spikes to give it strength. The density of the mineralised cartilage is less than that of the metaphysis. Finally there has not been sufficient time for bone deposition to strengthen the mineralised cartilage [KLEI1998A].

THE SUBPERIOSTEAL BONE COLLAR The relatively thick subperiosteal collar of bone prevents the planar fractures of the thin cartilaginous primary spongiosa commonly seen in abused infants from extending directly to the periphery. These fractures reach the bone surface via the trabecular (cancellous) bone of the more proximal metaphysis, and therefore undercut and isolate the bone collar. Depending on radiographic projection, this anatomical feature is responsible for the radiological “bucket handle” or “corner” fracture of the metaphysis that in the correct setting is almost pathognomonic of NAI [CAFF1957, KLEI1986, KLEI1995B]. This classical metaphyseal lesion (CML) is discussed in more detail in *Section 3.2* (page 57). See also *Figures 3.2-1* and *3.2-2* (page 58).

THE PERIOSTEUM Following trauma, subperiosteal haemorrhage produces elevation and separation of the periosteum from the underlying bone. The degree of elevation is much reduced in the perichondral regions where the periosteum is more firmly attached. The effects of this are demonstrated radiologically by the observation that the maximal thickness of haemorrhage and subsequent callus is along the diaphysis, with gradual tapering toward the epiphysis [KLEI1998A]. Physiological periosteal reaction is confined to the diaphysis [CART1993A, KWON2002] and never involves the metaphysis. See *Figures 3.6-1* and *3.6-2*, page 72.

MATURATION The skeleton matures as an infant grows. This process includes the replacement of woven by lamellar bone, the maturation of bone crystals, and the increasing mineralisation and organisation of the bone matrix. The result of the above processes is that the overall stiffness of bone increases with maturation from infancy through childhood to adulthood [BUCK1995A, TORZ1981BIB]. In response to a direct external force, the bones of children may bow (plastic deformity). If exposed to a compressive force they may buckle (torus fracture). Finally, a bending force may result in a greenstick fracture in which the cortex and periosteum on the side of the bone loaded in tension is disrupted (fractured), while the contralateral cortex and periosteum remains intact. In contrast, the stiffer bones of an adult when subjected to excessive external forces will break rather than deform [BUCK1987BIB, MABR1989].

BRITTLE BONES

MATRIX The effects of reduced organic matrix, causing bone to become more brittle and prone to fracturing has been discussed above. This is exemplified in osteogenesis imperfecta, a group of heterogeneous conditions in which there is an abnormality in either the quality or the quantity of Type I collagen. Patients have fragile bones with an increased tendency to fracture, and the condition must be considered a major radiological differential diagnosis of NAI.

MINERALISATION In rickets, there is normal osteoblastic activity, however there is defective bone mineralisation resulting in an excess of uncalcified osteoid. The effect of this is weakened bones with reduced bone density on radiographs. In severe rickets, the weakened bones have an increased tendency to incomplete insufficiency fractures (Looser zones) at characteristic sites (pubic rami, femoral necks, scapulae, ribs, long bones and metatarsals). Other radiographic features of rickets should avoid confusion with NAI.

2.4 Fracture Healing

The current understanding of the morphological sequence of fracture repair stems from the original work of John Hunter [KEIT1917]. Much of the work has depended on extrapolation from animal studies, and while some assumptions have had to be made, it is true to say that the repair process is faster in the infant than the child, and faster in the child than the adult [SALT1980BIB, CHAP1992].

Shaft fractures heal by the process of intramembranous ossification in contrast to physeal fractures, which heal by enchondral ossification [OCON1998A]. The healing of shaft fractures can be divided into the following stages – stage of induction, stage of soft callus, stage of hard callus, stage of remodelling.

STAGE OF INDUCTION This stage begins with the traumatic episode, and ends with the first appearance of new bone at the fracture site. This stage may be further subdivided into two overlapping phases.

REMOVAL OF NON-VIABLE TISSUE The traumatic incident leading to the fracture of a bone causes disruption of vessels in the bone marrow, cortex, periosteum and adjacent soft tissues. Shortly after the injury, there is soft tissue inflammation, with wide spread swelling associated with pain, which is accentuated by attempts to move the injured limb. The extent of haemorrhage and inflammation that ensues is dependent on the severity of trauma, and haemorrhage may recur whenever the fracture fragments are moved. As haemorrhage ceases and healing begins, there is an ingrowth of new capillaries that is necessary for the transport of inflammatory cells, precursor cells, macrophages and osteoclasts [OCON1998A]. The macrophages and osteoclasts are responsible for the resorption of haemorrhage and necrotic tissue in the vicinity of the fracture and from the fracture ends. Histologically, the mobilisation of osteoclasts and the presence of osteolytic activity can be identified by four to seven days after the initial injury [HEPP1980BIB].

DEPOSITION OF GRANULATION TISSUE, OSTEOID & BONE This stage of tissue metaplasia coexists with the removal of non-viable tissue described above. Preosteoblasts are stimulated to become osteoblasts that secrete bone matrix (osteoid). The most important variable that governs the duration of the stage of induction is the development of a significant amount of granulation tissue and its metamorphosis to

produce osteoid – the time scale is several days at a minimum, but most often three to four weeks [CHAP1992, OCON1998A].

STAGE OF SOFT CALLUS This stage overlaps the first, and is characterised by the formation of subperiosteal new bone and endosteal callus. It lasts until the bony fragments are no longer easy to move, and when separated start to be bridged by lamellar bone. Proliferating periosteal osteoblasts and precursor cells produce soft callus, which is a mass consisting of woven bone, cartilage, blood vessels and fibrous tissue. The uptake of calcium into the soft callus begins within a few days of the traumatic episode and reaches its peak at several weeks [OCON1998A]. The initial manifestation of this is seen histologically at one week, when calcification of new cartilage is demonstrable [CHAP1992].

STAGE OF HARD CALLUS Periosteal and endosteal woven bone is converted to lamellar bone, vascularity increased, osteoclastic activity diminished, and nearly all the haematoma and exudate and much of the granulation tissue resorbed. The end of this stage marks the solid union of the fracture fragments.

STAGE OF REMODELLING This stage involves the gradual replacement of woven by lamellar bone, and the restoration of the original contours of the bone and its medullary cavity. Even after significant deformity, displacement and angulation, fractures in children may show extensive remodelling with ultimately no evidence of the previous fracture. The process may continue throughout the period of growth, and may even continue after epiphyseal fusion [HEPP1980]. In children, remodelling may take as long as one to two years. However in adults remodelling may never be completed [OCON1998A].

2.5 Summary

Bone is a complex, highly organised and constantly changing tissue. It serves to protect the brain and other internal organs, and provides sites of muscle insertion. It is formed throughout life in the processes of formation, growth, modelling, remodelling and healing.

Based on their shape and size, the bones in the body can be classified as short, flat or tubular. Tubular bones of a growing child are subdivided into epiphysis, growth plate (or physis), and shaft (or diaphysis). In non-accidental trauma, different mechanisms produce different injuries to the various regions, knowledge of which is of assistance to the radiologist. The subdivisions are of reduced significance after skeletal maturity when fusion of the growth plates has occurred.

Based on its density (mass of bone matrix per unit volume) bone may be classified as cortical or cancellous. The thick dense cortical bone of the shafts of long bones provides maximum resistance to torsion and bending, while the thinner cortices and increased cancellous bone of the expanded metaphyses and epiphyses allow greater deformation, and so help to absorb impact loads applied across synovial joints [HOSH1987].

Both cancellous and cortical bone may be classified as woven (primary) or lamellar (secondary). Woven bone is weaker, more flexible and therefore more readily deformed than lamellar bone. The normal mechanical properties of a fractured bone are not restored until the woven bone of the soft callus has been replaced by lamellar bone. Bone matrix has organic and inorganic components that contribute defined characteristics to the bone – the organic component gives bone its ability to resist tension, while the inorganic component allows bone to resist compression.

The metaphyses and diaphyses have a dual blood supply in contrast to the epiphyses, which receive blood from only one source. This explains the increased tendency of epiphyses to avascular necrosis. The periosteal covering of bone contributes to its blood supply, and is a source of progenitor cells.

An understanding of the anatomy of growing bones helps in explaining the differences in the types of injury seen in children when compared to adults, and why the bones of the skeleton are prone to fracturing in certain conditions such as osteogenesis imperfecta and rickets.

Much of the current knowledge of the process of fracture healing has been extrapolated from animal studies. However it is true to say that the rate of fracture healing diminishes with increasing maturity. Comparison of the histological changes that occur in fracture healing with those that are seen radiologically provides a means of radiological dating of fractures. This topic is covered in the following chapter.

Chapter 3

Radiographic Evaluation of Non-Accidental Injury

Depending on the age of the study population, an estimated 10% to 70% of physically abused children manifest some form of skeletal trauma [KOGU1974, LAUE1974, AKBA1976, GALL1982]. Furthermore, fractures are second only to soft tissue injury as the commonest presentation of child abuse [ONEI1973].

This chapter begins with a review of the major musculoskeletal injuries seen in child abuse. Important radiological manifestations are highlighted. The chapter concludes with a discussion on the difficult task that the radiologist faces when attempting to date fractures in suspected NAI.

3.1 Soft Tissue Injury

Although the presence of multiple bruises is the commonest presenting feature in abused children [ONEI1973], it is also a common finding in the normal non-abused infant and child. Researchers have attempted to delineate the incidence and distribution of bruises following accidents in healthy non-abused children, and in suspected or proven cases of NAI. The aim has been to establish the likelihood of one or other causation in a given child. In one study of accidental fractures, Mathew et al found that 91% of children had no associated bruising at presentation, and most (72%) remained without evidence of bruising in the first week after their injury [MATH1998]. Carpenter examined 177 six to twelve month old babies presenting routinely to child health clinics, and found a prevalence rate of 12% for (presumed) accidental bruises [CARP1999]. This is comparable to the prevalence of 12.5% observed by Robertson et al in a study on 62 babies aged three to nine months old [ROBE1982]. Accidental bruising is most often found on the face and head, on the front of the trunk and over bony prominences. All accidental lower limb bruising occurs in mobile children. The incidence of bruising in children increases significantly with increasing mobility [CARP1999]. In contrast, multiple bruises of different ages, bruises over soft sites (e.g. the cheeks), and lower limb bruising in a non-mobile infant are all suggestive of abuse [CARP1999, RAO1999]. Some soft tissue injuries are obviously non-accidental e.g. cigarette burns and bite marks (*Figure 3.1-1*, next page).

Even minor injury to the soft tissues results in haemorrhage and inflammatory exudate. Radiologically this is demonstrated by obliteration of the normal radiolucency of the superficial and deep soft tissue planes. There may also be displacement of the fat planes around the site of injury [CHAP1992]. The degree of swelling is related to the presence of associated bony injury.

Bruising may or may not be associated with underlying bony injury [MCMA1995]. Conversely severe skeletal injuries involving acceleration/deceleration forces alone may occur in the absence of visible signs of injury [KLEI1991A]. This means that when NAI is suspected in an infant, the entire skeletal survey as outlined in *Box 1.3-1* (page 26) must be performed regardless of the presence or absence of bruising. Closer scrutiny and a lower threshold for repeating dedicated views of bones underlying clinical bruising may increase the detection rate of skeletal injury.

Generally speaking, bruising is not a radiological diagnosis, although reports exist describing radiological features such as calcified haematomas in older children [CART1991], as well as a case of so called “necklace calcification” in the soft tissues of the neck presumed due to fat necrosis following strangulation [CART1993B]. The major benefit in recognising the radiological features of soft tissue injury is that they help to determine the age of the fracture. The radiological dating of fractures is discussed in more detail later in this chapter (*Section 3.7*, page 74).

Figure 3.1-1: Lower limb bruising in a non-ambulant child subjected to non-accidental injury



The asterisk lies at the centre of a bite mark.

3.2 Metaphyseal Fractures

The incidence of metaphyseal fractures in NAI ranges from 11% to 53% [KOGU1974, WORL1986, LODE1991, CART2002]. It should be noted that the group who documented the lowest incidence of 11% [WORL1986] did not have a radiologist amongst them. Although less common than diaphyseal fractures [MERT1983, LODE1991, CART1993A], metaphyseal fractures are the most specific single sign of NAI [CAFF1972, LEON1983, MERT1983]. They occur most commonly in the lower limbs around the knees and ankles [RAO1999], but are also seen around the other joints of the upper and lower limbs [KLEI1990].

Metaphyseal fractures are variously known as metaphyseal infractions, avulsion fractures and metaphyseal spurs. Kleinman suggests they be referred to as classical metaphyseal lesions (CML) [KLEI1998A]. For the sake of consistency, the term “CML” has been adopted in the remainder of this text.

The CML was originally thought to represent an avulsion injury of the periphery of the metaphysis [ASTL1953]. However, Kleinman et al [KLEI1986, KLEI1995A, KLEI1996B, KLEI1996C, KLEI1996D, KLEI1998B] have characterised these lesions histologically, and thus explained their radiological appearances and likely mechanism of injury. In brief, the CML is a series of planar microfractures through the most immature portion of the metaphyseal primary spongiosa. The fracture line extends in a planar fashion towards the periphery (cortex) of the bone. As it does so, it veers away from the physis undercutting a bony peripheral segment that encompasses the subperiosteal bone collar. As a consequence, the peripheral bony fragment(s) will be thicker than the central portion. In other words a mineralised disc that is relatively thicker peripherally than centrally becomes separated from the metaphysis.

Traditionally the CML has been divided into two types based on radiological appearance; namely “corner” and “bucket-handle” fractures [MERT1983]. However these are in fact the same lesion. The radiological appearance depends on the radiographic projection [KLEI1998A]. When imaged with the beam at 90 degrees to the long axis of the metaphysis, the CML has a corner fracture configuration. The relatively thick peripheral portion of the fracture is seen end-on as a somewhat discrete triangular fragment. A bucket-handle appearance of the fracture results from imaging

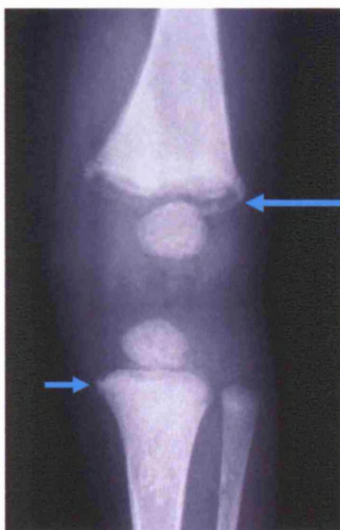
the same lesion with beam angulation. In this instance, beam angulation throws the fractured metaphysis off the diaphysis, and it is seen as a curvilinear radiodensity.

Figures 3.2-1 and 3.2-2 (below) illustrate how the same fracture may have a corner fracture or bucket-handle appearance depending on projection and beam angulation.

Figure 3.2-1: Classical metaphyseal lesion (corner fracture)



Figure 3.2-2: Classical metaphyseal lesion (bucket-handle fracture)



Note also the corner fracture of the proximal tibia (short arrow).

Seen from the side (*Figure 3.2-1*) the fracture of the distal femur has a corner-fracture appearance. Seen from the front (*Figure 3.2-2*), the same fracture has a bucket handle appearance.

Kleinman et al [KLEI1986, KLEI1991A, KLEI1991B] have demonstrated histologically that the radiolucencies seen occasionally in the subphyseal region in abused children might in fact represent another presentation of metaphyseal fractures. These lesions are usually asymmetrical, and should not be confused with similar radiolucencies seen sometimes in the metaphyses of children with leukaemia. Other authors have not collaborated this finding.

Metaphyseal lesions occur as a result of shearing or twisting forces, and are also said to occur during shaking when indirect acceleration-deceleration forces are applied to the infant's limbs [CART1993A, KLEI1998A, RAO1999]. Professor C Hall (consultant radiologist, GOSH and international expert witness in NAI) has previously expressed her doubts that metaphyseal fractures occur from shaking alone [personal communication]. If they do, then the incidence of metaphyseal fractures amongst the cohort of infants with other evidence of shaking injury (retinal haemorrhage, cerebral oedema, subdural haematoma, subarachnoid haemorrhage, hypoxic ischaemic encephalopathy [CART1997]) might be expected to be at least as high, if not higher than the incidence in infants without shaking injury. This should be true even assuming that shaken children are not subject to shearing and twisting injuries. (See also comments in *Section 3.6*, page 71).

Carty and Pierce [CART2002] demonstrated limb fractures in 28 out of 148 (19%) children deemed to have shaking injury. This figure includes both diaphyseal and metaphyseal fractures. The incidence of metaphyseal fractures alone in this group of children is not stated. Although the paper also reports the overall incidence of metaphyseal injuries (142 out of 268 – 53%), it is not clear whether this group includes, or is separate from the cohort with shaking injuries. It would be interesting to document the relative incidences of metaphyseal fractures in the two groups of children.

3.3 *Diaphyseal Fractures*

Although less specific for abuse, diaphyseal fractures are four times commoner than the CML of NAI [MERT1983, LODE1991]. Multiple fractures of the shafts of the long bones are highly suspicious [CRAM1996]. Apart from bruising, the most common initial presentation of abuse is an isolated diaphyseal fracture [KING1988, LODE1991, DRVA1992]. Of the fracture types, transverse fractures are the commonest [RAO1999, SCHE2000]. The middle (50%) and distal third (41%) locations are the most prominent sites of long bone fracture [KING1988]. Extremity fractures have been shown to occur at a younger age than skull fractures in a cohort of patients under a year old [MCCL1982].

The most commonly fractured bone varies from series to series, with the tibia, femur and humerus being variously cited [ONE1973, AKBA1974, KOGU1974, GALL1982, HERN1983, KING1988, LODE1991]. In the most recent series [CART2002], the commonest site of an isolated long bone fracture was the humerus (including one metaphyseal fracture) followed by the femur (including two metaphyseal fractures).

HUMERUS (*Figure 3.3-1*, next page) In young children, the presence of a humeral shaft fracture rarely occurs in accidental injury and has a high association with abuse [ONE1973, WORL 1986, KING1988]. Abuse should be considered in all children less than 15 months old with humeral fractures, including those children with supracondylar fractures [STRA1995].

TIBIA A tibial shaft fracture in a non-ambulatory child is highly suspicious of abuse, particularly when an inappropriate history is given [CRAM1996]. Although Loder and Bookout [LODE1991] reported the tibia as the commonest long bone to be fractured in abuse, it must be emphasised that two thirds of these tibial fractures were in fact metaphyseal and not diaphyseal. Toddler's fractures (hairline spiral fractures of the tibial shaft) occur in the ambulant child. Their recognition is important to avoid the over-diagnosis of abuse [RAO1999].

FEMUR Like tibial fractures, femoral fractures in the non-ambulant child are also highly suspicious of abuse. Of course ambulant children may also be abused, hence the importance of a detailed history [ANDE1982, BEAL1983, THOM1991]. Many practitioners think spiral fractures are pathognomonic of abuse [SCHE2000]. This is not the case, as no single type or site of fracture is significantly more associated with or characteristic of NAI [RAO1999]. Beals and Tufts [BEAL1983] suggest that

subtrochanteric femoral fractures are more common in non-accidental than accidental injury in children. This opinion is not supported by the work of Scherl et al [SCHE2000]. In fact these authors concluded that because spiral fractures are viewed as particularly suspicious, care must be taken not to miss cases of NAI in children with transverse fractures.

RADIUS/ULNA Although they are fractured commonly in accidental trauma, the radius and ulna are the least fractured long bones in child abuse [ONEI1973, AKBA1974, GALL1982, HERN1983, KING1988, LODE1991].

Figure 3.3-1: A transverse diaphyseal fracture of the humerus in non-accidental injury



Note also the multiple healing rib fractures (arrowheads).

Findings suggestive of abuse were summarised by Leventhal et al [LEVE1993], and include

- Fractures in children whose carers give a history of behavioural change in the child, but no accidental event, or a minor fall not consistent with the severity of the sustained injury
- Fractures of the radius and ulna, tibia and fibula, or femur in children less than a year old
- Mid shaft or metaphyseal fractures of the humerus (see *Figure 3.3-1*, page 61)

Mechanisms of injury include direct trauma (while fending off a blow), inappropriate pulling (causing the bone to fracture under the weight of the suspended struggling child), an awkward fall (as the child is thrown or pushed away), or a twisting force [HOBBS1989, CART1993A, RAO1999]. By their nature, spiral fractures imply a twisting force, and are therefore highly suggestive of abuse [WORL1986, CART1993A]. Care must be taken when attributing a spiral fracture to NAI – history; patient age and development; fracture age and the presence of other injuries must all be taken into consideration to reduce the risk of over or under diagnosis of NAI [BOAL2001].

3.4 Skull Fractures

Skull fractures are the commonest [LODE1991, LEVE1993] or second most common [CRAM1996] skeletal injury in cases of abuse, depending on case selection. They are said to be more frequent in abuse than in accidental injury [LEON1983]. This is particularly true of the younger child – 3% of skull fractures in one series of patients less than 13 years of age were due to child abuse [JOHN1996], compared to 33% in a group of children under two years of age [HOBB1984]. In another study of 189 battered children, skull fractures were the only fracture type more likely to be present in children aged less than a year compared to older children [KING1988].

A fall out of bed is a rare cause of skull fracture [HELF1977, NIMI1987]. Simple linear fractures (*Figure 3.4-1*, next page) occur from a height of three to five and a half feet, while more complex (accidental) fractures (*Figure 3.4-2*, next page) occur from a height of six or more feet [CHAP1990]. The majority of stairway injuries are relatively insignificant. Although falls may be associated with severe injury [CHIA1994], the presence of multiple sites of injury following an alleged fall down a flight of stairs should be viewed with more suspicion than should a solitary skull fracture [JOFF1988]. Most skull fractures occurring in cases of abuse cannot on their own be differentiated from those occurring in accidental trauma, and there is no single appearance that is pathognomonic of NAI [CART1991]. There are some features however which favour a diagnosis of NAI, and these are shown in *Box 3.4-1*.

Box 3.4-1

FEATURES OF SKULL FRACTURES ASSOCIATED WITH NAI

Complex fractures involving both sides of the skull
Multiple fractures
Non-parietal fractures
Diastatic fractures (greater than 3mm wide)
Growing fractures (leptomeningeal cysts)
Depressed fractures especially of the occiput
Associated intracranial injury

[HOBB1984, RAO1999]

Figure 3.4-1: A simple linear skull fracture in non-accidental injury

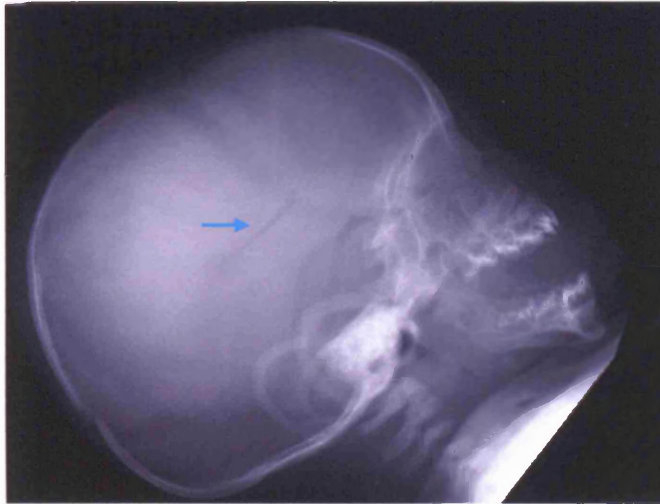
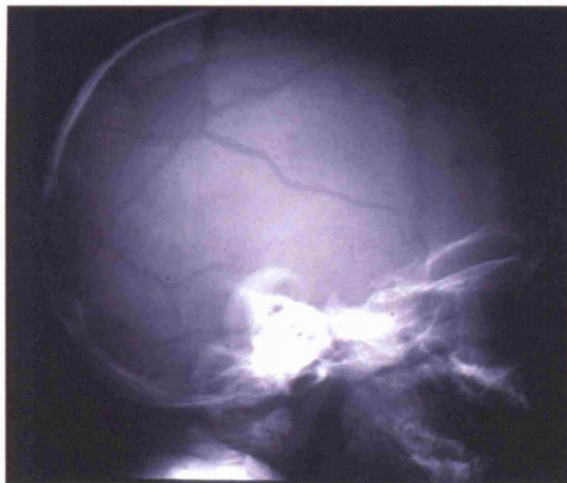


Figure 3.4-2: Multiple complex skull fractures in non-accidental injury



Both infants suffered inflicted injury. However (in the correct clinical setting) the nature of the fractures in *Figure 3.4-2* allows the radiologist to be more confident in the diagnosis of NAI than when diagnosing the aetiology of the fracture in *Figure 3.4-1* (arrow).

It must be remembered that a skull fracture crossing a suture to involve more than one bone may be the result of a single blow with the fracture line radiating in both directions from the single impact site [BOAL2001]. This occurrence is most frequent in the parietal bones, although occasionally the occiput may be involved.

The absence of a skull fracture does not exclude significant intracranial injury [RAO1999]. It has been recommended that following blunt trauma skull radiography should be performed in children older than two years of age only if NAI is suspected. It may also be performed to confirm the presence of a depressed fracture. On the other hand, skull radiography should be performed in all children less than two years old because of the higher likelihood of NAI in this group [LLOY1997]. In suspected NAI, even in the absence of neurological signs, intracranial injury should be excluded by cross-sectional imaging whenever the radiograph confirms a skull fracture [SAUL1982]. It has recently been advocated that cross-sectional neurological imaging be performed routinely in cases of suspected NAI [JASP2003], and it is now part of the routine protocol in the Radiology Department at GOSH.

3.5 Rib Fractures

90% of abuse-related rib fractures occur in children less than two years of age [MERT1983]. The presence of multiple rib injuries adds considerably to the radiologist's confidence in making a diagnosis of NAI. They were not mentioned in Caffey's original description of the association between long bone fractures and subdural haematomas [CAFF1946], but with the expansion of the radiological phenotype of child abuse, their importance was soon recognised [LIS1950, WOOL1955].

The ribs of infants and young children are relatively pliable, and therefore with normal day-to-day handling of the child, fractures at this site should be uncommon [CHAP1990]. Any of the 12 ribs may be fractured, and individual ribs may fracture anywhere along their arc depending on the mechanism of the inflicted injury. A compressive squeezing force in the AP direction results in lateral rib fractures, and in the lateral direction produces anterior or posterior fractures. Rib fractures in this age group may also occur as a result of accidental trauma (following notable trauma such as a road traffic accident), cardiopulmonary resuscitation (CPR*), bone fragility, birth trauma, chest physiotherapy and severe coughing [FELD1984, BUSH1996, BULL2000, CHAL2002]. However the occurrence of rib fractures due to these causes in infants is very uncommon. A case has been reported where CPR* did not lead to rib fractures even in a child with osteogenesis imperfecta (OI) Type II [SEWE2000]. (It should be noted that OI type II is a lethal condition, and the diagnosis in Sewell's case is questionable). Thomas [THOM1977] reviewed 10,000 infants, and found rib fractures (from any cause) in only 25. Others [LEVI1984] have failed to demonstrate rib fractures in a large cohort (greater than 13,000) of live births. Furthermore post mortem radiological and histological examination failed to demonstrate a single rib fracture in a cohort of 91 patients under a year old after failed cardiopulmonary resuscitation [SPEV1994]. In summary, child abuse must always be considered in an infant found to have rib fractures.

The reported incidence of rib fractures in NAI ranges from 5% to 29% [AKBA1974, KING1988, LODE1991, WORL1986, CART2002]. It has been said that these figures probably represent an underestimate [CHAP1990], with 80% of rib fractures being occult [MERT1983]. There are at least two reasons for the difficulties in radiographic

identification of rib fractures. Firstly the x-ray beam may not align with the fracture line. Secondly, the fracture line is easily obscured by overlapping structures (particularly in the acute phase) [CART1993A]. Kleinman et al [KLEI1996E] reported that of 84 rib fractures demonstrated on post mortem histopathology studies, only 30 (36%) were visible on the original skeletal survey. It is also known that high detail post mortem radiography of dissected ribs allows visualisation of fractures not visible on pre-dissection radiographs. This is illustrated in *Figures 3.5-1 and 3.5-2* (next page). These disturbing findings necessitate high quality radiographs. It perhaps underlies the advice given by the BSPR in their standard for imaging in NAI [BSPR2004] to perform left and right oblique projections of the rib cage in addition to the (AP) chest radiograph as part of the routine skeletal survey in suspected NAI. A study to demonstrate the actual benefit of oblique chest radiographs in the detection of (acute) rib fractures has not so far been reported in the literature.

Figure 3.5-1: Anteroposterior chest radiograph in a lethal case of non-accidental injury

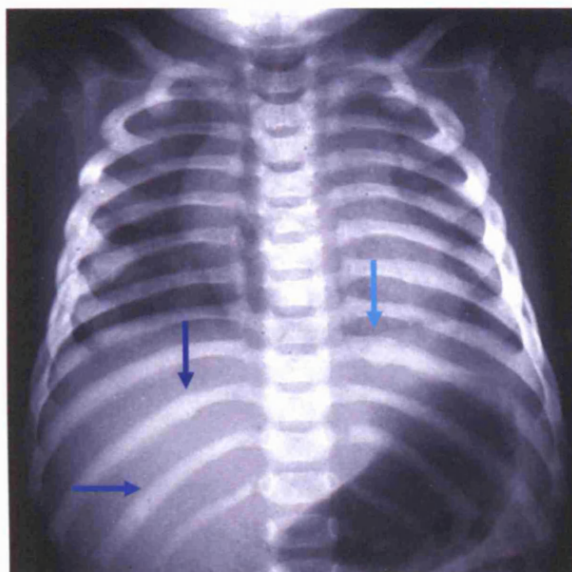
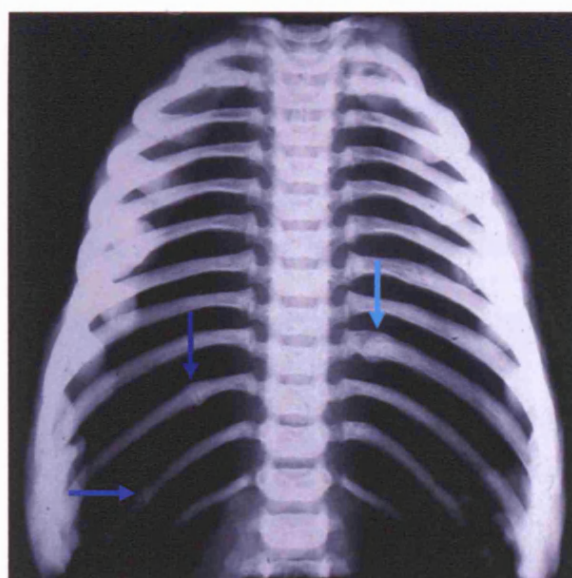


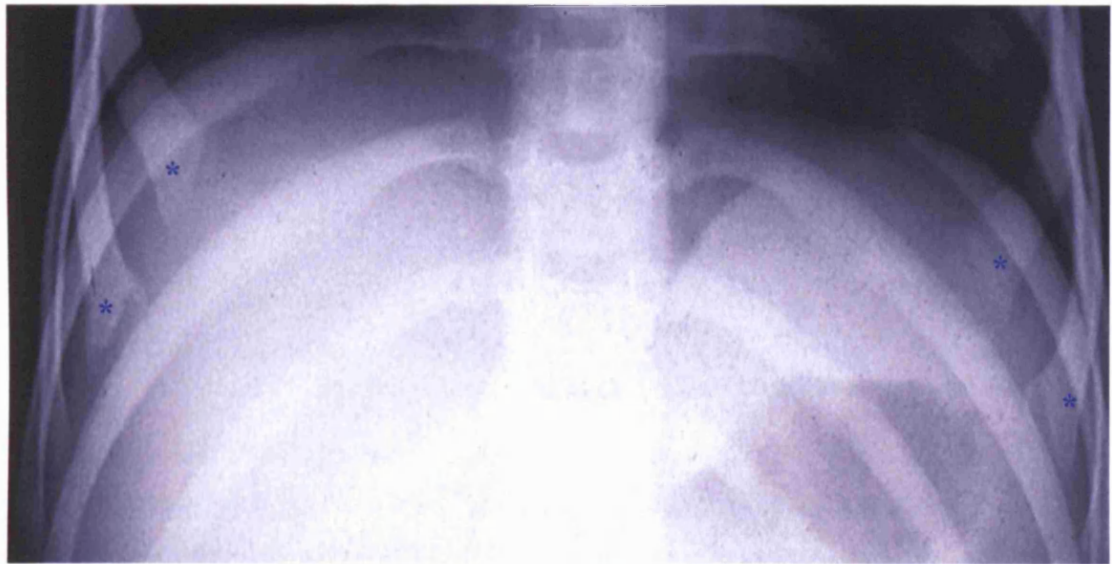
Figure 3.5-2: Anteroposterior chest radiograph following resection of the heart and lungs



These radiographs are of the same infant. Notice how the rib fractures (arrows) become more obvious following removal of internal organs. (There are more rib fractures on these radiographs than pointed out).

Ng and Hall [NG1998] reported a relationship between fractures of the anterior ends (costochondral junctions) of the lower ribs (6th – 9th) and intra-abdominal visceral injury (Figures 3.5-3 and 3.5-4, below). These fractures were difficult to visualise, were equated to the bucket handle metaphyseal fracture, and were associated with major abdominal visceral trauma.

Figure 3.5-3: Bilateral costochondral fractures of the lower ribs



Note the fractures of the anterior ends of several ribs (asterisks).

Figure 3.5-4: Pancreatic pseudocyst occurring in association with costochondral fractures of the lower ribs in non-accidental injury



Boal has published results on her analysis of 910 cases referred over 13 years [BOAL2001]. Her experience concerning those cases with rib fractures is summarised in *Box 3.5-1*.

Box 3.5-1

SITE OF RIB FRACTURES IN THREE GROUPS OF PATIENTS

	Abuse	Not Abuse	Unknown
CVJ	479 (33%)	23 (36%)	22 (27%)
Posterior	257	10	22
Lateral	301	17	3
Anterior	251	14	22
CCJ	175	0	12
Total	1,463	64	81

CVJ = costovertebral junction CCJ = costochondral junction

[BOAL2001]

Costovertebral junction (CVJ) fractures have a high specificity for NAI. From *Box 3.5-1* it will be noted that although in Boal's report it was the commonest site for all diagnostic groups (abuse, not abuse, unknown), fractures at the CVJ were relatively less common in the abused group than in the not abused. Whether this difference is statistically significant is uncertain. There were many more rib fractures seen in the abuse group than in either of the other two. However, the presence of multiple rib fractures is an important factor in making the original diagnosis. The high incidence of rib fractures when this same group was reanalysed is therefore not surprising. The lack of an objective gold standard is to blame for this somewhat circular argument.

3.6 Subperiosteal New Bone Formation

Subperiosteal new bone formation (SPNBF) may be seen in NAI in two contexts

- As a normal response to fracture healing
- In the absence of a fracture, as a radiological feature of abuse (periosteal trauma)

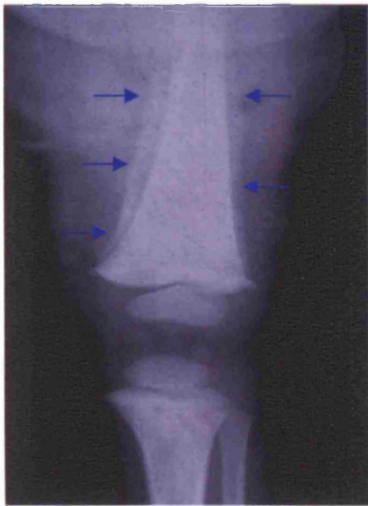
The radiological evidence of healing fractures is dealt with in *Section 3.7* (page 74), while isolated SPNBF as a feature of abuse is discussed below.

Caffey [CAFF1946] described the finding in his seminal paper, and it has since been demonstrated to be relatively common in abused children [DRVA1992].

The pathological finding is haemorrhage causing the osteogenic layer of periosteum to be stripped from the underlying cortex. As described in “The Periosteum” (page 42), the osteogenic layer of periosteum is tightly adherent to the metaphyses and epiphyses, and more loosely so to the diaphyses of bones. As a result, collections of subperiosteal blood are of maximum diameter along the shafts tapering towards the ends (except in the case of massive haemorrhage or repetitive trauma) [CHAP1990, CRAM1996, KLEI1998A].

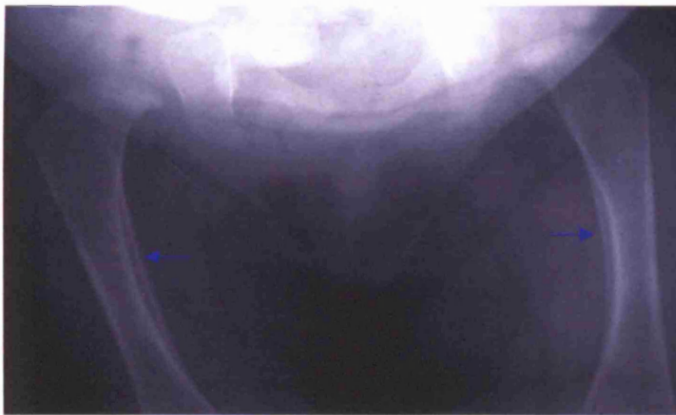
Tractional and torsional forces on the periosteum as a result of rough gripping and twisting or pulling of an extremity, was initially felt to be the mechanism of causation of SPNBF. Some workers also feel that SPNBF can occur following acceleration-deceleration forces [CHAP1990, KLEI1998A, RAO1999]. Professor C Hall (consultant radiologist, GOSH and international expert witness in NAI) doubts this mechanism of causation (see comments on the CML, page 59). However SPNBF is not specific to NAI. It may be seen as a result of infectious, traumatic, metabolic and neoplastic disease [KLEI1998A]. Another important differential to consider is benign periosteal reaction, which occurs physiologically and was initially described in infants between the ages of six weeks and six months [RAO1999]. It has since been shown that physiological SPNBF most frequently involves the femur or tibia, is usually symmetrical, never extends to the metaphysis, is very rarely greater than 2mm thick, and is commonest between the ages of one and four months [KWON2002] – *Figures 3.6-1 and 3.6-2* (next page).

Figure 3.6-1: Subperiosteal new bone formation in non-accidental injury



Appearances are not always so obvious.

Figure 3.6-2: Physiological periosteal reaction



Note the symmetry of the periosteal reaction and how it is limited to the femoral diaphyses (shafts).

As with many other fractures in NAI, there may or may not be soft tissue evidence of injury. Radiologically SPNBF can be easily overlooked, as it may appear only as a faint haziness/irregularity of the affected cortex. In other instances it may be seen as a thin layer of bone separated from the underlying cortex by a narrow radiolucent interval [KLE1998A]. High quality radiographs, and multiple and coned views may be required for confident diagnosis or exclusion of SPNBF.

SPNBF may occur in isolation in NAI. However its detection should prompt close scrutiny of the underlying bone to exclude a subtle hairline fracture. Once again the need for high quality examinations cannot be overstated.

3.7 Radiological Dating of Fractures

It has been said that in making a diagnosis of NAI, the single most important factor is the relationship between the alleged timing of the injury and the radiographic appearance of that injury [OCON1998A]. However it may be argued that the single most important factor is the multiplicity of injuries, and that fracture age becomes more important as the number of fractures detected decreases. This by no means belittles the role played by the radiographic dating of fractures in the diagnosis of NAI, as evidenced by the fact that in a recent publication it was recorded that an isolated long bone fracture was seen in 89 of 467 (19%) children with suspected NAI [CART2002]. The correct dating of injuries is also of importance to the courts when establishing culpability.

The radiographic changes parallel the histopathological changes and have been timetabled by O'Connor and Cohen as shown in Box 3.7-1.

Box 3.7-1

TIMETABLE OF RADIOLOGICAL CHANGES IN CHILDREN'S FRACTURES*

Category	Early	Peak	Late
1. Resolution of soft tissues	2 – 5 days	4 – 10 days	10 – 21 days
2. SPNBF	4 – 10 days	10 – 14 days	14 – 21 days
3. Loss of fracture line definition	10 – 14 days	14 – 21 days	
4. Soft callus	10 – 14 days	14 – 21 days	
5. Hard callus	14 – 21 days	21 – 42 days	42 – 90 days
6. Remodelling	3 months	1 year	2 years – physeal closure

* Repetitive injury may prolong categories 1, 2, 5 and 6.

SPNBF = subperiosteal new bone formation

[OCON1998A]

It should be noted that there is a significant subjective element to fracture dating, and not all radiologists would agree with the time sequence shown above.

The significance of detecting the radiographic features of soft tissue injury described in *Section 3.1* (page 55) is that initially they may be the only indication of an underlying fracture. When the fracture is apparent on radiographs, the presence of significant soft tissue swelling with loss of the normal fat planes informs the radiologist that the injury is recent, probably within the preceding seven (and certainly within the preceding ten) days.

SPNBF is seen on radiographs only once calcification has begun. Repetitive injury to a non-immobilised fracture as may be seen in abuse, leads to further subperiosteal haemorrhage and subsequent exuberant callus formation [CRAM1996]. It should be noted that SPNBF might not be seen in the healing process of metaphyseal [OCON1998A] or skull fractures.

FRACTURE MARGINS An acute fracture has well defined sharp margins. In the early stages of fracture repair, macrophages begin to resorb non-viable tissues including the ends of the affected bone (*Section 2.4* page 50). Radiographically this corresponds to a loss of definition of the fracture margins, with apparent widening of the fracture gap. This is the only reliable means by which metaphyseal fractures can be dated [OCON1998A].

SOFT CALLUS The laying down and calcification of osteoid is visible on radiographs as a subtle increase in density around the fracture site. At this stage the fracture line is still discernible.

HARD CALLUS The complete conversion of woven to lamellar bridging bone marks the stable union of the fracture. Radiographically this is evidenced by definite sclerosis around the fracture. By this stage the fracture line may or may not be discernible.

THE REMODELLING of bones following a fracture has been discussed in *Section 2.4* (page 50). The variability in duration of this phase means that it is not a reliable means of dating fractures radiographically. By this stage however, the acute healing phase is over and the fracture line is not discernable.

The radiographic appearance of fractures at various stages of healing is shown in *Figures 3.7-1 to 3.7-4* (next page).

Figures 3.7-1 to 3.7-4: Healing diaphyseal fractures

3.7-1

Less than 7 days



3.7-2

2 to 4 weeks



3.7-3

6 to 8 weeks



3.7-4

3 months



There are some exceptions to the generalisations given above.

Firstly, unless the adjacent periosteum is damaged, SPNBF does not occur with the healing of metaphyseal fractures. In such cases the most reliable means by which these fractures can be dated is by assessment of the soft tissues and fracture line [OCON1998A]. Kleinman et al [KLEI1991B] correlated radiological with histopathological changes of metaphyseal fractures in a retrospective analysis of 13 distal tibial metaphyseal fractures. Nine of these fractures were shown histologically to be in a healing phase, and all nine were associated with a focal radiolucent extension from the growth plate into the metaphysis. The authors imply that with knowledge of the relative growth rates of various bones, the minimum age of a metaphyseal fracture can be calculated based on the depth of the radiolucency into the metaphysis. There has been no further evidence to substantiate this view.

Secondly, skull fractures do not demonstrate the radiological features listed. The associated scalp swelling may help to date acute fractures, but literature on this topic is limited.

Thirdly rib fractures are difficult to detect radiographically, particularly in the acute phase (see *Section 3.5* page 66). SPNBF may not be differentiated from overlying pulmonary vascular markings. Indeed SPNBF may not develop, particularly with anterior rib fractures [KLEI1998C, NG1998]. This is similar to the healing pattern of metaphyseal fractures, with which they are analogous. The subsequent formation of callus helps to identify and date previously unidentified fractures or suspicious areas. In one study, repeat radiographs approximately two weeks after the initial ones increased the pick-up of fractures by 27%, and yielded important information regarding age of fracture in 19% of 70 previously detected fractures. The majority of these fractures were rib and metaphyseal fractures [KLEI1996A]. Follow-up surveys might therefore be recommended in suspicious cases to provide a more accurate assessment of bony injury. In some institutions follow-up surveys form part of the routine skeletal survey. The BSPR standard [BSPR2004] does not raise this issue.

The healing of fractures is dependent on many variables including patient age, affected bone, degree of displacement, force of injury, fixation and immobilisation of the affected fragments etc. Box 3.7-2 illustrates this fact by summarising the effect of age on the healing rate of immobilised femoral fractures.

Box 3.7-2

THE HEALING RATE OF WELL MANAGED FEMORAL SHAFT FRACTURES

AGE OF PATIENT	TIME TO FULL UNION
Birth	3 weeks
8 years	8 weeks
12 years	12 weeks
20 years +	20 weeks

Adapted from [SALT1980BIB]

3.8 Summary

Soft tissue and bony injury in children may occur following both accidental and non-accidental injury. Numerous studies have been performed documenting the mechanisms and distribution of injuries. The aim of such studies has been to provide an aid for the clinical and radiological differentiation of these two broad mechanisms of injury.

The presence of multiple fractures at various stages of healing is the radiological hallmark of NAI. The radiologist must therefore not only identify, but also be in a position to date fractures. This is particularly true in the presence of a single fracture, when the age of the fracture may collaborate or refute the clinical history. The presence of a single fracture is not an uncommon occurrence in NAI, as demonstrated by Carty's review [CART2002].

Any bone may be affected, and careful scrutiny of the skeletal survey is required, along with knowledge of the manifestations of these injuries and the normal variants and other pathological processes with which they may be confused.

The features that allow radiologists to date fractures mirror the underlying histopathological processes that occur with fracture healing. A major problem with this is that histopathologists are also in the position of having no gold standard with which to compare their findings. The situation is complicated by the variability in the rate of fracture healing. This depends on numerous factors including patient age, affected bone, extent of fracture displacement and degree of immobilisation.

O'Connor and Cohen point out certain gaps in current knowledge [OCON1998A] concerning the radiographic dating of fractures. What is the earliest time of visualisation of SPNBF? Is this dependent on the extremity that has been injured? Objective criteria have not been developed for the assessment of fracture line definition. The precise chronology of fracture line definition with age of fracture is yet to be determined. It is likely that different fractures have different healing rates, yet no studies have specifically attempted to date for example, rib, skull or metaphyseal fractures.

The radiological dating of fractures is by no means an exact science, and although the information in *Box 3.7-1* (page 74) is useful, currently most radiologists rely mainly on (personal) experience when dating fractures. The design of an ethical prospective

study would be fraught with difficulty. Retrospective studies (even on accidental fractures which differ from those of NAI) have their own problems. These include the variable frequency of repeat radiographs (if any – the need for repeat radiographs is largely determined by the individual needs of the patient); the presence of plaster of Paris masking subtle radiographic signs; limb immobilisation (compared to NAI in which the fractures are often not immobilised); the lack of definite knowledge regarding the age of the fracture etc. Even if ethical approval were granted, it cannot be assumed that results from animal studies would reflect the changes seen in humans. For these reasons it will be difficult to improve upon our current level of knowledge regarding radiographic dating of fractures in children. The role of cross sectional imaging (ultrasound, computed tomography and magnetic resonance imaging) in fracture dating in the context of NAI is not known.

Bony injury in NAI often manifests as subtle radiographic change, with little clinical evidence of the underlying bony injury. Identification of radiological signs, even by experienced radiologists is dependent on the quality of the images obtained. It is imperative that radiographs obtained as part of a skeletal survey in NAI are of the highest possible quality. In the past the production of high quality images with traditional film-screen radiographic techniques has been optimised. It needs to be shown that the newer imaging modalities, notably digital imaging, can produce images of sufficient quality for the detection of subtle findings such as SPNBF and the rib and metaphyseal fractures seen in NAI.

Image quality, particularly in the context of computed radiography, forms the topic of the next chapter.

Chapter 4

Image Quality and Computed Radiography

This chapter begins with a discussion on quality as it applies to diagnostic radiology and ways by which it may be measured. There follows a section on computed radiography, briefly describing the technology and highlighting its differences from, and similarities to conventional radiography. There is then a review of clinical studies that have been performed comparing digital to conventional radiography. The chapter ends with a summary of the conclusions that may be drawn from the results of such studies.

4.1 Defining Image Quality

Barnhard touched upon the subjectivity associated with determining the quality of an image when he wrote,

“...Image quality is in the eye of the beholder...” [BARN1982]

Aesthetics is not the only factor to consider. There is an association between image quality and the detectability of pathology, and between both of these and radiation dose. Image quality therefore has implications to the patient both in terms of reaching the (correct) diagnosis, and in terms of the radiation dose incurred for a given examination. Rossman has defined image quality as

“...That attribute of the image which affects the certainty with which diagnostically useful detail can be detected visually by the radiologist.” [ROSS1969]

The same author goes on to say

“A radiograph is of the highest quality if it does not adversely affect diagnosis” [ROSS1969]

Along this vein, Martin et al state that the purpose of diagnostic radiology is to

“Obtain images which are adequate for the clinical purpose with the minimum radiation dose to the patient”. [MART1999]

There are obvious difficulties with these definitions. How should “adequate” be defined? Can image quality be expressed objectively? What level of quality is required for any given examination? An increase in the aesthetic value of a radiograph requires a corresponding increase in radiation dose. When expressed in terms of technical (physical) parameters, do the highest quality images (highest dose) necessarily yield the most information when assessed in the clinical context?

If, as in Rossman’s first statement above, the final endpoint is to enable the detection and interpretation of abnormality, and not merely to provide “high quality images”, then several important factors can be separated. These are listed below, adapted from an original diagram by Vyborny [VYBO1997].

Box 4.1-1

DETERMINANTS OF RADIOLOGICAL DIAGNOSIS

Clinical Parameters

- History
- Examination
- Clinician's suspected diagnosis

Observer Parameters

- Experience/Knowledge
- Level of confidence
 - In imaging modality
 - In area of interest (e.g. NAI, oncology, head and neck imaging etc.)

Image Quality Parameters

- Imaging modality

Image quality determines a given observer's ability to detect pathology. However the diagnostic usefulness of the radiograph is dependant on the experience of that observer. An inexperienced observer might fail to observe abnormality on a radiograph due to his ignorance in such matters – totally unrelated to the intrinsic quality of the radiograph. What level of experience should be aimed at? Most studies quote observers that are "board-registered" (USA), or "post- fellowship" (UK). In other words they are trainees who have successfully sat all examinations, and who would therefore be expected to detect most abnormalities. This minimum level of observer experience is assumed in the remainder of this text and for the purposes of further discussion image quality will be described in isolation from the other parameters (clinical history and observer parameters) affecting radiological diagnosis.

The following sections are generalised to conventional as well as computed radiography, and to any relevant clinical indication (including NAI).

There is some confusion in the literature regarding the terminology of the various measures of image quality. The most intuitive classification is that which divides the measures into three groups, namely objective (physical), semi-objective and subjective

measures [BOSM2001]. The first two are discussed in *Sections 4.2* and *4.3* (following pages). The last is touched upon in *Section 4.6*, page 97.

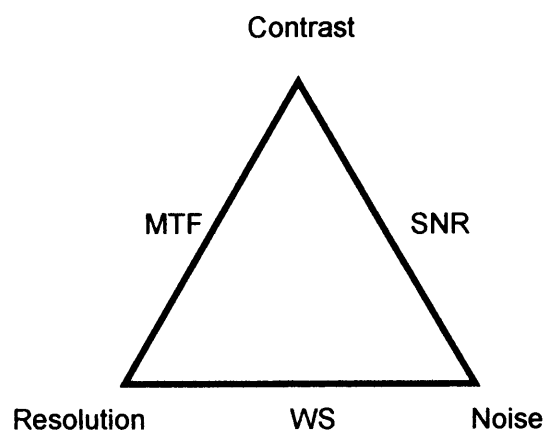
4.2 Physical Measures of Image Quality

These parameters do not take the role of the observer into account, and as such do not demonstrate a linear relationship with clinical image quality. However they are the major tests performed for quality control and allow direct comparison of the performances of different imaging systems. Because there is no observer bias, they provide objective and reproducible measures of the likely performance of a given piece of equipment [BIR2001].

Physical parameters that may be measured include signal to noise ratio (SNR), modulation transfer function (MTF), noise equivalent quanta (NEQ), detector/detective quantum efficiency (DQE), Wiener (or power) spectrum (WS), contrast, latitude, spatial resolution, characteristic curve and others [BIR2001, LAUN 2001, MARS2001A].

Marsh and Malone [MARS2001A] have identified four physical parameters that are fundamental to the characterisation of image quality, namely SNR, MTF, WS and the characteristic curve. They selected SNR, MTF and WS on the basis that these parameters encompass noise, contrast and resolution of the image without reference to the system from which they were generated. The relationship between the three is depicted in *Figure 4.2-1*.

Figure 4.2-1: Relationship between physical measures of image quality



NOISE/QUANTUM MOTTLE is due to the random fluctuations in x-ray photons reaching the film/mm². In other words it is the radiographic recording of the statistical fluctuations in a beam of x-ray photons. It has major effects that degrade the image; it reduces radiographic contrast causing small structures to be less distinguishable from their surroundings. For Poisson noise, recording N events gives a signal to noise ratio of \sqrt{N} . Therefore increasing the dose X times reduces quantum mottle by \sqrt{X} [CURR1990]. Noise limits the visibility of low contrast objects.

RADIOGRAPHIC CONTRAST refers to differences in density between areas on the radiograph. It reflects the ability of the system to record differences between normal and pathological regions, and may be defined thus

$$\text{Contrast} = \frac{\text{Difference in intensity between regions}}{\text{Mean intensity of regions}}$$

It depends on three factors; subject contrast (differences in x-ray attenuation of different tissues within the patient), film contrast (the response of the film to differences in exposure produced by subject contrast) and lastly fog and scatter (which degrade radiographic contrast as mentioned above). High contrast images are sharpness limited, while low contrast images are noise limited. Sharpness is the ability of the film or film-screen system to define an edge.

THE RESOLVING POWER of a film or film-screen system is the ability of that system to record separate images of two or more small objects placed very close together. It is often expressed in terms of “line pairs/mm” (lp/mm) – a line pair actually representing a line and a space.

THE SNR represents the relationship between contrast and noise in an image for large-scale objects.

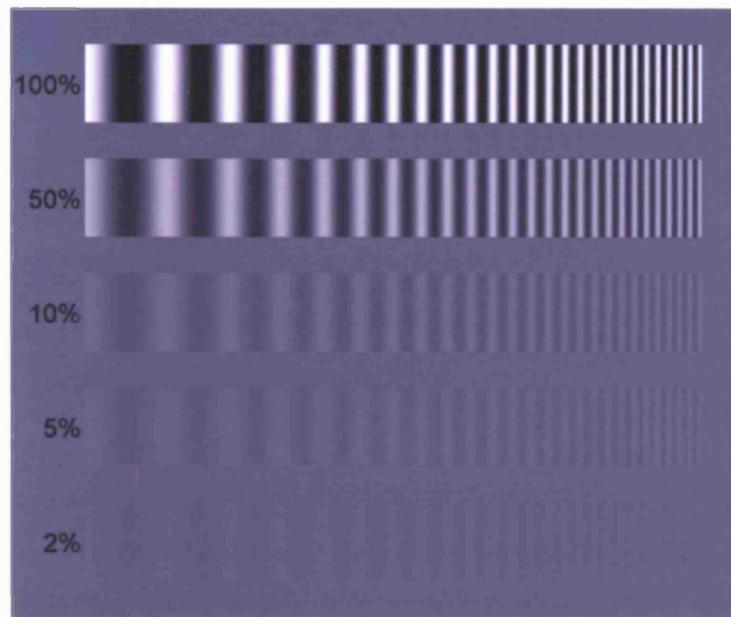
THE MTF provides an objective measure of the combined effects of sharpness and resolution. MTF is a function of spatial frequency, f, and can be thought of as

$$\text{MTF} = \frac{\text{Information recorded}}{\text{Information available}} \quad \text{or} \quad \text{MTF}_{(f)} = \frac{\text{Modulation of image at } f}{\text{Modulation of object at } f}$$

The MTF shows us how well frequency information is transferred from object to image. An MTF of 100% implies that all available information (contrast) has been recorded,

while an MTF of 2% implies a loss of nearly all the available information (contrast). Almost nothing has been recorded. This is illustrated in *Figure 4.2-2*.

Figure 4.2-2: Relationship between MTF and contrast [KORE2004]

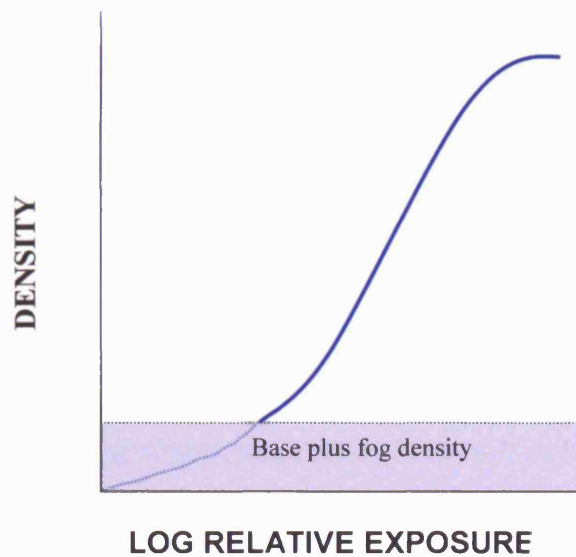


Because it is not possible to record more information than is available, MTF can never be greater than one.

WS is a measure of the total noise recorded by the film as a function of spatial frequency i.e. it represents the relationship between noise and resolution. Although graphically it is usually a curve, a formula exists whereby it may be linearised [MARS2001A].

THE CHARACTERISTIC CURVE is a plot of the relationship between exposure and density for a given film or film-screen system. An example is shown in *Figure 4.2-3* (next page), following which some important concepts are defined.

Figure 4.2-3: The Characteristic Curve



THE SPEED of a film-screen system is defined as the reciprocal of the exposure required to produce a density of 1.0 above base plus fog density. A slower system will require more exposure to produce equal density (assuming the overall shape of the curve, i.e. the contrast, of the two films is identical).

THE LATITUDE of a film refers to the range of log relative exposure (mAs) that will produce density within the accepted range for diagnostic radiology (usually between 0.25 and 2.0).

Speed and latitude have less relevance to computed than to conventional radiography as discussed in *Section 4.5* (page 93).

4.3 **Semi-Objective Measures of Image Quality**

These include high contrast limiting resolution and threshold contrast detail detectability (TCDD) tests. Semi-objective assessments may also be performed using more complex phantoms or well-defined clinical conditions such as the hand changes of rheumatoid arthritis or hyperparathyroidism. These tests allow a group of observers to compare the performance of different imaging systems in a way that allows for human perceptual variability. They produce results that can be used to make rational decisions about the application of new technology [LAUN1995].

The Leeds TO.10 and TO.16 TCDD phantoms [LEEDSTO] will be briefly described.

The Leeds TCDD phantoms are circular Perspex plates, mounted within which are discs of lead, copper and aluminium in a range of thicknesses and diameters. Different test objects have been designed for the assessment of the wide variety of conventional and digital systems that exist. The Leeds TO.10 test object has been specifically designed for the assessment of television and small-format fluorography, while the TO.16 is specifically designed for computed radiography systems. *Appendices III and IV* (pages 272 and 273) illustrate the TO.10 and TO.16 test objects. Both test objects are used and interpreted in the same way.

Images of the TCDD test objects must be obtained under the manufacturers standardised conditions for the particular object being used. This includes the use of a copper filter (provided with the test object) to override inherent tube filtration. Under specified x-ray beam conditions the test details produce calibrated input contrasts to the recording device. The observers must read the resulting images under standardised conditions. The number of detectable details of each size is recorded, and calibrated tables received with the test objects are used to calculate threshold contrast values. Half counts are permitted.

If $C_T(a)$ represents the minimum x-ray contrast required for a detail (a) to reach the threshold of visibility, and A is the area of that detail, then the detection index (H_T) has been defined by the developers of the Leeds test objects as

$$H_T(a) = [C_T(a) \times \sqrt{A}]^{-1}$$

The manufacturers provide values of H_T for a beam of 75kVp, and C_T for a range of kVp's. Values of \sqrt{A} for the various detail diameters, as well as detection index and x-ray contrast values (for a given KVp) are provided (see *Appendices V and VI* pages 274 and 275). Detection index diagrams with H_T along the Y-axis and \sqrt{A} on the X-axis can be plotted, and allow visual comparison of the performance of different imaging systems, exposure parameters etc (see *Figures 10.6-1 and 10.6-2*, page 189).

These test objects have an advantage over physical methods of assessing quality in that the visual mechanisms of observers (radiologists) are taken into account. They relate imaging performance to the x-ray exposure used to acquire the image. Theoretically, the SNR and therefore the detectability of the test details is defined and only exposure levels limit threshold contrast detection. However in practise image quality is also limited by quantum mottle and the subjective perceptions of the observers.

Another semi-objective means of assessing image quality is based on the Commission of European Communities quality criteria, discussed in the next section.

4.4 The Quality Criteria Concept

As discussed above, there is (roughly) an inverse relationship between radiation dose and image quality. In keeping with the ALARA principle, radiation dose must be kept to the minimum level that will allow an accurate diagnosis to be made. This is particularly true in paediatrics, where there is an increased individual lifetime risk of the somatic complications of radiation compared to adults. Therefore to keep radiation dose to a minimum, image quality has to be not as good as possible, but as good as necessary to answer the diagnostic question [BUSC1995].

In a bid to standardise clinical image quality, the CEC developed guidelines for the assessment of the quality of radiographs based on the visualisation of certain anatomical features. The CEC have therefore provided a semi-objective means of assessing image quality. These criteria have been developed for both adult and paediatric practise [CEC1996, EUR1996]. The assumption is that radiographs of sufficient quality to allow the depiction of important anatomical structures are therefore of sufficient quality to allow the detection of pathology.

The CEC criteria define levels of visibility as follows

VISUALISATION Characteristic features are detectable but details are not fully reproduced; features just visible

REPRODUCTION Details of anatomical structures are visible but not necessarily clearly defined, details emerging

VISUALLY SHARP REPRODUCTION Anatomical details are clearly defined; details clear

IMPORTANT DETAILS These define the minimum limiting dimensions in the image at which specific normal or abnormal anatomical details should be recognised

The paediatric guidelines are available for a range of common radiographic examinations, and guidelines for each anatomical area are displayed on individual pages. Each page is divided into three sections. The first section indicates the diagnostic requirements (image criteria) that specific radiographs are expected to fulfil. The number of criteria varies for the different projections. The second section states the criteria for radiation dose to the patient. For some projections such as the lateral segmental spine, no values for entrance surface doses are currently available. The third and final section lists examples of good technique, citing such parameters as patient position, radiographic devices, exposure parameters etc. that should allow the criteria in the first section to be fulfilled at doses quoted in the second.

Appendix II (page 270) illustrates the CEC guidelines for the paediatric lateral segmental spine, and serves to illustrate the above outline.

The guidelines were developed following deliberation between a panel of experts from countries within the European Community, and trials have been carried out to evaluate them [MACC1995, VANO1995A, VANO1995B, COOK2001A]. Cook et al [COOK2001A] found that they needed to modify the CEC criteria in their study on the quality of paediatric radiographs obtained at district general and teaching hospitals. However Guibelalde et al [GUIB1996] concluded that they were a “reasonably valid and objective method” for the comparison of imaging systems. The general consensus seems to be that the CEC quality criteria are a useful tool for optimisation of imaging parameters.

4.5 Computed Radiography

Despite advances in cross-sectional imaging (CT, MRI, US), radiography is still the first line investigation for a vast array of clinical investigations. With conventional radiography comes a need to provide storage for the large number of radiographs performed, as well as the manpower for their storage and retrieval. The ergonomic advantage of digital imaging, with the ability to store “soft copy” images is a major attraction for radiology departments.

The four most important digital technologies in current use are phosphor plates, the selenium drum (dedicated to chest radiography), flat panel detectors and charged coupled devices [FRIJ1998, MARS2001B]. The remainder of this section deals with phosphor plate technology, which is also referred to as computed radiography (CR), storage phosphor radiography and photostimulable phosphor radiography.

The concept of storing an x-ray image in a phosphor screen was the first step in the development of CR, and is credited to Luckey [LUCK1975] working for Kodak. Kotera et al [KOTE1980] (working for Fuji) produced the first medical images.

A major difference between conventional radiography and CR is that in the former the radiographic film is used for image capture, display, storage and transmission. In contrast, with CR the initial capture stage is separated from the others. With CR there are six major steps; image acquisition, processing, display, communication, archiving and erasure. There is no need to purchase new imaging equipment because the radiographs can be generated with the same tubes used for conventional radiography. In conventional radiography, the useful optical signal is derived from light emitted as an immediate response to incident radiation exiting from the patient. However with CR, the x-ray exposure produces a latent image stored on an imaging plate containing a special photostimulable phosphor [FUJI1996]. The phosphors are usually from the barium fluorohalide family activated with europium, with BaFBR:Eu²⁺ being the first to be used [ROWL2002]. The latent image that is produced on exposure to x-rays consists of trapped charge stored within the barium fluorohalide crystals. In essence some electrons are held at high energy levels, leaving vacancies (holes) where the electrons used to be [KANT1997]. In conventional radiography the electrons very rapidly reoccupy the holes, releasing light and producing the definitive image as they do so. In CR, the energy is trapped (latent image) until stimulated optically. The imaging plate (IP) is held in a light-tight cassette, reducing decay of the latent image

before read out. Although fading of the image is said to commence within the first ten minutes following exposure, it takes more than six hours to detect clinically significant differences when compared to an image that was read out immediately [SCHA1997]. After exposure the IP is inserted into the CR reader, which consists of a laser scanner and transport system. Either a helium-neon or a semiconductor laser is used [FUJI1996], with a spot size of 50 – 200 μ m [SCHA1997]. Exposure to the laser scanner triggers a process known as photostimulated luminescence in which shorter wavelength (blue) light is emitted in an amount proportional to the original x-ray irradiation [ROWL2002]. This emitted light is collected with a light guide and detected with a photomultiplier tube (PMT). The electrical signals produced by the PMT are digitised to form the image on a point-by-point basis [FUJI1989]. Digital processing is introduced to adapt the image to the specific diagnostic need [FUJI1996]. By exposing the IP to strong light, any residual data can be erased, and the plate becomes reusable.

There are three read-mode options, namely auto, semi-auto and fixed. The first is the usual setting in clinical radiographic practise [COWE1993]. In the auto mode the system reader adjusts parameters such that images of constant density are produced regardless of exposure parameters. Unlike conventional radiography there is no direct relationship between exposure and film density, and the reject rate is much reduced. The disadvantage of this increased latitude with CR is that patient overexposure is less readily identified. A further disadvantage is in the assessment of bone density (osteopaenia), which is rendered more difficult than with conventional radiography.

CR systems have a unique feature – they display information about the x-ray exposure to the IP, and therefore about the x-ray exposure to the patient [CESA1997]. This information was alluded to in the preceding paragraph (parameters adjusted in auto mode). These parameters are the latitude and the exposure index. They appear both on hard and on soft copies of the radiographs. The latitude (L) represents the dynamic range of the system. A reduction in L causes a reduction in the range of intensities that the system can image; in other words there is an increase in the gradient of the characteristic curve and an increase in the contrast of the image. CR systems are able to give an indication of the x-ray exposure to the imaging plate. Different manufacturers have developed different exposure indices. Fuji has called their exposure index “sensitivity” (S). S represents the centre of the detected object range,

and has an inverse relationship with exposure. If X represents S_k , the median (or maximum) signal intensity of the image, then Fuji have defined S as follows

$$S = 4 \times 10^{(4 - X)}$$

S has an inverse relationship with exposure. A number of other factors including patient centring and collimation affect the S value; therefore care must be taken with its interpretation [COWE1993]. Studies have shown significant variability in S among multiple CR readers and daily variation within individual readers, although the latter did not exceed tolerance limits [FAUB2002]. Fuji's recommendation is that S values for any given system should not vary by more than $\pm 20\%$. It is recommended that departments set target S values for individual examinations [SCHA1997]. To set target "ranges" is probably more realistic.

The (limited) ability to post-process images is a significant advantage of CR over conventional radiography. When used optimally it improves visualisation of pathology, and allows the display of the full object irradiated range while improving local contrast [FRIJ1998]. In other words both bone and soft tissue detail (for example) may be clearly visualised on the same radiograph. Techniques include non-linear grey-scale enhancement, non-linear unsharp masking (edge-enhancement) and single or dual exposure energy subtraction [KANT1997]. Edge-enhancement emphasises the edges and contrast of a lesion, compensating for the lower spatial resolution of CR systems [OEST1989]. It may improve image quality and enhance the visualisation of pathology; however it may also suppress pathological lesions, or produce artefacts simulating pathology. Optimisation of parameters by departments for different examinations is advised [SCHA1997].

With the Fuji CR system, factors that affect optical density (contrast) are referred to as "G" (gradient) factors, while those that affect spatial resolution (sharpening or blurring of edges) are referred to as "R" factors [FREE1997].

The various factors and what they represent are summarised in *Box 4.5-1* (next page).

Box 4.5-1

THE “G” AND “R” FACTORS IN DIGITAL IMAGING

ABBREVIATION	INTERPRETATION	EFFECT
GA	Gradient angle Slope of steepest portion of LUT*	Steep slope = high contrast Gentle slope = low contrast
GC	Gradient centre Optical density point around which the GA rotates the LUT	High GC = low optical density
GS	Gradient shift Affects overall density of the image	High GS = high optical density
GT	Gradient type Basic shape of the graph Allows black / white inversion	N = upward curve M = downward curve
RN	Frequency number Also known as kernel size Range 1 (large) to 9 (small)	Large RN emphasises larger structures Small RN emphasises smaller structures and noise
RT	Frequency type Blurs image in light exposure areas Options include R, T and F	

[FREE1997] * LUT = look up table

The G factors can be looked upon as the electronic equivalents of the shape of the characteristic curve described in *Figure 4.2-3* (page 88). In the case of digital imaging, the graph is known as a look-up table (LUT). It demonstrates the effects of changing the G and R factors on contrast and density. In other words the LUT relates input to output values. The designer may choose these values such that the resultant graphs can resemble a straight line, an “S” curve or even a “W”. As long as each input value has only one output value, then an image can be produced [FREE1997].

As mentioned in *Section 1.5* (page 30), CR has reduced spatial but increased contrast resolution compared to conventional radiography. How these differences in objective (physical) parameters of image quality relate to clinical practise is reviewed in the following section.

4.6 *Review of Clinical Studies*

Clinical studies may measure semi-objective or subjective parameters of image quality. The former were discussed in *Section 4.3* (page 89). Subjective measurements require the observer to either rank a group of radiographs in order of preference, to judge individual radiographs or to compare radiographs (either with one standard radiograph or with several) and assign a numerical score based on predetermined ordinal scales. Statistical analyses are then performed to evaluate the significance of differences in the scores of the various radiographs. Clinical studies have been performed on both digitised and CR images.

DIGITISED IMAGES Initially, a large number of clinical studies [LAMS1986, MURP1989, MURP1990, WEGR1990, WILS1995, YOUM1998] were performed in which analogue radiographs were digitised at various resolutions. Detection of pathology and subjective image quality of the digitised were then compared to those of the analogue images, and spatial resolution requirements for different clinical tasks determined. Studies showed for example that spatial resolution requirements for septal lines on chest radiographs was 1.25lp/mm [LAMS 1986], for subperiosteal resorption 5.7lp/mm [MURP1989], for cortical fractures 2.88lp/mm, with perhaps even greater resolution being required for certain fractures such as the metaphyseal fractures of child abuse [MURP1990]. Authors of another study concluded that a spatial resolution of 5lp/mm was required for some subtle musculoskeletal abnormalities (defined as changes in bone or articular architecture, soft tissues or alignment that were a) minimal or hidden by overlapping structures and b) required careful inspection for their recognition), otherwise 2.5lp/mm was adequate for musculoskeletal radiography [WEGR1990]. Following a study in which the detection of fractures from original analogue and soft copy digitised images were compared, the authors concluded that the digital system tested was not a satisfactory alternative to the original radiograph in the routine reading of fracture films [WILS1995]. Specific to non-accidental injury is the study by Youmans et al. In this study the authors digitised the skeletal surveys of 20 control and 20 consecutive children in whom abuse had been confirmed. Observers compared and rated the original and soft copy digitised radiographs for image quality, fracture detection and suspicion of child abuse. The conclusion was that failure to identify the characteristic fractures of abuse on digitised images probably rendered digitised

images inadequate for the interpretation of skeletal surveys performed in suspected NAI [YOUM1998].

In this last, and other similar studies, researchers digitised analogue images and then compared the two for conspicuity of abnormality. The digital images could never record more information than was on the original analogue images. Furthermore the quality of images was dependent on the quality of the digitiser. Although providing some useful information regarding the likely requirements for digital imaging, the results of these studies cannot be directly extrapolated to CR.

COMPUTED RADIOGRAPHY IMAGES Review of the literature reveals that phantom (semi-objective) and observer (subjective) studies have been performed to compare CR to conventional radiography. Comparisons include image quality and radiation dose to the patient, various post-processing parameters and soft and hard copy image display. The majority of studies have related to chest radiography, although more recently there has been an increase in the number of studies of the musculoskeletal system, and it is some of these that are reviewed.

COMPUTED VS CONVENTIONAL RADIOGRAPHY A large study was performed by Prokop et al in 1990 in which 110 segments of human femoral shafts split in half longitudinally formed the basis of a skeletal phantom [PROK1990]. Conventional film-screen images were obtained with a film of speed 250, and CR images with a Fuji system. Various exposure factors were used. From their results the authors concluded that digital radiography performed at least as well as conventional radiography with respect to contrast resolution.

Wilson et al compared CR radiographs of the extremities of patients presenting with minor trauma to film-screen radiographs of the same extremities obtained at the same time [WILS1991]. From their results they questioned the adequacy of CR for the imaging of skeletal trauma compared to conventional radiography. They suggested that in situations where CR is the primary imaging technique, close co-operation between clinician and radiologist, careful clinical examination and the selective use of conventional radiography in appropriate patients is necessary for the reliable detection of subtle fractures. This of course leads to the question of the definition of “appropriate patients”. For instance, would it be deemed “appropriate” to routinely perform skeletal surveys in cases of suspected NAI with conventional film-screen technology on the basis of the results of this paper?

There is no doubting that the increased contrast resolution of CR is a great advantage when compared to conventional radiography. This was well demonstrated in a study by Wilson et al [WILS1994], in which CR scored better in those patients with cervical trauma all of whom were imaged with both modalities while wearing a cervical collar. Interestingly in this study, the observer who ranked conventional radiography above CR was the most experienced radiologist, suggesting that aspects of learning and experience interact in complex ways and may be critical in the acceptance and effectiveness of new techniques. Although it scored higher for overall image quality, the advantage held by CR in terms of visibility of structures was only true for the soft tissues and not for the bones. If this is true then CR would have an advantage over conventional radiography in detecting the soft tissue swelling that accompanies acute trauma.

Other studies have been performed comparing the two techniques for visualisation of soft tissue foreign bodies [REIN1996], bone abnormalities in the hands of adults [SWEE1997], early erosions of rheumatoid arthritis (again in adults) [VAND2000] and artificially created lesions and fissures in porcine bones [ZAHR2001]. Results of these studies have led the involved authors to conclude that CR is at least as good as conventional radiography in imaging of the musculoskeletal system.

Another area of interest when comparing the two techniques is their respective dose implications. Generally speaking, the CR system requires a higher radiation dose to achieve the same (low) degree of quantum mottle as a conventional film-screen system [LIND1996]. However because of the wide dynamic range (1:10,000 compared to 1:100) and the ability to post-process, there has been much expectation of a substantial reduction in radiation dose with the implementation of CR.

Murphey et al [MURP1992] state that dose reductions of 25% to 50% are possible with CR in musculoskeletal imaging compared to conventional imaging.

Prokop et al [PROK1990] showed that a dose reduction by a factor of four although tending to decrease the area under the ROC curve did not significantly impair the diagnostic performance of observers compared to film-screen images. Conversely an increase in exposure led to a significant diagnostic advantage over film-screen images. Siefert et al [SIEF1996] using a real female head with a skull fracture were able to demonstrate that a dose reduction of 57% compared to conventional radiography was possible while still maintaining satisfactory image quality.

Jonsson et al [JONS1996] showed that although image quality declined with declining exposure, there was no significant difference in ranking between 50% and 25% exposures compared to 100% exposures.

Hufton et al [HUFT1998] on a study of 900 children found it was possible to reduce dose by at least 33% for chest radiographs and 60% for other examinations in departments using conventional film of 400 or less, again with comparable image quality.

In contrast to the studies cited above, Bragg et al [BRAG1997] reported a significant increase in radiation dose (particularly in thicker body parts) for CR compared to conventional radiography. James et al [JAME2001] from their experience conclude that although the reduction of total patient dose by reducing the number of repeated exposures is well established, the magnitude of dose reduction with CR has probably been overstated. With reduction in radiation dose, although the digital image is reproduced with constant density, there is an increase in quantum mottle. The possible dose reduction therefore varies with the clinical indication. Lindhardt suggested that examinations of the musculoskeletal system in which high resolution is not required such as scoliosis and limb length radiographs are those examinations in which significant radiation dose reductions can be made [LIND1996]. This is supported by the work of Peer et al [PEER2002], who concluded that to allow “reliable” (sic) detection of wrist fractures, exposures equivalent to those required for conventional film of speed 200 are necessary. However they also concluded that for general-purpose skeletal radiography, dose reductions of up to 62% might be achieved with no detrimental effects on diagnosis.

EDGE-ENHANCEMENT VS NO EDGE-ENHANCEMENT Of the post-processing options available to the observer, at GOSH edge-enhancement (unsharp mask filtering) parameters are the least likely to be altered, with radiologists being much more aware of such tools as magnification, grey-scale, contrast, brightness etc.

In a phantom study, it was shown that small kernel size and moderate enhancement factors reduced observer performance [LOO1985]. On the other hand, in a clinical study on chest radiographs, the same parameters led to the improved detection of septal lines [OEST1989].

In the study by Prokop et al [PROK1990], it was demonstrated that unsharp mask filtering did not improve performance. In fact with larger factors there was a reduction in the detectability of cortical lesions compared to 1) digital images when smaller

enhancement factors were used, and 2) standard conventional radiography with no edge-enhancement.

In contrast, Wilson et al [WILS1994] showed that observers rated edge-enhanced radiographs higher than radiographs with no edge-enhancement except for the assessment of vertebral alignment in which non edge-enhanced radiographs scored better. This study however did not consider abnormal radiographs – the assumption was made that improved visibility of normal anatomy would lead to improved detection of abnormality. However in their discussion, the authors suggested that more extensive studies of proven injuries were required.

Kaji et al [KAJI1995] were unable to demonstrate any significant advantage of edge-enhancement in the detection of skeletal fractures, although they did state that it was easier to detect “small fractures” (sic) on the edge-enhanced images.

Lindhardt [LIND1996] reports that in his department, edge-enhancement is not used when imaging the musculoskeletal system because of the effect this will have in exaggerating overshoot artefacts caused by metallic implants and at the borders of cortical bone.

Prokop et al [PROK1990] suggest that the unselective nature of the filtering process may partially explain the failure of edge-enhancement to improve performance. The filtering process also leads to enhancement of physiological trabecular irregularities, which may then be misinterpreted as cortical defects. Another reason put forward by these authors is the influence of observer subjectivity. Images with low or no edge-enhancement more closely resemble the conventional film-screen radiographs that observers are used to. This may certainly be true during the learning curve, when departments have only recently purchased their CR systems. The situation once they have “got their eye in” is less clear.

Despite these uncertainties, in the radiology department at GOSH, the standard setting for imaging of the skeletal system includes minimal edge-enhancement, with routine parameters for chest radiographs as follows: GA = 1.3, GT = E, GC = 1.6, GS = variable, RN = 4, RT = R, RE = 0.5. These parameters were chosen based on the subjective preferences of the radiologist mainly involved in interpretation of skeletal surveys for NAI. It is not known how these parameters have affected diagnostic accuracy in children and infants presenting to GOSH with suspected NAI.

HARD VS SOFT COPY IMAGES Hard copy images are printed out on film. Soft copy images are read directly from a monitor. Lesion conspicuity on soft copy images will

depend on the resolution of the monitor. Most departments have the standard 1K² monitors, while others have the more expensive 2K² monitors, which have a higher resolution.

In their study on cervical spine radiographs, Wilson et al [WILS1994] allowed observers to use all the standard imaging functions available on a 1K² monitor. Observers scored soft copy higher than hard copy images for all categories including soft tissue structures, vertebral margins and alignment and other bony structures.

Kaji et al [KAJI1995] allowed observers to use only the magnification function available on a 1K² monitor. They found that although observers were three to four times slower at reading an image from the monitor, there was no significant difference in fracture detection between the two.

Reiner et al [REIN1996] allowed observers to modify window and level settings, magnification and zoom, but spatial resolution and contrast functions were not available on their 2K² monitor. They showed that soft tissue foreign bodies were more readily visualised using soft rather than hard copy radiographs.

An interesting study by O'Connor et al [OCON1998B] showed that while observers preferred the images as presented on a 2K² monitor, the 2K² monitor did not lead to an improved diagnostic performance compared to the 1K² monitor for the detection of subperiosteal erosions and acro-osteolysis. These authors point out the cost implications of their results; including hardware drivers, at the time of their study the difference between 1K² and 2K² monitors was approximately 500%, and is currently approximately 300% [personal communication with Mr. Liam Maguire, Sales Representative, Fuji Co Ltd, UK].

Finally Eng et al [ENG2000] compared the interpretation of casualty radiographs from soft and hard copy formats. Digital images were read from a 2K² monitor. It is not certain what modifications (if any) of contrast, brightness etc the observers were permitted to make. In contrast to the studies above, the results of this study showed a significant reduction in the detection of subtle abnormality from a variety of radiographs (including 62 skeletal radiographs) when viewed as soft compared to hard copy. This study also demonstrated differences of equal or even greater magnitude associated with the training level and physician speciality of each observer. Although ROC studies are said to take observer differences into account, it may still be necessary to consider observer characteristics when evaluating teleradiology and other services.

4.7 Summary

Because it involves (human) observers, there is a subjective element to the assessment of image quality. The production of aesthetically pleasing radiographs does not necessarily result in improved diagnostic performance, and may well result in increased radiation dose to the patient. Optimisation of radiographic parameters for specific examinations and clinical indications is advised. Objective methods of assessing image quality consider the performance of the imaging system. Semi-objective (e.g. the CEC quality criteria [CEC1996, EUR1996]) and subjective methods take into consideration the effects of observer perceptions and preferences.

CR is a digital technique in which crystals of photostimulable phosphors are used. It differs from conventional radiography in that there is no direct relationship between film density and radiation exposure. Rather, departments must monitor and optimise values for exposure indices (sensitivity) for individual examinations.

Generally speaking, computed radiography has wider exposure latitude than conventional radiography and improved contrast resolution. Other advantages include reduced radiation exposure (mainly because of fewer repeated examinations), the post-processing capabilities, and the future promise of filmless departments. In practice, departments have documented an initial steep learning curve, with a need to optimise radiographic parameters rather than merely relying on those set up by manufacturers [KANG1988, LIND1996, BRAG1997].

Controversy exists as to the magnitude of achievable dose reductions. However the general consensus is that examinations such as scoliosis and limb length determination, in which mottle will not adversely affect the response to the clinical question, are those examinations in which dose reductions of up to 95% are possible. Although edge-enhancement has generally been of use in the detection of pulmonary nodules, its benefit in the musculoskeletal system remains unclear. There are also uncertainties as to the merits of soft compared to hard copy interpretation of images.

Despite its reduced spatial resolution, CR has generally been found to be as good as conventional radiography in imaging of the musculoskeletal system. Controversial areas in terms of the detection of the subtle fractures of NAI include optimal exposure parameters, optimal S levels, and the roles of post-processing and soft copy interpretation.

Chapter 5

Optimising Image Quality for the Diagnosis of NAI

In this chapter the concept of the evaluative framework for the measurement of image quality is introduced, with emphasis on the challenges that might be faced when applying this framework to the use of CR in NAI.

5.1 *The Need for Optimisation*

With the widespread use of digital imaging in trusts throughout the UK, radiology has entered the computer age. The challenge now is the smooth transition into “filmless” departments. With CR, as with any new technology, there has been much research as regards the quality of images obtained, dose implications, spatial and contrast resolution, and the comparison of all of these parameters with conventional film-screen imaging systems. The advantages of CR with its linear detector response, improved detector efficiency (compared to slow but not fast film-screen systems) and digital processing capabilities have all contributed to its increasing use. Observer studies have generally shown no significant difference in diagnostic accuracy between conventional film-screen and CR images in general, and of the musculoskeletal system in particular. The majority of studies have been performed in adults, and in those studies that have been performed in children only a small minority have discussed the use of CR in the diagnosis of NAI. Furthermore, most studies have compared images obtained with digital against those obtained with conventional film-screen techniques using fixed radiographic parameters (kVp, mAs) with no attempt at optimising these parameters for a given clinical indication. Due to the need to limit radiation dose, most have been phantom studies, which are limited by the difficulty of extrapolating results to clinical use. The reduced spatial resolution of digital when compared to film-screen systems would suggest that the former do not produce images of sufficiently high quality for the diagnosis of NAI. This has not prevented departments that deal with the imaging of children from purchasing digital systems and attempting to go “filmless”. The current situation is that many departments, having installed their digital systems are now asking (personal communication, on the internet, discussion at meetings etc) whether these systems are appropriate for the diagnosis of NAI, and which radiographic parameters and protocols will produce images of sufficient quality. The question that now needs answering is not whether CR is comparable to film-screen in the diagnosis of NAI, but how departments can optimise their (new) CR systems.

In an attempt to clarify the situation, it is possible for individual departments to alter their radiographic parameters for NAI skeletal surveys such that the radiologists involved with reporting them are satisfied with the images produced. However this is

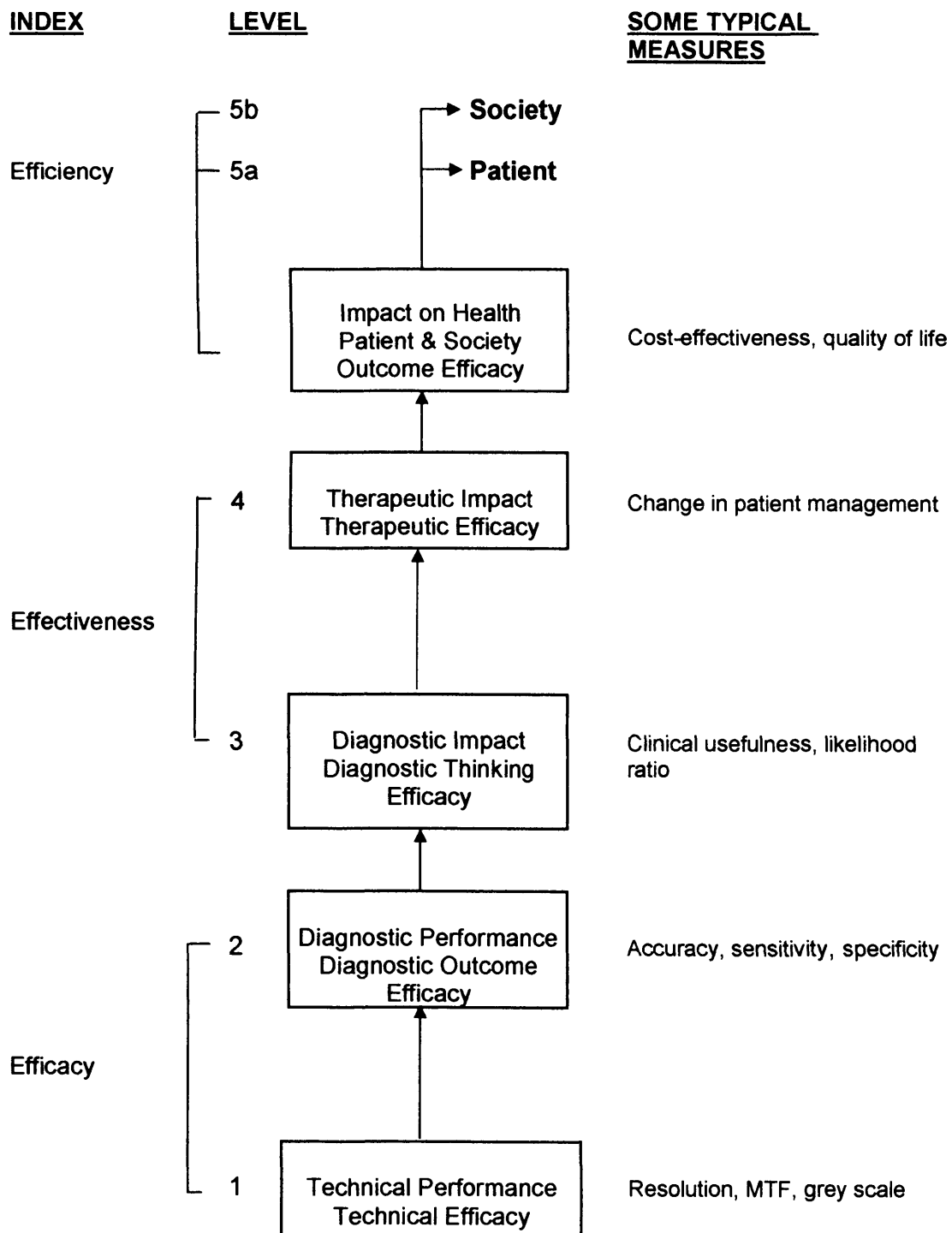
an unsatisfactory approach for several reasons. Firstly, many departments do not have specialist paediatric radiologists with sufficient time to dedicate to this task. Secondly, a large number of films are sent for a second opinion by paediatric radiologists who specialise in the field of NAI. Additionally, these radiographs may ultimately end up as evidence in court. To some extent the quality of the report is dependent on the quality of the radiograph. There will always be a subjective element to the assessment of image quality; however attempts should be made to reduce this as much as possible. Finally, much emphasis is currently being placed on the practice of evidence-based medicine. This necessitates well-designed scientific studies with reproducible results that will form the foundation for changes in policy and practice.

5.2 The Evaluative Framework

A review of the literature demonstrates a move away from the simple physical assessment of image quality to the more complex approach of health technology assessment (HTA) [DOH1991, HTA1992, THOR1994, MACK1995, BREA2001]. This is defined as the “assessment of the costs, effectiveness and broader impact of all methods used by health professionals to promote health, prevent and treat disease and improve rehabilitation and long term care” [DOH1991, HTA1992]. HTA encompasses the measurement of the efficacy, effectiveness and efficiency of an imaging technique, both in its own right and in comparison to other techniques, and for general as well as specific clinical indications. The ultimate aim of HTA is improved diagnostic accuracy leading to more streamlined and cost-effective healthcare, resulting in a measurable positive impact on individual patients and society at large. *Figure 5.2-1* (next page) illustrates a modified version of the (hierarchical) evaluative framework alluded to by many authors [FRYB1991, THOR1994, LANG1996, PEAR1999, BREA2001]. The figure also lists some typical measures used to evaluate each level.

The list of diagnostic indications to which CR may be put to use is “endless” [CORM1992], and it is not possible or indeed necessary to carry out full health technology assessment at all five levels for each and every condition. The framework should not be seen as a compulsory chain of events intended to be rigidly adhered to, but rather as a guideline for standardisation of research methodology [THOR1994, REIN1997].

Figure 5.2-1: An evaluative framework for the measurement of the effects of an imaging system.



5.3 Efficacy, Effectiveness and Efficiency

Assessing an imaging technique/strategy according to the framework outlined in *Figure 5.2-1* (previous page) considers the efficacy, effectiveness and efficiency of that technique/strategy. Levels 1 and 2 assess efficacy – i.e. whether the technology actually works for the indication to which it is being put to use; Levels 3 and 4 assess effectiveness – i.e. the impact of the technique as regards changes in diagnosis and management; Level 5 assesses changes in quality of life as well as of the economic efficiency of the technique. It is usually measured in terms of cost-effectiveness or cost-benefit to the individual and/or society. The terms efficacy and effectiveness are often used synonymously, with the terminology being further complicated by the use of the term “clinical efficacy” where effectiveness might have been less confusing [THOR1994, KENT1992]. Measurements of efficacy are more objective than those of effectiveness, and certain parameters may be measured in the laboratory or by the use of phantom studies. Effectiveness requires patient involvement and is measured in the clinical setting. To avoid confusion, the terms efficacy, effectiveness and efficiency are perhaps best replaced by the terms technical efficacy, diagnostic-accuracy efficacy, diagnostic-thinking efficacy etc. as shown in the text boxes in *Figure 5.2-1* (previous page).

As mentioned earlier, the diagnosis of NAI hinges greatly on the quality of the images obtained. NAI is one condition that merits individual and specific research particularly as regards Levels 1 and 2 in the context of CR, where very little research has so far been performed. This chapter reviews the measurements of the effects of imaging techniques with specific reference to CR and NAI based on the model illustrated in *Figure 5.2-1* (previous page). Some of the difficulties that may arise when applying this framework to NAI, and how they might be overcome are discussed.

5.4 Level 1. Technical Performance/Efficacy

This level deals with the traditional methods of assessing the quality of an imaging system, namely the physical parameters of spatial and contrast resolution, modulation transfer function, sharpness and grey-scale/dynamic range. Using these parameters, the technical performance of one imaging technique may be compared to that of another, as may the performances of the same imaging technique using either different imaging algorithms/parameters or different systems developed by various manufacturers.

Specific to the assessment of technical performance of a CR system is the determination of the relationship between “exposure index” and plate exposure. This is so because with CR, unlike traditional film-screen imaging, there is no direct correlation between film density and exposure. The “exposure index” and its relationship to plate exposure varies from manufacturer to manufacturer [BIR2001].

Kodak

Exposure Index EI $\cong 1000 \times \log_{10}(\text{Exposure in mR}) + (\text{Constant})$

Aqfa

IgM $\cong \log_{10}(\text{Exposure in mR}) + (\text{Constant})$

Fuji

Sensitivity S $\cong \text{Constant} + \text{Exposure or}$

$S = 4 \times 10^{(4-X)}$ (where X represents S_k , the median/maximum image intensity)

It is essential to confirm a consistent relationship between exposure index and plate exposure. For any change in plate exposure (i.e. radiographic parameter) there should be a predictable change in the “exposure index”. This allows a rough assessment of radiation exposure to the patient by noting the value of the “exposure index”. When using a Fuji system, a 20% increase or decrease in plate exposure should result in S decreasing or increasing by approximately 17% or 25% respectively [BIR2001].

When assessing a CR system, it is also worth considering the read mode. CR system readers have three selectable modes: fixed, semi-auto and auto. In normal day-to-day

practice the auto mode is selected, allowing the system reader to optimise the sensitivity and latitude values and produce images of near constant density regardless of exposure (with reduced exposures image quality will be limited by quantum mottle). In Level 1 studies it is often extremely useful to employ the semi-auto or fixed modes as these allow assessment of the consistency of the system. The fixed mode operates with fixed sensitivity and latitude values, and requires accurate selection of radiographic parameters for the given clinical indication and patient size in a similar way to the conventional film-screen technique [COWE1993]. It may be that the image quality requirements for the diagnosis of NAI are such that the fixed mode will be preferable to the semi-auto or auto modes.

Some studies have delineated spatial resolution requirements for various diagnostic indications [MURP1989, FOLE1983, LAMS1986, MACM1986, GOOD1986, SEEL1987, MURP1990, COX1990]. Generally a spatial resolution of less than about 2.88lp/mm results in a significant decrease in the detection of non displaced or minimally displaced extremity fractures. It is said that the effect is most pronounced in torus fractures, metaphyseal fractures of NAI, minor avulsion injuries and in undisplaced fractures in which the only detectable abnormality was trabecular disruption [MURP1990]. It is known that standard CR imaging plates have a maximum spatial resolution of 2.5 to 5lp/mm [KOTT1997A]; however the ACR guidelines for skeletal surveys in suspected NAI recommend a limiting resolution of at least 10lp/mm for all anatomic regions in infants [ACR1997]. The higher spatial resolution of 10lp/mm is only achievable using high resolution (HR) imaging plates, which result in an increase in radiation dose. For this reason, paediatric radiology departments do not favour their use. Not all studies have shown satisfactory diagnostic performance [WILS1995]. Furthermore, although magnification and air-gap techniques have been shown to either directly improve or compensate for the poor spatial resolution of CR [NAKA1987, KOTT1997A, KOTT1997B], such studies have not concentrated on the subtle fractures of NAI.

An interesting approach was adopted in a collaborative study between researchers in Sweden and the UK, which showed significant correlation between measures of clinical and measures of physical image quality for certain investigations. For instance regarding trabecular markings on AP radiographs of the lumbar spine, there was significant correlation between contrast and signal-to-noise ratio (on the one hand) and fulfilment of CEC criteria (on the other) [SAND2001]. The authors studied adult

patients. However the technique may also be extended to children, by basing the assessment of clinical image quality on the CEC criteria for paediatric radiographic images [EUR1996].

5.5 Level 2. Diagnostic Performance/Accuracy Efficacy

In contrast to Level 1 evaluation, the evaluation of diagnostic performance is of more direct clinical relevance. It is the commonest level of the framework to be researched. The questions to be answered are whether the technology is able to distinguish between normality and abnormality, and if so how well (relative to other technologies or to different applications of the same technology). Measurement parameters include accuracy, sensitivity, specificity and ROC curves.

Many phantom, animal and human studies have shown a favourable comparison between digitised, digital and film-screen images in terms of subjective image quality and the detection of abnormalities such as pulmonary nodules, subtle/undisplaced fractures and the hand changes of hyperparathyroidism, whether the digital images are printed as “hard copies” or read from a monitor as “soft copies”. Digital images have often had the added benefit of dose reduction [FURH1987, KANG1988, PETT1988, MURP1989, WEGR1990, MURP1992, BUCK1992, DON1999]. However other authors have been more cautious [WILS1991, LIND1996, BRAG1997, YOUM1998, JAME2001, PEER2002].

An assessment of diagnostic performance requires independent confirmation of the presence or absence of an abnormality [MACK1995]. Generally speaking, it is the pattern of detected injuries coupled with an unacceptable history that allows the radiologist to make a diagnosis of NAI. The fractures not only need to be detected, but also need to be interpreted as being secondary to non-accidental trauma. Experience and an understanding of the mechanisms of such fractures is required in order to assess the reliability of the given history, and to correctly date the injuries. To limit the effects of observer experience on these variables, studies in respect to NAI should probably concentrate mainly on the detection and relative ease of detection of (listed?) abnormalities from hard and soft copies, and not on their overall interpretation.

A further confounding issue in the diagnosis of NAI is the absence of a gold standard. As alluded to above, simply detecting the injury/injuries will not necessarily lead the radiologist to reach a diagnosis of NAI – in fact a recent study has concluded that under-recognition of NAI in infants is certain [BALF2002]. A suitable gold standard need not be another test – it may be the opinion of an experienced radiologist or perhaps more ideally a consensus opinion of a group of radiologists [BREA2001]. It

has been shown that there is significant interobserver variability between radiologists in the interpretation of accident and emergency radiographs [ROBI1999], and this presumably also holds true for NAI. Results of a study to determine the degree of interobserver variability and the effect of consensus opinion amongst a group of paediatric radiology consultants in the UK who act as expert witnesses in the diagnosis of NAI would be interesting. Indeed it seems that such a study is currently under way (Carty H, Hall CM, personal communication). However, observer variability aside, it is true to say that the more fractures detected, the more likely a diagnosis of NAI will be made – re-emphasising the importance of high quality imaging in suspected cases. It is well recognised that many fractures undetected by skeletal survey are diagnosed by specimen radiology, and even more are detected by histological examination. Of fractures diagnosed by histopathology, 92% were detected by specimen radiology and only 58% from prior skeletal surveys [KLEI1995A]. Histopathology could therefore serve as a gold standard for the purposes of research, however in the clinical setting it is usually reserved for those areas that are radiographically abnormal, and it is doubtful if ethical approval could be obtained to perform histology on radiographically normal areas. As it is, histologists face very similar diagnostic difficulties to radiologists. Problems include experience, plane of dissection relative to the plane of the fracture and difficulties with fracture dating. Therefore even histology is not the ideal gold standard.

Studies have shown increased detection of abnormalities when observers are presented with a relevant history. This is particularly true of the musculoskeletal system. It has been shown that a history of localising signs and symptoms leads to an increase in the true positive rate combined with a decrease in the false positive rate. In other words there is an improvement in the observers' perceptive ability [BERB1988]. For the sake of standardisation, participants in such studies should be informed of a history of suspected NAI with no localising signs/symptoms. Although it might appear to introduce an element of bias by allowing the radiologist(s) to look carefully for the subtle fractures of NAI, this simulates the usual clinical scenario. Furthermore, the fact that all observers would have the same information would tend to cancel out this source of bias.

Finally, any evaluation of the diagnostic performance of an imaging system must of necessity take into account errors of observer perception, which are now said to be the weakest aspect of clinical imaging [ROBI1997]. The reasons for these errors include

poor image quality (including poor technique), failure to perceive abnormalities, lack of experience or knowledge, and misjudgements. In regards to failure of perception, do senior radiologists trained in the conventional film-screen era have more difficulty than their junior colleagues who have been trained in the “digital age” when it comes to interpreting CR images, despite their greater general experience? Wilson et al [WILS1994] have also raised this possibility (see also *Section 4.6* page 97). It has been suggested that the visual acuity of radiologists’ for both high and low contrast objects should be tested [STRA1991]. These authors would advocate correlating the visual acuity of a group of observers with their detection rates of fractures in NAI.

Measures of diagnostic systems and observer performance have been well described [HANL1982, METZ1986, POSN1990, BRIS1991, TUDO1997]. Parameters include

ACCURACY This is a measure of the percentage of correct diagnoses. It suffers from the disadvantages of being dependent on the prevalence of the condition being reported and of giving no distinction between false positive and false negative results.

SENSITIVITY This indicates the fraction of patients who actually have the disease that have been correctly diagnosed as positive. It is also called the true positive fraction (TPF).

SPECIFICITY This indicates the fraction of patients actually without the disease that have been correctly diagnosed as negative. It is also called the true negative fraction (TNF).

FALSE NEGATIVE FRACTION (FNF) This defines the fraction of patients who actually have the disease that are incorrectly diagnosed as negative. Mathematically it equals 1 minus TPF.

FALSE POSITIVE FRACTION (FPF) This is the fraction of patients actually without the disease that have been incorrectly diagnosed as positive. Mathematically it equals 1 minus TNF.

RECEIVER OPERATING CHARACTERISTIC (ROC) CURVES plot the TPF against the FPF of a wide range of repeated observations. They indicate the tradeoffs between sensitivity and specificity that are available from a diagnostic system, and allow the comparison of two or more systems. By comparing the area under the ROC curves (A_z) for different systems/observers/post-processing parameters etc, the researcher has the ability to compare the inherent discrimination performance of such systems/observers etc independent of possible variations in the confidence threshold of the observers [SWET1979]. For the purposes of ROC analysis, it is essential that a gold standard (measure of diagnostic truth) is available, and that the patient population is defined in

such a way as to meet the purposes of the study [METZ1986]. It should be noted that methods of ROC analysis that do not require a gold standard are currently being developed.

In terms of the observers, there are two commonly quoted parameters, namely **INTEROBSERVER RELIABILITY** This represents the consistency of diagnostic ratings between two or more different observers analysing the same data under the same conditions.

INTRAOBSERVER RELIABILITY This represents the consistency of diagnostic ratings of one observer analysing the same data on two or more separate occasions under the same conditions.

Both inter and intra observer reliability can be referred to numerically as a (Cohen's) kappa score, interpretation of which is shown in *Box 5.5-1*.

Box 5.5-1

INTERPRETATION OF COHEN'S KAPPA/KAPPA/K

KAPPA SCORE	DEGREE OF RELIABILITY
< 0.20	Poor
0.21 – 0.40	Fair
0.41 – 0.60	Moderate
0.61 – 0.80	Good
0.81 – 1.00	Excellent

[TUDO1997]

5.6 *Level 3. Diagnostic Impact/Thinking Efficacy*

Studies at this level assume that patient outcome can only be affected by a radiological test if there is a change in the clinician's way of thinking/differential diagnosis because of the test results. An evaluation of diagnostic impact is therefore an evaluation of the clinicians' confidence in both the imaging tool and the radiologist's report [THOR1994, FREE1987, MAIS1991]. Related to this is an assessment of the extent to which the imaging system under evaluation can replace more standard techniques [MAIS1991]. An important feature of this level of evaluation is the consideration of the diagnostic confidence before and after application of the diagnostic tool, described in terms of likelihood ratios and predictive values. In the context of NAI because of the lack of other diagnostic tests, the paediatrician's confidence in the diagnosis is to some extent dependant on the findings of the radiologist, who must in turn be confident in the imaging technique employed.

It is possible to design a questionnaire based study of diagnostic impact comparing the effects of reports issued to clinicians on the change in their level of confidence in the diagnosis of NAI before and after obtaining the reports. However as the skeletal survey remains the only reliable means of detecting skeletal injury, and as the clinicians' diagnosis will clearly be greatly influenced by the result of such surveys, studies at this level in NAI may in fact represent a test of diagnostic performance rather than diagnostic impact.

5.7 Level 4. Therapeutic Impact/Efficacy

Exposing the patient to ionising radiation is not justifiable if reaching a diagnosis is purely of academic interest. To help the patient, there must be a change in management either as a direct consequence of the diagnosis, or because of the establishment of a firm prognosis. This will allow both patient reassurance [KELS1984] and in the case of paediatric patients, reassurance of parents and guardians. Generally speaking the subtle metaphyseal and rib fractures of NAI do not require treatment; however displaced diaphyseal fractures may require immobilisation. There will certainly be a change in management if a diagnosis of OI (for example) is confirmed, excluded or made. Furthermore, reaching a diagnosis of NAI will most definitely influence the social management of the patient and his/her family.

Clinicians may fill out questionnaires before and after radiological investigation for suspected NAI to assess the diagnostic (see previous section) and therapeutic impact of computed radiography in this scenario. Such studies may reveal deficiencies in selection criteria for infants and children undergoing skeletal surveys. However, as previously mentioned, results might in fact be more a reflection of diagnostic performance or clinicians' confidence in the radiologist and his/her report than of diagnostic or therapeutic impact.

5.8 Level 5. Impact on Health/Patient & Societal Outcome Efficacy

Studies of the impact of an imaging technique on health are divided into two levels – firstly how the technique impacts on the health of the patient. Secondly, at a higher level, how it impacts on the health of the general society. Measurement parameters include risk-benefit analyses (including the justification of radiation exposure), change in quality adjusted life expectancy and cost-benefit and cost-effectiveness analyses [THOR1994].

Compared to conventional film-screen techniques, with CR there is potential for a reduction in radiation dose of up to 60% for radiographs of the paediatric abdomen, pelvis and skull, and 33% for paediatric chest radiographs [HUFT1998]. As mentioned earlier, reductions in radiation dose are made possible with CR in auto read mode, as the adjustment of sensitivity levels allows for the production of images of near identical display characteristics. However dose reduction is limited by the reduced SNR (increased quantum mottle) that occurs at lower exposures [COWE1993]. For this reason, it has been suggested that significant dose reduction is only possible with musculoskeletal examinations not requiring high detail e.g. scoliosis radiographs [LIND1996, PEER2002]. The potential for dose reduction with CR leaves room for manipulation and optimisation of radiographic parameters. While it is recognised that the high image quality required for the diagnosis of NAI will lead to increased dose, these doses can only be justified if they remain within nationally acceptable limits and increase the detection of (subtle) fractures.

The aim of cost-benefit and cost-effectiveness studies is to inform the efficient allocation of resources. There has been a general increase in the number of cost-effectiveness studies in the literature, however only a small number relate to radiology, and these have generally fallen short of acceptable standards [BLAC1997]. In one study, it was estimated that the minimum annual cost of assessing children suspected of being victims of abuse in 1992 in the authors' institution was £63,500 per child [SUMM1992]. The authors calculated this estimate by doubling the cost of investigations on 181 children over a six-month period. The costs included salaries, incidental expenses, additional (out of hours?) medical time, and the costs of investigations and hospitalisation. However, to this can be added the costs incurred by

holding case conferences and of involving social services. Further costs not considered by the authors include those of conducting criminal and care proceedings, the time spent on getting to and appearing in court, of following-up the proband (index case), investigating siblings and placing the children in care. In addition are the costs of physical and psychological therapy. It can be seen that the investigation and subsequent management of suspected or confirmed NAI incurs a huge financial burden, the estimation of which is fraught with difficulties. This large amount of spending calls for optimisation of radiology, with its relatively low cost and upon which action is (partially) based.

Although rarely lethal in themselves, most infants who die from NAI have associated skeletal injury [BALF2002]. If not removed from their abusers, these infants are at risk of being subjected to increasingly violent attacks, which may eventually end in long term neurological disability or death [ALEX1990, CHAP1997, BALF2002]. Even in the absence of detailed cost-effectiveness studies, there are risks associated with returning a child to an abusive environment. There is also much anguish when a child is removed in error from the care of loving parents. Both these scenarios justify any costs incurred in reaching and ensuring the correct diagnosis once the suspicion has been raised.

In terms of the effect on quality of life (QoL), an objective evaluation of the benefits to the patient and society of the skeletal survey in the case of NAI is not an easy task. Authors have emphasised the validity of measuring QoL as an end point in medical research. They have also discussed the importance and means of maintaining high standards in studies of QoL, and highlighted the general considerations and designs of questionnaires used in the measurement of patient satisfaction [SHYE1989, FITZ1991A, FITZ1991B, GILL1994, EDIT1995, FAYE1995, FALL1996]. It is not obvious however who (in the case of suspected NAI) the questionnaire should be administered to. Articles have been published giving guidelines on the differentiation of child abuse from unintentional injuries and sudden infant death syndrome (SIDS) [LEVE1993, AAP2001]. The attitudes and results of a survey of the parent of a child diagnosed with the latter will differ greatly from those of a parent convicted (or even acquitted) of child abuse. Furthermore it is not reasonable to conclude that the results of such surveys are a direct result of the use of digital imaging systems.

In unequivocal physical abuse cases, removal of the child to a safe environment will be of benefit to that child. However, following a positive skeletal survey, will the child

necessarily be removed from his/her home environment? A recent article warned that the CPR should be seen as a record of those children in need of a protection plan, and not as an endpoint in itself – a means of simply recording the numbers of abused children [SIBE2002]. Elsewhere the same group reported that there was a failure of secondary prevention of child abuse with many infant victims of physical abuse being returned home where they suffered further abuse [RANT2002] (i.e. no change or perhaps even deterioration in QoL). This study concluded that there was a need for child protection services to concentrate more on doing just that, and less on returning the children to their families. In another recent study, it was concluded that social workers placed more emphasis on the child's subsequent psychological QoL than on past physical injury (except for sexual injury) in reaching a decision to return them to their parents [DAVI2001].

Can we therefore infer that the skeletal survey is not cost-effective? It has been shown that a thorough radiographic assessment (followed by histological examination) can impact on the investigation and prosecution of fatal infant abuse [KLEI1989]. The answer to the above question obviously is, "No".

The above debate serves to illustrate the complex and emotional nature of NAI (perhaps more so in non-fatal cases), and our current emphasis on attempting to return the child to his/her parents where possible. In fact this attitude is felt by some to be due in part to misinterpretation of the Children's Act 1989 by social workers, guardians ad litem and the courts [SPEI2000]. These authors would argue that the Act has caused more harm than good to the abused child.

In conclusion, the skeletal survey is just one link in a long chain of events that ultimately impact on the QoL of children suspected of being victims of abuse, their families and society at large. Prospective studies are required investigating the link between the presence of injury and QoL assessment [DAVI2001]. Currently, as far as NAI is concerned, it would be an oversimplification to directly link the impact of the skeletal survey alone, on QoL of patients and society.

5.9 Summary

The hierarchical framework outlined in *Figure 5.2-1* (page 108) may be used to evaluate and optimise outcome when employing CR for the diagnosis of NAI and is particularly relevant to the assessment of technical and diagnostic performance. As one moves up the hierarchy, the nature of the studies involved becomes more complicated, requiring a multi-disciplinary approach, and as such are more difficult and more expensive to conduct.

The design of scientifically sound and reproducible studies culminating in the optimisation of digital image quality for the diagnosis of NAI is a challenge, but should ultimately prove worthwhile.

Section B

Aims and Objectives

Chapter 6

Study Hypotheses

As a result of the literature review in the previous chapters, many variables associated with the radiological diagnosis of NAI and potential areas for research have been identified and summarised in *Sections 6.1 to 6.4*. The aims and objectives of this study follow. The chapter concludes with a statement of the study hypotheses.

6.1 *Obtaining the radiographs*

THE SKELETAL SURVEY Professor C Hall (consultant radiologist, GOSH and international expert witness in NAI) receives skeletal surveys from all over the United Kingdom for a second opinion in suspected NAI. Anecdotally, it seems that these radiographs vary considerably from institution to institution, and even within institutions. Not only do the specific anatomical sites differ, but so also do the projections and timing of the radiographs. For instance some departments will routinely perform oblique views of the ribs, while others perform oblique hand views. There is little in the literature demonstrating the benefits of oblique views, either of the ribs or of the hands. Furthermore the ACR guideline [ACR2001] stipulates a different set of images from the BSPR standard [BSPR2004].

Delayed radiographs are said to increase the visibility of fractures because of the increased callus associated with healing – again there is only one published study supporting this well established opinion [KLEI1996A]. Even so, not all departments in the UK perform delayed radiographs (and they are certainly not performed routinely at GOSH).

The extent of the variability between different radiology departments in the UK is not known. In a matter of such social importance it seems unacceptable that there should be any variation at all.

IMAGE QUALITY

TECHNICAL PARAMETERS of the imaging system being used and the exposure parameters selected by the radiographer will both affect image quality. New technologies are continuously being developed, and parameters for different projections and possibly different clinical indications need to be optimised. In the case of soft copy digital image interpretation, technical parameters of the viewing monitor need also to be considered.

Potential for improving CR systems lies in the optimisation of parameters and in improvement of the imaging plates. It is known that high resolution imaging plates necessitate a higher radiation dose to the patient. However the merits (or otherwise) of high over standard resolution imaging plates for the diagnosis of non-accidental injury have not been documented. Adequate selection of size of the imaging plate and close collimation are also important factors for consideration.

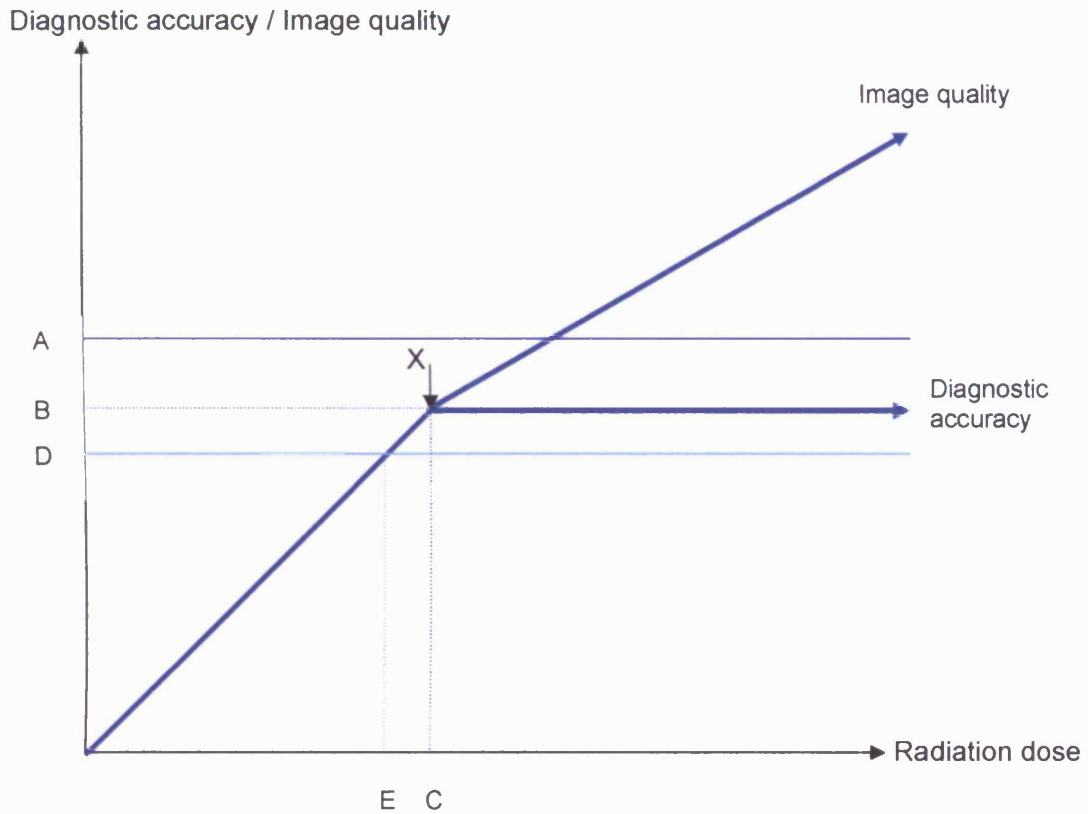
CLINICAL IMAGE QUALITY includes such factors as collimation, the presence of artefact and adequate patient positioning. Motion artefact is not a factor in post mortem cases of suspected NAI. However depending on the time interval since death (and onset of rigor mortis), patient positioning may be less than adequate. Other important parameters (in the context of NAI), which however do not impact on the diagnosis, include radiographer's identification and the presence of side markers and patient details.

Clinical image quality is also dependant on viewing conditions such as the level of ambient light and the light colour and luminescence of the viewing box.

TECHNICAL QUALITY VS DIAGNOSTIC ACCURACY If a radiograph is of sufficient quality to allow pathology to be detected, then further improvement in quality is superfluous to the task. This unnecessary level of quality would be of no significance if it were not that ionising radiation was involved. Image quality is directly related to radiation dose, (at least up until the crucial point where quality is such that maximum diagnostic accuracy has been attained). Radiation has adverse effects, and particularly so in children. There is therefore a real need to limit radiation exposure, and as such there is a trade off between the quality and the diagnostic accuracy of an image. In the case of NAI, it is generally felt that the need for high quality images is such that an increase in radiation dose is acceptable. The radiation dose incurred by a full skeletal survey in cases of suspected NAI is not known, and variations in radiation dose have not been compared to the diagnostic accuracy of the resultant images.

Even for this important clinical indication however, an upper limit must be established. Where this point is in relation to diagnostic reference levels and accuracy in NAI is not known. The situation is illustrated diagrammatically in *Figure 6.1-1* (next page).

Figure 6.1-1: Relationship between radiation dose and diagnostic accuracy



Diagnostic accuracy increases with increasing radiation dose and image quality up to Point "X". After this, accuracy remains constant despite increased radiation exposure and increased image quality.

If "A" were the diagnostic reference level for a given investigation (e.g. chest radiograph), then that dose "B" which led to maximum diagnostic accuracy "C" would be acceptable.

However if "D" were the diagnostic reference level, rather than accept reduced diagnostic accuracy "E", the radiologist would need to demonstrate that diagnostic accuracy was indeed increased by increasing radiation exposure. The diagnostic reference level (for that clinical indication) could then, legitimately, be set at a higher level.

For other indications (e.g. scoliosis), reduced image quality might be acceptable while also reducing the radiation dose incurred by the patient, with no reduction in diagnostic accuracy.

6.2 *Display and Interpretation of Radiographs*

POST-PROCESSING Suggested advantages of digital over conventional film-screen imaging include the ability to post-process. Post-processing includes magnification, grey-scale, contrast and brightness adjustment capabilities and edge-enhancement. The perceived value of these functions differs from author to author, and no studies exist evaluating their use in cases of suspected NAI.

HARD VS SOFT COPY As with post-processing, so also are there conflicting results in the literature concerning the benefits of soft (monitor) compared to hard copy (film) reporting of radiographs. The majority of studies are in favour of soft copy reporting, but none has involved the subtle fractures of NAI. Should soft copy reporting in NAI prove comparable to hard copy reporting, this would have important implications in suspected NAI. Teleradiology would allow the transmission of radiographs from remote sites. Experts in the field would more readily exchange opinions with each other. The positive aspects of this would include an improved service. However the workload of those specialising in this field might considerably increase. In any case, the need for high quality radiographs would remain.

OBSERVER EXPERIENCE – “THE EXPERT WITNESS” An interesting but not obvious question to ask is, “Who are the experts?” Currently there are few obstacles in the way of a radiologist wishing to become an expert in any given field, including NAI. Ideally an expert should have a minimum level of experience, but who is to say that this is the case? And who is to set the minimum level? Even between experienced experts, opinion may differ. In suspected NAI, this is usually in the area of interpreting the abnormalities. Occasionally however, differences exist amongst experts even in the detection of abnormality. A study is currently underway assessing this very problem among experts in NAI in the UK. The results are awaited with interest.

In optimising image quality, what level of experience should be aimed at? District General consultant radiologists with an interest in paediatrics will almost all come into contact with possible cases of NAI. It would seem sensible to direct studies at observers who have successfully obtained their FRCR examination.

The visual acuity of observers may also be called into question. Ensuring that an observers’ vision is accurate is currently (and rightly?) left to the discretion of that observer. However some authors advocate studies comparing diagnostic accuracy with visual acuity [STRA1991].

6.3 *Interpreting the Findings*

THE GOLD STANDARD – RADIOLOGIST VS HISTOPATHOLOGIST There is no gold standard for the diagnosis of NAI. Even if a fracture is detected, unless the perpetrator confesses (and maybe not even then), the diagnosis will always be one of assumption (i.e. that the aetiology was non-accidental).

The radiologist may detect fractures on radiographs that (because of their plane) are missed by the histopathologist. Similarly, histopathology may detect fractures (particularly acute rib fractures) that are missed by the radiologist. A suitable gold standard might be the combination of expert radiological and histological opinions.

ACCIDENTAL OR NON-ACCIDENTAL INJURY? Some fractures such as metaphyseal and rib fractures, spiral fractures of long bones in non-ambulant infants and fractures of certain bones such as the pelvis, scapula or phalanges have a high specificity for NAI. Studies exist in which the incidence of (e.g. rib) fractures in cases of accidental and non-accidental injuries have been documented. The flaw in these studies is that no external gold standard exists for making the initial diagnosis. Infants with multiple rib fractures will be diagnosed as having NAI, and therefore when these same groups are studied, the incidence of rib fractures will be higher in the NAI group than in any control groups.

The answer might be for a researcher to pool together the radiographs of a large cohort of infants and children. That researcher would be blinded to the presence or otherwise of the fracture under investigation. The researcher would then attempt to separate the radiographs into diagnostic groups (accidental, non-accidental and uncertain) based on findings from the other radiographs in the skeletal survey. Only after this blinded segregation had been performed would the incidence of the particular fracture in the three groups be compared.

UNDERLYING PATHOLOGY? The presence of underlying pathology may confound the diagnosis. The radiologist might assume that the disease condition predisposes the infant to fractures. This may be true; however infants who have an underlying disease may also be abused. Proving the case is often difficult.

CAUSATION/MECHANISM OF INJURY

SHAKING Can shaking alone lead to metaphyseal fractures or SPNBF? That it can is the generally accepted answer; however this has not been conclusively shown. Does it matter? The significance lies in the fact that the diagnosis of NAI is often reached by

the realisation of inconsistency between the clinical history given by the carer(s) and the mechanism of the injury detected on the radiograph. If there is controversy as to that mechanism of injury, then the case against the presumed perpetrator (or in defence of the innocent) is weakened.

CARDIOPULMONARY RESUSCITATION (CPR*) It is widely believed that CPR* does not cause rib fractures in infants. However, careful histological examination in post mortem cases would seem to suggest that this is not the case. Further research in this area is required.

DATING THE INJURY Much of our current knowledge about the radiological (and histological) dating of fractures is based not on scientific evidence, but on the experience of a few practitioners in the given fields. It is likely that significant variation would exist amongst multiple observers requested to date a given fracture. This has not been objectively documented. Objective scientific evidence for the precise dating of fractures in NAI is extremely difficult to obtain. The reasons for this are discussed in the following section.

6.4 Research Difficulties

ETHICAL CONSENT In light of the Alder Hey scandal, it is conceivable that difficulties might arise when obtaining local ethics committee approval for a given study in paediatric cases in general and NAI in particular. Increased radiation cannot necessarily be justified in live infants. Should ethical approval be given for research on dead infants? If so, in the case of NAI who should give consent? It is obviously unreasonable on the one hand to accuse a carer of intentionally harming an infant, while on the other requesting their consent to enrol that infant into a study. This difficulty might be overcome in post mortem cases by obtaining the coroner's consent.

FRACTURE DATING – ACCIDENTAL VS NON-ACCIDENTAL FRACTURES Dating accidental fractures is made possible because both the time and mechanism of injury are known. However, precise documentation of the radiological changes may be difficult because of the presence of plaster of Paris in retrospective and prospective studies, and because ethical approval for the repeated exposures required would be difficult to obtain in prospective studies. This is particularly true because the findings from studies of accidental fractures could not, in any case, be directly extrapolated to NAI. The reason for this is that the fractures differ in type and location, in mechanism and in how they are clinically managed. Accidental fractures will usually present on the day of occurrence and are then immobilised. This is not the case for NAI where repetitive trauma to the same injury (as well as repeated trauma to other sites) is common. As such, even diaphyseal fractures in NAI are not immediately immobilised, and the effects of displacement on fracture healing are not well documented.

In the same way, animal studies cannot be directly extrapolated to humans, even if ethical approval to fracture the bones of these animals were obtained.

Finally, follow-up studies in fractures of NAI are not possible because the researcher could never be sure of the initial date of injury, and because such fractures once discovered would be managed differently to undiscovered fractures of NAI.

There is also likely to be much interobserver (and perhaps) intraobserver variation when it comes to dating the same fracture. The results of a study designed to determine this would be interesting. For all these reasons progress in improving our current knowledge of dating fractures in NAI will, for the conceivable future, remain slow.

POSTMORTEM STUDIES

UNAERATED LUNG Anecdotal evidence supports the view that rib fractures are more easily detected in post mortem cases in which the lungs are unaerated. This might be because there are no overlying lung parenchymal and vascular markings to confound the appearance of rib fractures. It may therefore not be possible to extrapolate the results of studies performed to optimise imaging parameters on post mortem cases to live cases of suspected NAI.

MOTION ARTEFACT Motion (limb, cardiac and respiratory) artefact will obviously not be a problem in post mortem cases. However even in live infants motion does not appear to detract significantly from image quality. Studies comparing image quality in the two groups have not been performed.

6.5 Aims and Objectives

Digital radiography in its various forms will almost certainly replace film-screen systems. Computed radiography has an advantage over other digital techniques in that the same x-ray equipment as used with analogue systems may be employed. Initial overheads for departments wishing to change to digital imaging systems are therefore smaller.

The radiology department at Great Ormond Street Hospital for Children has installed a Fuji 5000R CR system. Furthermore, one of the UK's leading experts in NAI works in the department. In addition, the only accredited paediatric Home Office histopathologist in the UK works in the pathology department at GOSH. There is much awareness therefore of the challenges listed above.

As can be seen from the preceding sections, there are a number of variables (technical parameters of the imaging system; radiographic parameters; image display and viewing conditions; observer factors etc.) involved in the optimisation of the radiological diagnosis of NAI.

This study does not set out to investigate them all. Rather the goal is to optimise radiographic parameters and image display.

The aims and objectives can therefore be summarised as follows

1. To investigate whether, with the advent of computed radiography, there has been a reduction in image quality
2. To document the extent of variation in the number and quality of radiographs obtained in the UK for suspected NAI
3. To determine the relationship between radiation dose, image quality and diagnostic accuracy in suspected NAI
4. To determine the effect of edge-enhancement on diagnostic accuracy in suspected NAI
5. To establish the accuracy of soft compared to hard copy interpretation of images in suspected NAI

6.6 Null Hypotheses

Given the aims and objectives listed in the previous section, the following null hypotheses were postulated

In the United Kingdom (UK), regarding imaging in suspected NAI

1. The CEC criteria are not appropriate for the objective assessment of the quality of skeletal surveys
2. Image quality of computed radiography systems is neither inferior nor superior to that of traditional film-screen systems
3. There is no significant variability in the quality of images obtained and therefore
4. There is no need to standardise radiographic imaging
5. There is no direct relationship between radiation exposure and image quality (as determined by the detection rate of abnormality e.g. fractures). Therefore increasing exposure will have no effect on image quality or on diagnostic accuracy
6. Edge-enhancement is a post-processing capability of digital imaging systems that has no effect on diagnostic accuracy or image quality
7. There is no difference in diagnostic accuracy whether interpreting radiographs from a monitor (soft copy) or from printed film (hard copy)
8. There is no difference in image quality of soft and hard copy image display modalities

The studies described in *Section C* (page136) are aimed at accepting or discarding the above null hypotheses.

Section C

Original Research

Local research ethics committee approval (*Appendix VIII*, page 276) was granted for the studies in this section.

Chapter 7

Image Quality, the CEC and “S”

Publication

- *Evaluation of the Commission of European Communities quality criteria for the paediatric lateral spine*
Offiah AC, Hall CM Br J Radiol 2003;76:885 – 890

Oral Presentations

- *Safety issues in digital imaging in paediatric work*
UKRC, Manchester, June 2005
- *Optimisation of image quality in NAI*
ICH/GOSH Grand Round, March 2003
- *The sensitivity value “S” is an insensitive measure of digital image quality*
Radiological Society of North America, 88th Scientific Assembly and Annual Meeting, Chicago, December 2002
- *Evaluation of the CEC criteria for paediatric lateral spine radiographs*
ESPR Annual Conference, Bergen, June 2002
- *Image quality, the CEC and “S”*
N Thames (East) Academic Meeting, London, March 2002

Poster Presentations

- *Image quality of film-screen Vs digital radiographs*
RCR Annual Conference, London, September 2002
- *Image quality, the CEC and “S”*
UKRC Radiological Conference, Birmingham, June 2002

7.1 **Abstract**

Aim: To evaluate the Commission of European Communities (CEC) quality criteria for paediatric lateral spine radiographs, and to use these to assess and compare the quality of film-screen and digital images.

Materials and Methods: 286 paediatric lateral spine radiographs (89 film-screen and 197 digital) were independently analysed by two observers according to the CEC criteria. Based on fulfilment of criteria images were assigned two scores, an image criteria score and a visual grading analysis score. Sensitivity values (S) on digital radiographs were recorded and correlated with image quality. Analysis of variance for fulfilment of criteria between techniques, and (for digital images) age and sensitivity values was calculated.

Results: Film-screen did significantly better ($p < 0.05$) than digital imaging for Criterion 6 (visually sharp reproduction of the cortex and trabecular markings consistent with age). Film-screen did significantly worse for Criterion 7 (reproduction of the adjacent soft tissues). Variability in assignment of scores between observers was lower for the image criteria than the visual grading analysis technique. There was a significant difference in mean S values for each age group when Criterion 6 was or was not met.

Conclusion: Although interpretation between two observers was ambiguous, the CEC criteria were able to detect differences in quality of film-screen and digital images. It is also possible to use them when optimising target S values.

7.2 Introduction

Every radiology department, be it film-screen or digital, hard copy or filmless, optimises and maintains the quality of the radiographs it produces. When we ask, “What is the quality of a given radiograph?” we are asking what degree of excellence that radiograph has attained. Unavoidably there is a subjective element to the assignment of image quality.

To standardise image quality throughout Europe, the Commission of European Communities (CEC) published guidelines on quality criteria for diagnostic radiographs in adult [CEC1996] and paediatric practice [EUR1996]. These criteria were developed by a panel of expert European radiologists and are based on the visualisation of certain anatomical structures. Studies have been performed to evaluate these criteria [MACC1995, MCNE1995, VANO1995B, ALME2000, COOK2001A]. Most of these studies have been in the adult population. Some have involved members of the original panel. One paediatric study that did not, found that modification of the criteria was required in order to meet the authors’ purposes [COOK2001A].

The quality of a radiograph may be influenced by a number of factors, not least being the radiation dose incurred by the patient. Studies have been performed assessing the relationship between dose and image quality [VANO1995A, JONS1996, ALME1996, HUFT1998]. It is recognised that a degree of compromise is required. Some loss of quality is acceptable in order to limit radiation exposure. In the case of digital radiography the relationship between image quality and dose is further confounded. This is because of the lack of a direct correlation between film density and exposure. To overcome this, manufacturers have defined “exposure indices”, and their relationship to plate exposure [BIR2001]. When (as in usual practice) the system’s read mode is set at “auto”, the system reader optimises the exposure index and latitude values. This produces radiographs of almost constant density regardless of plate exposure [COWE1993]. The latitude and more significantly the exposure index appear on both hard and soft copy images of the radiograph. This gives an idea of the radiation exposure to the patient.

Manufacturers suggest reference ranges for exposure indices for each examination. Fuji Co Ltd. has called their exposure index “Sensitivity” (S). Its relationship to plate exposure is given by the following equation

$$\text{Sensitivity } S \cong \frac{\text{Constant}}{\text{Exposure}}$$

A rise in S of 33% is equivalent to a 25% decrease in radiation dose.

A fall in S of 33% is equivalent to a 50% increase in radiation dose [BIR2001].

The S range recommended by Fuji to the authors' Department for the paediatric lateral spine (entire or segmental) is 50 – 600. Given that patients may range from pre term to 16 years of age, such a wide range is not helpful for the individual case.

The purpose of this study was (a) to evaluate the applicability of the CEC criteria with reference to the paediatric lateral spine by applying them to digital and film-screen radiographs and (b) to evaluate potential relationships between S and the CEC quality criteria.

7.3 *Materials and Methods*

The study involved a retrospective analysis of 286 paediatric lateral spine radiographs.

Patients

125 patients from each of four years were randomly selected from a computer printout of over 1000 patients. All patients had a skeletal survey performed between January 1998 and December 2001. Of these, 286 lateral spine radiographs were available from the patients' film packets for inclusion in the study. Reasons for the unavailability of 214 radiographs included no lateral spine as part of survey (n = 98), lateral spine missing from packet (n = 16), film packet not located for various reasons (n = 89), and exclusion of radiograph from study (n = 11) because (a) patient greater than 16 years of age at time of examination (n = 7) or (b) severe pathology (osteoporosis, osteosclerosis or scoliosis) in patient (n = 4).

Mean age at time of the examination was four years (range < 1 month to 15 years). Radiographs were subdivided into three groups based on patient's age as follows, Group 1; ≤ 11 months of age (n = 100), Group 2; 1 – 5 years (n = 97), Group 3; 6 – 15 years (n = 89).

Skeletal surveys were performed for the exclusion of a wide range of constitutional bone disorders as well as for suspected non-accidental injury (NAI).

32 post mortem radiographs were included in the study, with age distribution Group 1 (n = 22), Group 2 (n = 7) and Group 3 (n = 3). Indications for all patients in Groups 1 and 2, and one patient in Group 3 (age = five years) was for the exclusion of NAI with or without a history of sudden infant death. The indication for two patients in Group 3 (aged 9 and 10 years) was road traffic accident.

In a minority of patients (n = 15) the indication for the survey was a rheumatological condition. The vast majority of rheumatology patients belonged to the group (n = 98) in which a lateral spine was not performed as part of the survey.

The Radiographs

The four years from which radiographs were selected were divided into two groups based on imaging modality, and included 1998 (FS = last year of film-screen in the authors' Department) and 1999 – 2001 (DR = first three years of digital radiography). Numbers of radiographs within the two groups included FS (n = 89; Age Group 1 = 22, Group 2 = 36, Group 3 = 31), DR (n = 197; Age Group 1 = 78, Group 2 = 61, Group 3 = 58).

Film-screen images were obtained using film of medium speed (400), and digital images with a Fuji 5000R CR system. Imaging parameters are shown in *Table 7.6-1* (page 150). Images were obtained in one of two rooms, Room 1 (Siemens Optilix; nominal focal spot size fine/broad = 0.6/1mm, inherent tube filtration 1.5mm Al, additional filtration 0.1mm Cu) and Room 2 (Wolverson Comet; nominal focal spot size fine/broad = 0.6/1mm, inherent tube filtration 1mmAl, additional filtration 1.5mmAl).

Image analysis

Two observers (a paediatric clinical radiology research fellow and a consultant in paediatric radiology) assessed each image independently. Assessment of images was based on the CEC quality criteria for the paediatric lateral spine radiograph (column 2, *Table 7.6-2*, page 151). Prior to the study, the observers discussed in detail their understanding of the criteria. A consensus opinion for the interpretation of each was then reached (column 3, *Table 7.6-2*, page 151).

Images (within their film packets) were shuffled in an attempt to achieve some randomisation in reading order between imaging modality (FS and DR) and age groups. Observer 1 read the radiographs in reverse order to Observer 2. This was to reduce effects on image quality as a result of a possible learning curve in the application of the criteria.

Images were read under standardised conditions as recommended by the CEC guidelines. A Wardray viewing light box with a film illuminator of 4000cd/m² was used. The illumination colour was white. Restriction of illumination to the area of the radiograph was by the use of cardboard sheets. A magnifying glass of magnification factor x3 was available. Overexposed areas on the image were viewed with an additional spotlight. Low levels of ambient light were achieved.

Each image was assigned two scores, an image criteria score (ICS) and a visual grading analysis score (VGAS). For the ICS, each image was assigned a score of 1 if a given criterion was fulfilled and 0 if it was not. The ICS was the number of criteria fulfilled divided by the total number of criteria (seven for the lateral spine). For the VGAS, each image was compared to a reference image, and for a given criterion scores ranged from +2 (clearly better than) to -2 (clearly worse than). The VGAS was the sum of scores divided by the total number of criteria [ALME2000].

For the purposes of the VGAS, the reference image was a film-screen lateral spine radiograph of a three-year-old chosen at random from the original computer printout.

Over-collimation causing the skin surface to be excluded was recorded. This occurred in 33 instances, distribution by technique included FS (n = 24), DR (n = 9) and by age group distribution included Group 1 (n = 11), Group 2 (n = 11), Group 3 (n = 11).

Observer 1 documented S for all digital images (n = 197). Observer 2 was unaware of this aspect of the study in order to reduce bias.

Statistical analysis

Statistical analysis was performed using SPSS 10.1 for Windows.

Interobserver reliability was calculated for each criterion, ICS and VGAS using Cohen's kappa. Analysis of variance (ANOVA) was performed between Criteria 1 to 7 and imaging modality. ANOVA was also performed between S, age group and Criteria 6 and 7. All analyses were performed for both observers individually. When analysing Criterion 7, those cases (n = 33) in which the skin surface was omitted due to over-collimation were excluded. The results of statistical analyses concerning S and fulfilment of Criteria 6 and 7 by Observer 2 were given more weight. This was because at the time of image assessment Observer 2 was not aware that S values were being recorded.

The nominal level of significance was set at 5%.

7.4 Results

Evaluation of applicability of the CEC criteria

The percentage of radiographs fulfilling individual criteria is shown in *Figure 7.6-1* (page 154). Note that this figure illustrates the mean values for both observers. *Figures 7.6-2 and 7.6-3* (pages 154 and 155) demonstrate the ICS and VGAS for Observers 1 and 2. There was no significant difference in the means for each observer. 2 out of the 286 (1%) radiographs in the study scored zero by at least one observer. The lumbar spine in one image with a score of zero was obscured by contrast in a child who had undergone a barium study in the preceding 24 hours, highlighting the need to rationalise radiographic investigations. The other radiograph with a score of zero was associated with poor collimation and movement artefact. Neither image was of diagnostic quality.

Table 7.6-3 (page 152) illustrates that interobserver reliability was fair to moderate for the majority of criteria. Interobserver reliability tended to be better for the ICS than the VGAS.

Digital compared to film-screen radiographs

Figures 7.6-1 (page 154) and *7.6-4* (page 155) compare film-screen with digital radiographs. For both observers there was a significant relationship between the fulfilment of Criteria 6 (visually sharp reproduction of the cortex and trabecular markings consistent with age) and 7 (reproduction of the adjacent soft tissues) on the one hand and imaging modality on the other. There were no significant relationships between fulfilment of Criteria 1 – 5 and imaging modality. Digital images scored better for Criterion 7 and worse for Criterion 6 than did film-screen radiographs.

Digital image quality and sensitivity values

13 out of 197 radiographs (6.6%) had an S value less than 50 (age Group 1 n = 8, age Group 2 n = 5) and 17 out of 197 radiographs (8.6%) had a value greater than 600 (age Group 1 n = 1, age Group 2 n = 2, age Group 3 n = 14). Mean S values for each age group was significantly related to the fulfilment of Criterion 6 (visually sharp

reproduction of the cortex and trabecular markings consistent with age). Although there was some overlap, for each age group the standard deviation of S was smaller when Criterion 6 was met compared to when it was not (*Figure 7.6-5*, page 156). Means, standard error of the means, standard deviations and quartile values for both groups (Criterion 6 fulfilled and Criterion 6 not fulfilled) are shown in *Table 7.6-5* (page 153).

There was no significant relationship between S and fulfilment of Criterion 7 (reproduction of the adjacent soft tissues).

7.5 Discussion

There is a subjective element to the assessment of image quality. The CEC has published guidelines [CEC1996, EUR1996] aimed at standardising image quality throughout Europe at acceptable radiation doses. Previous studies [MACC1995, VANO1995, COOK2001A] have shown that over 90% of films fulfil the CEC criteria, and advise their stricter application. A strict approach was attempted in this study. The two observers involved reached a consensus regarding the interpretation of each criterion. This approach yielded a fulfilment rate for six or seven criteria of only 50% for film-screen radiographs and 56% for digital radiographs. Despite this low fulfilment rate, 99% (284 out of 286) of radiographs were diagnostic. These results highlight the fact that while image quality scoring may be useful for audit purposes they do not necessarily impact on patient diagnosis.

The mean image criteria and visual grading analysis scores masked differences in quality scores between groups and between observers. Furthermore these scores did not indicate which particular criterion had not been fulfilled. Presently it is advisable to present results for individual criteria.

Despite discussion between the observers regarding interpretation of the criteria, overall interobserver reliability was moderate or better in only 6 out of 14 comparisons (*Table 7.6-3*, page 152). This suggests that there is considerable room for interpretation of these criteria. The different levels of experience of the two observers may have also contributed. A second reading of a proportion of films to evaluate intraobserver reliability might have helped to define the source of the low kappa scores.

There was a tendency towards higher interobserver reliability for the image criteria compared to the visual grading analysis technique. Subjectively however, the latter was felt by both observers to be the easier to apply. Despite this, both scoring methods showed similar relationships to patient age, imaging modality and S. If a department uses the visual grading analysis technique, then it is advised that the same reference image be used in any future studies. This will allow direct comparison of results between studies. Clearly different departments will use different reference images. It is therefore uncertain if visual grading analysis results between departments can be directly compared. For this reason, and for the improved interobserver reliability, it is suggested that the image criteria technique is that of choice.

If they are to be used as a measure of clinical image quality then some modification of the CEC criteria is required. Currently they do not allow for the presence of artefact as a reason for failing to fulfil a criterion. This may confound the relationship between age, imaging modality etc. These relationships may also be masked by over-collimation, which would be a cause of failing to fulfil Criterion 7 (reproduction of the adjacent soft tissues) not related to exposure parameters or imaging modality. Such cases were eliminated from statistical analysis in this study. The presence of severe pathology in the patient may be another cause of failure to fulfil a criterion. Such patients were also excluded from this trial (see “patients” in materials and methods section). Finally the guidelines do not state the number of vertebral bodies that should meet a given criterion. In this study the authors agreed that all vertebral levels had to meet each criterion (except for Criterion 1) in order to consider that criterion fulfilled. This may explain the relatively low fulfilment rate of all criteria demonstrated. It also explains the high incidence of films of diagnostic quality, as the majority of radiographs were performed for the diagnosis of constitutional bone disorders. These conditions can be diagnosed even if one or two vertebral bodies are obscured or exposure is less than adequate.

Cook et al [COOK2001A] developed their own scoring system for the assessment and optimisation of clinical image quality. The experience from this study also suggests that modification of the criteria is required when clinical quality is being assessed. However it should be noted that the CEC intend the criteria to be used for the optimisation of radiographic technique and reduction of patient dose. In this regard they have previously been shown to be useful [MOON1998].

Compared to digital radiography, traditional film-screen radiography has improved spatial resolution [COWE1993]. In this study this was reflected in the significant numbers of film-screen radiographs fulfilling Criterion 6 (visually sharp reproduction of the cortex and trabecular markings consistent with age) compared to digital radiographs. Conversely, digital techniques have improved contrast resolution compared to traditional film-screen techniques [COWE1993], as demonstrated by the significant numbers of digital radiographs fulfilling Criterion 7 (reproduction of the adjacent soft tissues) compared to film-screen radiographs. It is relevant to note that the American College of Radiology (ACR) guidelines for the limiting spatial resolution in the investigation of suspected NAI is 10lp/mm for all anatomical sites [ACR1997]. This degree of spatial resolution is not achievable by digital radiography [COWE1993].

For the diagnosis of constitutional bone disorders these differences are probably of no significance. However careful investigation is required to determine the full implications of the reduced spatial resolution of digital imaging for the diagnosis of NAI. It should be mentioned that digital systems might compensate for the reduced spatial resolution compared to film-screen systems by their improved detector quantum efficiency (DQE), which leads to a reduction in noise and improved contrast.

Given that it is a proxy measure of radiation dose [BIR2001], the potential relationship between S and digital image quality as assessed by the CEC criteria was evaluated. CEC Criteria 6 (visually sharp reproduction of the cortex and trabecular markings consistent with age) and 7 (reproduction of the adjacent soft tissues) are also related to radiation dose. The lack of a significant relationship between S and fulfilment of Criterion 7 at first glance appears surprising. Perhaps S is related to gradations of soft tissue visualisation, which was masked by the use of a bright light for overexposed radiographs.

Fuji has suggested that the authors' department aim for S values within the range of 50 – 600 for the lateral spine radiograph over the entire paediatric age group. However S is significantly related to patient age as confirmed by this study. The results also indicate a significant relationship between mean S values and CEC Criterion 6 (visually sharp reproduction of the cortex and trabecular markings consistent with age) within individual age groups. However, despite the significance between mean S levels when Criterion 6 was or was not fulfilled, there was a large standard deviation with overlap between the two groups. This renders the S value, when taken in isolation, an insensitive measure of image quality. However, selecting the 25th and 75th quartile values for each age group when Criterion 6 was fulfilled (see *Table 7.6-5* page 153 and *Figure 7.6-5* page 156), allowed the department to set acceptable S ranges for each age group for the lateral paediatric spine as follows

< 11 months 70 – 153
1 – 5 years 80 – 245
6 – 15 years 142 – 348

There is a trade off between image quality and radiation dose [VANO1995, JONS1996, ALME1996, HUFT1998]. Lower S values for a given patient age and size imply higher radiation exposure. Radiation dose incurred by patients undergoing lateral

spine radiographs in the authors' department have previously been found to be well within diagnostic reference levels. The indication for the radiograph also affects what is deemed an acceptable level of quality [LAMS1986, MURP1990]. A skeletal survey performed for NAI should of necessity be of the highest possible quality even at the risk of increased exposure [ACR1997]. For most indications, an upper limit for S (lower radiation dose) does not need to be strictly adhered to – unless a level of dose reduction is reached when pathology becomes obscured by increased quantum mottle. The constraints of a retrospective study are such that the target S ranges set by the department are somewhat arbitrary. Prospective studies relating S values directly to radiation dose and quality criteria are required.

7.6 Tables and Figures

Table 7.6-1: GOSH departmental parameters for lateral lumbar spine radiographs

Parameter	< 1 yr	1 – 5 yrs	5 – 10yrs	10 –15 yrs
kV	60 – 65	65 – 70	70 – 75	75 – 85
mAs	2 – 4	3 – 6	8 – 25	16 – 25
FFD	100	100	100	100
Grid	No	No	Yes	Yes

kV = kilovoltage

mAs = milliampere second

FFD = film focus distance in cm

Table 7.6-2: The CEC quality criteria for the paediatric lateral segmental spine [EUR1996]

No.	Criterion	Comments on Interpretation ^a
1	Reproduction as a single line of the upper and lower plate surfaces in the centre of the beam	-
2	Full superimposition of the posterior margins of the vertebral bodies	At all levels
3	Reproduction of the pedicles and the intervertebral foramina	At least 50% of foramina clearly visible at all levels
4	Visualisation of the posterior articular processes	With full superimposition at all levels
5	Reproduction of the spinous processes consistent with age	Age related changes discussed and agreed
6	Visually sharp reproduction of the cortex and trabecular markings consistent with age	Age related changes discussed and agreed
7	Reproduction of the adjacent soft tissues	Skin surface must be visible at all levels

CEC = Commission of European Communities

a. The presence of artefact e.g. lines, contrast etc obscuring even one vertebral body resulted in a score of 0

Table 7.6-3: Interobserver reliability (Kappa)

CEC Criterion	Image Criteria Technique	Visual Grading Analysis Technique
1	Fair (0.330)	Fair (0.288)
2	Fair (0.349)	Poor (0.124)
3	Fair (0.381)	Moderate (0.429)
4	Fair (0.341)	Moderate (0.464)
5	Moderate (0.498)	Fair (0.209)
6	Excellent (0.819)	Fair (0.280)
7	Good (0.656)	Moderate (0.493)

CEC = Commission of European Communities

Table 7.6-4: Significance levels between fulfilment of Criterion 6 and sensitivity

Age Group	Observer 1	Observer 2
1	0.011	0.002
2	0.016	0.011
3	0.065	0.013

Table 7.6-5: Sensitivity values ^a

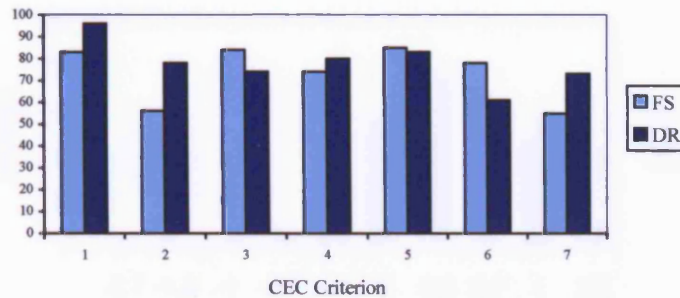
Sensitivity	Criterion 6 Fulfilled			Criterion 6 Not Fulfilled		
	Age Group 1	2	3	Age Group 1	2	3
	(n = 54)	(n = 38)	(n = 39)	(n = 24)	(n = 23)	(n = 19)
Mean	127	171	307	211	270	560
SE Mean	11	17	40	31	39	115
SD	80	107	249	153	186	502
Quartile 25%	70	80	142	96	126	236
50%	111	164	210	169	241	348
75%	153	245	348	313	325	855

a. See also *Figure 7.6-5* (page 156)

SE = Standard error

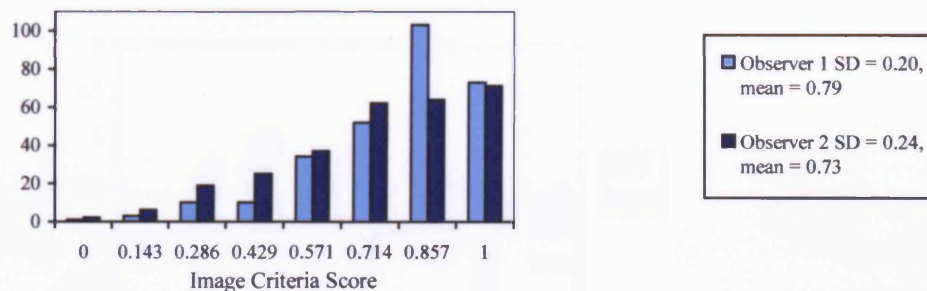
SD = Standard deviation

Figure 7.6-1: Percentage of images fulfilling the CEC criteria



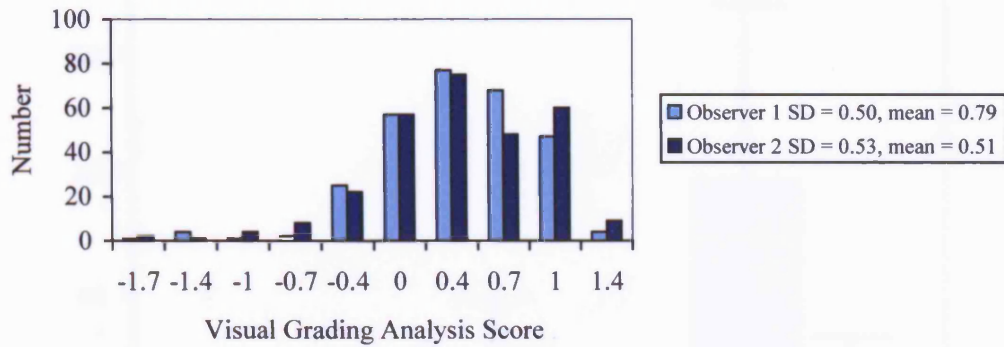
Criterion 1 was the criterion most frequently fulfilled – 74 out of 89 (83%) for film-screen and 189 out of 197 (96%) for digital images. The least fulfilled criteria were Criterion 7 (49 out of 89 (55%) for film-screen radiographs, and Criterion 6 120 out of 197 (61%) for digital radiographs.

Figure 7.6-2: Image criteria scores (Observers 1 and 2)



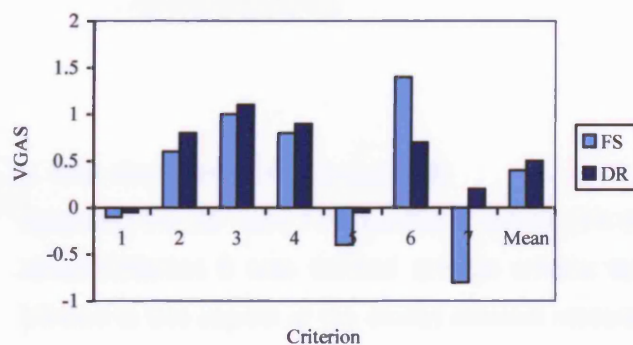
The lumbar spine in the image with a score of zero was obscured by contrast in a child who had undergone a barium study in the preceding 24 hours, highlighting the need to rationalise radiographic investigations. This image was non-diagnostic. There was no significant difference in the mean image criteria scores for Observers 1 and 2.

Figure 7.6-3: Visual grading analysis scores (Observers 1 and 2)



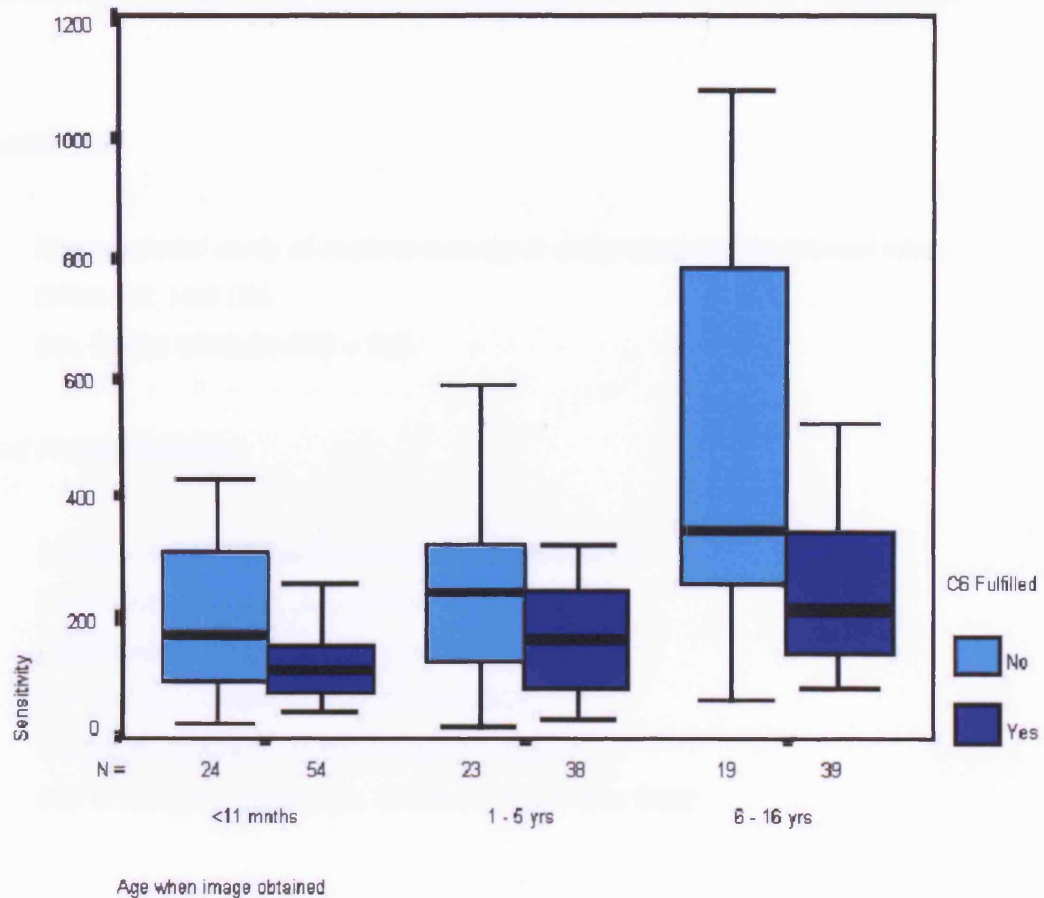
As regards visual grading analysis, the majority of images were equal to or slightly better than the reference image. There was no significant difference in mean visual grading analysis scores between the observers.

Figure 7.6-4: Fulfilment of criteria Vs imaging technique (Observer 2)



This figure depicts clearly how the CEC criteria may be used to detect differences in image quality based on imaging technique. Note particularly the differences in fulfilment of Criteria 6 and 7 between film-screen (FS) and digital radiographs (DR).

Figure 7.6-5 Sensitivity values Vs. Criterion 6 (Observer 2)^a



a. See also Table 7.6-5 (page 153)

Selecting the 25th and 75th quartile S values (for digital images) for each age group when Criterion 6 was fulfilled (image criteria technique Observer 2 – who was blinded to this aspect of the study) allowed narrower target ranges to be set.

Chapter 8

Variability in Quality of NAI Imaging in the United Kingdom

Publication

- *Observational study of skeletal surveys in suspected non-accidental injury*
Offiah AC, Hall CM
Clin Radiol 2003;58:702 – 705

Oral Presentations

- *Safety issues in digital imaging in paediatric work*
UKRC, Manchester, June 2005
- *Optimisation of image quality in NAI*
ICH / GOSH Grand Round, March 2003
- *Variability in quality of NAI imaging in the UK*
BSPR Annual Conference, Sheffield, November 2002

8.1 Abstract

Aim: To document variability in the standard of skeletal surveys received for a second opinion in suspected non-accidental injury (NAI).

Materials & Methods: The skeletal surveys of 50 consecutive infants and children under 2 years of age were reviewed. A simple scoring system was developed based on fulfilment of specific parameters. Each radiograph was then assigned a score reflecting its overall clinical quality.

Results: There was an average of 10 radiographs per skeletal survey (range 2 - 13). Of the 50 surveys assessed, there were 37 different combinations. These included 5 babygrams. No survey complied with the current draft standard of the British Society of Paediatric Radiology (BSPR).

Conclusion: There is significant variability in skeletal surveys referred for a second opinion in suspected NAI. Standardisation of projections and improvement in quality of radiographs obtained for this indication is required. The study highlights the need for timely publication of definitive national guidelines.

8.2 *Introduction*

The diagnosis of suspected non-accidental injury (NAI) is a sensitive and topical issue. Radiology plays a pivotal role. It has been estimated that greater than 80% of diagnosed child abuse related injuries in the United States are detected through medical imaging [BROW1995]. Radiographs may be the only documentation of injury and furthermore may be used as evidence in court. The need for high quality radiographs, even at the expense of increased radiation dose has been recognised [ACR1997]. The American College of Radiology (ACR) has published definitive standards for skeletal surveys in the child with suspected physical abuse [ACR1997]. Currently only a draft standard is available for practitioners in the UK. These can be found on the British Society of Paediatric Radiology (BSPR) website [BSPR2003]. In the absence of national guidelines, there are likely to be differences in the number and quality of images obtained in skeletal surveys throughout the UK. The purpose of this study was to evaluate and document variability in skeletal surveys received for a second opinion in suspected NAI.

8.3 *Materials and Methods*

General

The skeletal surveys of 50 consecutive patients were reviewed. The surveys were referred for a second opinion in suspected NAI between January 2000 and September 2002. Exclusion criteria included

- Surveys in which only relevant/worrying films had been sent as determined from the referral letter
- Surveys with less than three films (except for babygrams) in order to further reduce the likelihood of including surveys in which radiographs had been retained by the referring hospital
- Surveys in patients greater than two years of age

General data collected included referring county, number of radiographs per survey, specific projections obtained, and whether radiographs were original or copy, film-screen or digital.

Assessment of clinical image quality

All radiographs were individually assessed and assigned an image quality score. The Commission of European Communities quality criteria [EUR1996] were not felt to meet the requirements of the study. Each image was therefore assigned a quality score based on a simple system devised for this purpose. *Figure 8.6-1* (page 169) summarises the criteria that were considered in each evaluation. For each criterion except collimation, a score of 0 or 1 was available. A score for each collimation mark visible on the radiograph to a maximum of 4 was also available. Certain provisos were attached to the fulfilment of given criteria as follows. All hand written criteria except for radiographer's identification were penalised (score = 0). Adequate exposure allowed visualisation of bony and soft tissue details with or without a spotlight. Significant artefact obscured bony or joint detail. Insignificant artefact was at a distance from the anatomical area of interest except in the case of the assistant's hand(s). The presence

of the assistant's hand(s) on the radiograph was always penalised (score = 0) because of its radiation dose implications.

The sum of scores for each radiograph was equal to the clinical image quality. Based on this system, the maximum possible score for any radiograph was 15.

8.4 Results

The 50 children had a total of 467 radiographs performed as part of routine skeletal surveys. The average was 10 radiographs per survey per child with a range of 2 – 13. Of the 467 radiographs, 48 (10%) did not comply with the draft standards (*Figure 8.6-2*, page 169). The majority of radiographs were copies (94%), and only a small number were digital (12%). No survey completely complied with the combination of projections recommended in the draft standards (*Table 8.6-1*, 167).

Of the 50 skeletal surveys there were 37 different film combinations. These included a “babygram” (single frontal and lateral exposures of the entire child) in five patients (10%). *Table 8.6-2* (page 168) lists the most frequent combination of projections, which (like the babygram) was also performed in five patients (10%). *Table 8.6-2* (page 168) also shows how the radiographs in this commonest survey differed from the BSPR standards.

The most frequent projections to be obtained were of the lateral skull and the lower limbs in 48 children each (96%). Excluding the babygram, the least frequent projection was of the feet in only 13 children (26%). Radiographs of the hands were also relatively infrequent (*Figure 8.6-2*, page 169).

The least fulfilled quality criterion was a means of identifying the radiographer(s) who performed the study (*Figure 8.6-3*, page 170). This was present on only 103 radiographs (22%).

Of the 163 (35%) radiographs with significant artefact, the presence of the hand(s) of an assistant holding the child in position was identified in 150 (32%). Other artefacts alone or in combination included lines, buttons and ID bands.

Relative to the number of radiographs obtained for a given projection, the assistant’s hands were most likely to appear on radiographs of the limbs, while AP skull radiographs were the most likely to be overexposed and significantly rotated (*Figure 8.6-3*, page 170).

In some instances hand-written information was present on the radiographs and positive scores were not assigned. These included side marker (11%), hospital number (6%), date of birth (6%), patient’s name (3%), and date of examination (2%).

No radiograph scored the maximum of 15 points. Scores ranged from 4 to 14. The median score was 12; the modal scores were 12 and 13 in 121 radiographs each. 134

radiographs (29%) scored a total of 13 or 14, while 213 (46%) scored a total of 11 or 12 points.

8.5 Discussion

The study has shown that currently in England there is wide variability in the number and standard of radiographs obtained for skeletal surveys in suspected non-accidental injury. However the limitations of the study are firstly that it did not review surveys from a random selection of radiology departments throughout the country. Although surveys were referred from 22 British counties including district general and teaching and paediatric hospitals, bias from the referral pattern cannot be excluded. Secondly, despite our efforts some incomplete surveys may have been included in the study, although we think this unlikely. However this raises the issue of which radiographs should be sent when a second opinion is sought in suspected NAI. The simplest (and arguably best) solution is to include them all.

Exposures of individual anatomical regions should be made on separate films [BSPR2003]. A significant number of babygrams were performed and referred for a second opinion. Babygrams do not provide images of the skeleton of sufficient quality for the diagnosis of non-accidental injury and should not be performed in this clinical context [KLEI1989].

No survey completely complied with the BSPR draft standards. The reasons for this were that all views of the hands were performed as straight AP radiographs (and not oblique as recommended), and no routine oblique chest radiographs were performed. The value of delayed chest radiographs in the dating of rib fractures has been well documented [KLEI1996D], however the routine performance of left and right oblique chest views at initial presentation is more controversial. Even excluding oblique projections only 3 surveys complied completely with the current standards. Widespread publication of the final version of the guidelines is indicated.

The BSPR standards stipulate an AP view of the abdomen to include the pelvis and both hips [BSPR2003]. The majority of surveys reviewed in this study included a view of the pelvis alone (*Figure 8.6-2*, page 169). Injuries to intra-abdominal organs and viscera in cases of abuse have been well documented [LEDB1988, COAN1992, NG1997]. Injuries to the abdomen are the second most common cause of child fatalities in NAI, with an estimated mortality of 40% to 50% [COOP1988, BERK1995]. Radiographs of the abdomen may reveal evidence of free intra-peritoneal air or dilated loops of bowel as a result of ileus or obstruction (by intra-mural haematoma for

example). These reports support the need for, and reflect the importance of abdominal radiographs in suspected NAI. Interestingly, the ACR standards recommend only an AP view of the pelvis (to include the mid and lower lumbar spine), and not the entire abdomen [ACR1997].

Although unusual, fractures of the hands and feet in infants are highly specific for NAI. As with other skeletal injuries in child abuse, there may be no external evidence. Nimkin et al [NIMK1997] published features of 22 hand and foot fractures in 11 patients. They emphasised the value of oblique hand views in detecting subtle buckle fractures, and consequently altered their routine skeletal survey to include oblique rather than straight views of the hands. Small patient numbers were involved, however to our knowledge this is currently the only study in which this issue has been addressed. Results of further research in this area would be interesting.

Less than half of all radiographs showed four collimation marks. It is not only important to improve image quality by reducing the glare from unexposed margins, but careful collimation also reduces patient dose. In the case of digital images, electronic shutters exist allowing the radiographer to compensate for poor collimation. The British Institute of Radiology [BIR2001] encourages all final (digital) images to show the edges of the radiation field. Therefore four collimation marks should be visible on all radiographs be they film-screen or digital.

That an assistant's hand was irradiated in a third of radiographs has implications for radiation exposure. Improved technique particularly in views of the limbs is warranted. AP and lateral skull radiographs were the most likely to be overexposed, rendering the soft tissues difficult to visualise. The presence (or absence) of scalp swelling may be the only clue as to the age of a skull fracture. Optimisation of radiographic parameters for skull radiographs would be beneficial.

Only a fifth of the radiographs demonstrated a means of identifying the radiographer(s) involved. In order to establish continuity of evidence it is advised that the name or initials of the radiographer(s) performing the investigation be recorded on the radiographs at the time of the examination [SR1999]. Although we could not find it specifically stipulated, we would recommend that details not be hand-written on radiographs. It is possible to argue that such hand-written details were included on the radiograph at a later date. The practice of hand-written details may also increase the incidence of errors (such as incorrect side markers).

ACR standards [ACR1997] recommend a minimum spatial resolution of 10lp/mm for all radiographs obtained as part of a skeletal survey in suspected NAI. These guidelines predate the widespread use of digital systems, which cannot achieve this degree of spatial resolution [COWE1993]. The full implication of the reduced spatial resolution of digital systems in the clinical context of NAI is uncertain. We made no attempt to assess the overall quality of images in terms of spatial resolution requirements for the subtle fractures of NAI. The limiting spatial resolution required using digital systems is not known, and such an assessment was felt to be outside the scope of this study.

In conclusion, allowing for patient mobility, there is no reason why radiographs performed as part of skeletal surveys in suspected NAI should score less than 13 based on the system reported in this article.

The results highlight the need for the publication and widespread distribution of definitive guidelines for skeletal surveys in suspected NAI.

Much emphasis is currently placed on evidence-based medicine. If best medicine is to be practised, then all infants presenting with suspected NAI should have the same (complete) skeletal survey performed, regardless of which UK department they present to.

8.6 Tables and Figures

Table 8.6-1: BSPR draft standard [BSPR2003]

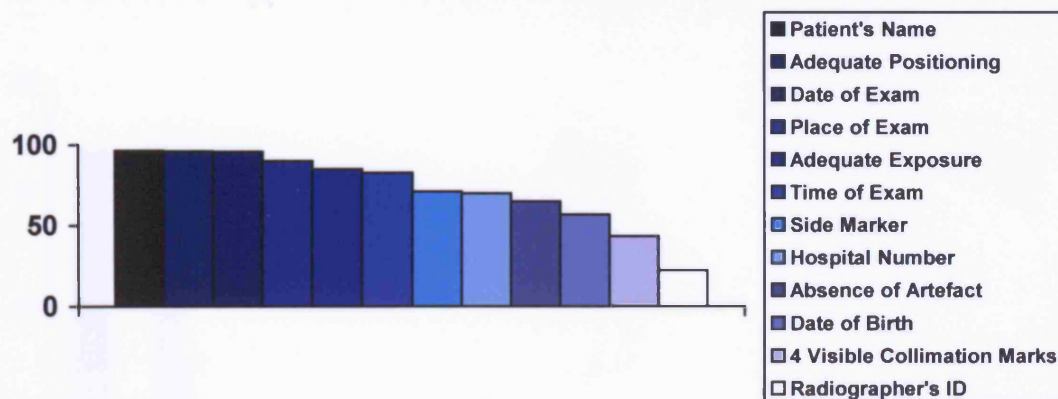
Anatomical Site	Projection	Comment
Skull	AP	Towne's if occipital injury suspected
	Lateral	
Chest	AP	Including both clavicles
	Oblique	Right and left (for ribs)
Abdomen	AP	Including pelvis and hips
Spine	Lateral	Entire spine
Upper limbs	AP humerus	Right and left
	AP radius and ulna	Right and left
	Oblique PA hand	Right and left
	AP femur	Right and left
Lower limbs	AP tibia and fibula	Right and left
	DP foot	Right and left

The table depicts only those radiographs that the guidelines suggest should be performed routinely in all case of suspected NAI. The guidelines also advocate additional coned and lateral views of suspicious areas and further imaging modalities for the assessment of neurological injury [BSPR2003].

Table 8.6-2: Most frequent skeletal survey obtained (10% of patients)

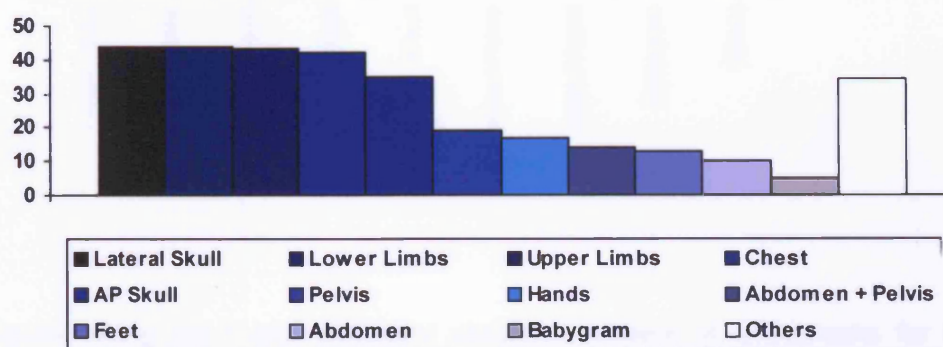
Radiographic Projection	Comment
AP skull	-
Lateral skull	-
AP chest	No oblique radiographs
AP pelvis	Abdomen omitted
AP both upper limbs	Hands omitted
AP both lower limbs	Feet omitted

Figure 8.6-1: Quality indices fulfilled (%) by 467 radiographs obtained for suspected NAI



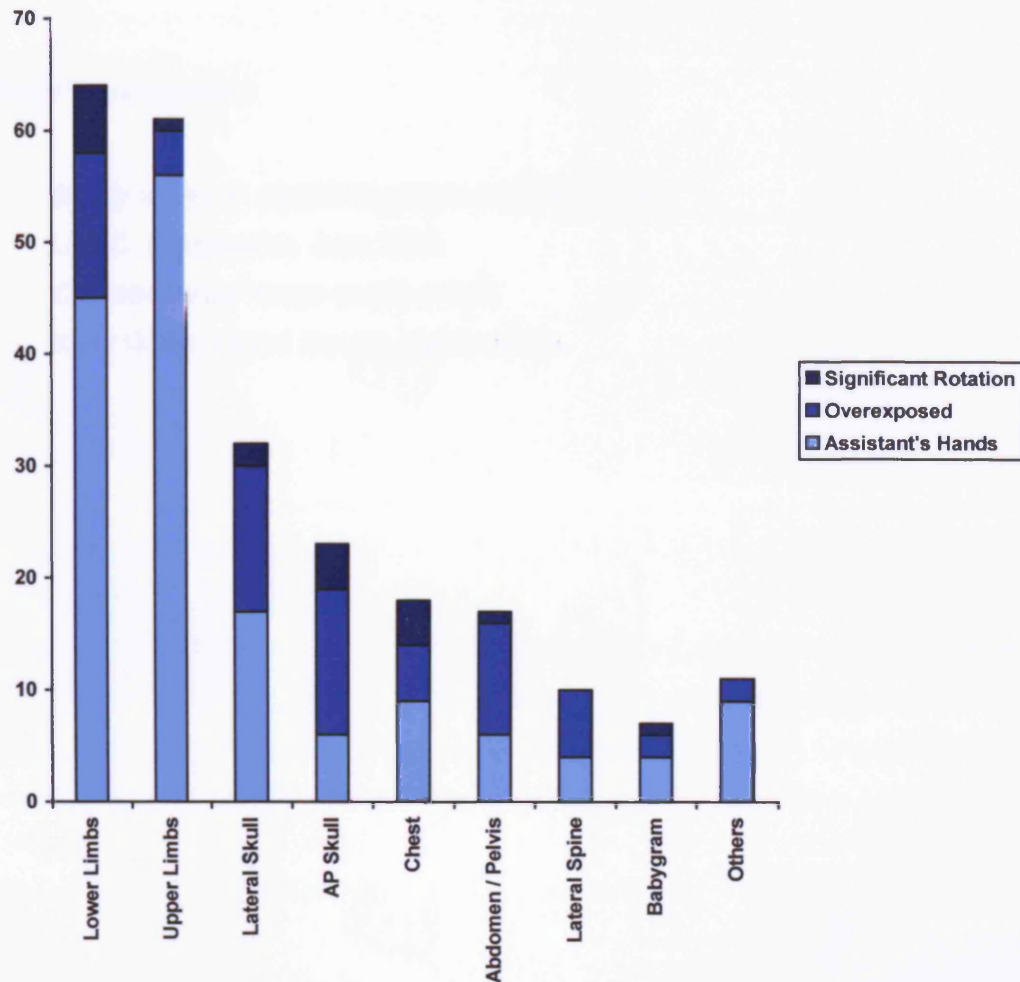
None of the 467 radiographs scored the maximum possible 15 points.

Figure 8.6-2: Projections obtained for skeletal surveys in 50 patients with suspected NAI (n = 467)



"Others" includes a single AP spine, and coned and lateral views of the limbs. From the times of exposure, referral letters and reports, some appear to have been performed in areas of raised suspicion/obvious abnormality, while others (particularly the coned views) were performed routinely.

Figure 8.6-3: Failure of fulfilment of criteria by individual projections



Figures along the Y-axis represent absolute numbers of radiographs for individual projections penalised (score = 0) for the reasons indicated. Lower limbs include feet, and upper limbs include hands. Abdomen/pelvis includes those in which one or other region was exposed singly or in combination. For explanation of the term "Others" please see legend *Figure 8.6-2* (previous page).

Chapter 9

The Phantom Studies: Leeds TO.10 Test Object

Oral Presentations

- *Safety issues in digital imaging in paediatric work*
UKRC, Manchester, June 2005
- *Optimisation of image quality in NAI*
ICH / GOSH Grand Round, March 2003

9.1 **Abstract**

Aim: To ensure consistency in film density regardless of radiation exposure.

Materials and Methods: Exposures were made (with the same radiographic equipment, and a constant output of 63kVp) of the Leeds TO.10 test object on an 18cm x 24cm Fuji imaging plate. Standard and high resolution imaging plates were used. Images were developed on a Fuji 5000R CR system on fixed and semi-auto read modes and contrast setting on “test”. Density was measured as background density with a Victoreen 07-423 dual reference densitometer. The densitometer was calibrated to give a density reading of 3.00 on a reference standard image. Five readings were taken on the central background area of each film, and the average calculated.

Results: The sensitivity value was directly related to density in fixed read mode. In semi-auto read mode sensitivity was inversely related to kVp and mAs, with insignificant variation in film density. Even with an 11cm thickness scattering object, almost all details were visible even at the lowest exposure levels of 60kVp and 1mAs.

Conclusion: The digital radiography system is able to adjust sensitivity values such that constant radiographic density is produced regardless of exposure parameters. Therefore given constant reading conditions, changes in detail detectability (by the same observer) are due to changes in radiographic parameters and not due to changes in radiographic density. The TO.10 test object is of insufficient sensitivity for the purposes of optimising digital radiographic parameters.

9.2 Introduction

A major difference between CR and conventional radiography is that with the former there is no constant relationship between exposure and film density. Rather the system adjusts sensitivity values such that radiographs of constant density are produced regardless of exposure.

Whether employing test objects or radiographs of real patients, detail detection may be affected both by radiographic parameters and by film density. Therefore before attempting to optimise radiographic parameters, it is important to establish that radiographs of constant density are indeed produced, even when radiographic parameters are altered.

The fixed read mode of CR systems operates with fixed sensitivity and latitude, and in order to obtain images of satisfactory quality exposure factors must (as with conventional radiography) be carefully selected. In the semi-auto mode, the system operates with fixed latitude, varying sensitivity values in such a way as to maintain constant density. Both modes are useful in performance testing and/or quality control programmes [COWE1993].

The Leeds test objects provide a semi-objective means of assessing image quality. They relate imaging performance to the x-ray exposure, while taking variability in observer perception into account. The Leeds TO.10 test object was designed for the assessment of television and small-format fluorography and not specifically for CR systems. However it was employed in the initial phantom studies, as it was the only threshold contrast detail detectability (TCDD) test object initially available, and it was considered adequate for the purpose of determining a constant relationship between exposure and film density.

9.3 Materials and Methods

The x-ray equipment used was a Siemens Optilix with nominal focal spot size fine/broad = 0.6/1mm, inherent tube filtration 1.5mm Al and additional filtration 0.1mm Cu. All exposures of the Leeds TO.10 test object were made on a standard (5lp/mm) or high (10lp/mm) 18cm x 24cm Fuji imaging plate. A latitude value of 2.2 was used (median latitude for skeletal surveys in infants).

Fixed read mode (FRM)

All exposures were made with a constant kVp of 63. Initially collimation was to the borders of the imaging plate (IP), but was then subsequently made slightly wider at 3mm outside the borders. In a bid to render visualisation of details more difficult, two exposures were made with an 11cm scattering object. Sensitivity values were set at 100, 200, 300 and 400.

Semi-auto read mode (S-ARM)

Exposures were made at 1.0, 1.6, 2.0, 2.5, and 3.2 mAs for each of 40, 50, 60, 70, 80, 90 and 100 kVp.

An initial experiment of 10 exposures (constant kVp of 60) and varying mAs (as above) was performed without a scattering object. Subsequently, an 11cm scattering object was added.

Coning was to 3mm outside the IP borders.

Sensitivity values (as displayed on both the monitor and radiographs) were recorded.

All radiographs

Radiographs were developed on a Fuji 5000R CR system.

Density was measured as background density with a Victoreen 07-423 dual reference densitometer. The unexposed portion of a standard film was calibrated to give a density reading of 3.00. 5 readings were taken on the central background area of each film, and the average calculated.

Statistical analysis

One-way analysis of variance (one-way ANOVA) was performed comparing differences in mean densities of the radiographs using SPSS 10.1.

9.4 Results

Fixed read mode

Table 9.6-1 (178), and *Figure 9.6-1* (page 180) illustrate the results obtained on FRM. Films B – D differed only in the degree of collimation. Mean density for films A – D was 1.71 (95% confidence interval [CI] = 1.16 – 2.26) with a standard deviation of 0.28 and a standard error of 0.14. There was no significant variation in the mean density values for these four films ($p = 0.76$).

It can be seen that density was directly related to sensitivity and mAs. The effect of the scattering object was to reduce density. The high resolution IP produced images of lower density than the standard resolution IP, even with an 11cm scattering object.

Semi-auto read mode

Tables 9.6-2 and *9.6-3* (page 179) demonstrate the results (at 63kVp) with and without an 11cm scattering object. Density remained constant irrespective of exposure. Image quality was such that almost all details were visible even at the lowest exposure of 60kVp and 1mAs. *Figure 9.6-2* (page 180) shows the almost constant film density produced regardless of mAs and kVp. It also illustrates the inverse relationship between S and exposure.

The mean density for the 66 radiographs processed on S-ARM was 0.948 (95% CI = 0.89 – 1.01) with a standard deviation of 0.03 and standard error of 0.004. Differences in density were not significant ($p = 0.07$).

All radiographs

All objects on the Leeds TO.10 object could be seen even with the lowest mAs of 1.0 (kVp = 60) when no scattering object was used (*Figure 9.6-3* page 181). Compare with *Figure 9.6-4* (page 181), which shows an exposure with identical parameters except for the use of an 11cm scattering object, and *Figure 10.6-3* (page 190), which shows an exposure of the Leeds TO.16 test object also at 60kVp and 2.0mAs. Note the increased visibility of quantum mottle between the images, causing reduced detail detectability, despite the insignificant differences in optical density.

9.5 Conclusions

The relationship between S and exposure is given by the equation

$$\text{Sensitivity } S \cong \frac{\text{Constant}}{\text{Exposure}} \quad [\text{BIR2001}].$$

This was confirmed by the inverse relationship between S and both kVp and mAs demonstrated by this study. Furthermore the density of the images produced on semi-auto mode was almost constant, regardless of the exposure. The implication is that for a given observer and constant reading conditions variations in detail detection are not due to changes in film density, but rather to changes in exposure parameters (quantum mottle). As suspected, the Leeds TO.10 test object (designed for fluorography systems) does not have the sensitivity required for the purposes of optimising parameters for digital imaging. Meaningful results will require the use of the TO.16 test object, designed specifically for assessing CR systems.

9.6 Tables and Figures

Table 9.6-1: The effects of mAs and sensitivity on density (fixed read mode)

Image	mAs	Sensitivity	Coning	Plate Resolution ^a	Scattering Object	Average Density
A	2.5	200	To plate	High	None	1.680
B	2.5	200	To plate	High	None	1.732
C	2.5	200	3mm within plate	High	None	1.710
D	2.5	200	3mm outside plate	High	None	1.744
E	2.5	100	3mm outside plate	High	None	0.910
F	2.5	400	3mm outside plate	High	None	2.612
G	1.6	200	3mm outside plate	High	None	1.294
H	1.6	303	3mm outside plate	High	None	1.770
I	1.6	303	3mm outside plate	Standard	None	2.996
J	1.6	100	3mm outside plate	Standard	None	1.578
K	2.5	200	3mm outside plate	High	11cm	0.382
L	2.5	400	3mm outside plate	High	11cm	0.892

a. High resolution = 10lp/mm, Standard resolution = 5lp/mm

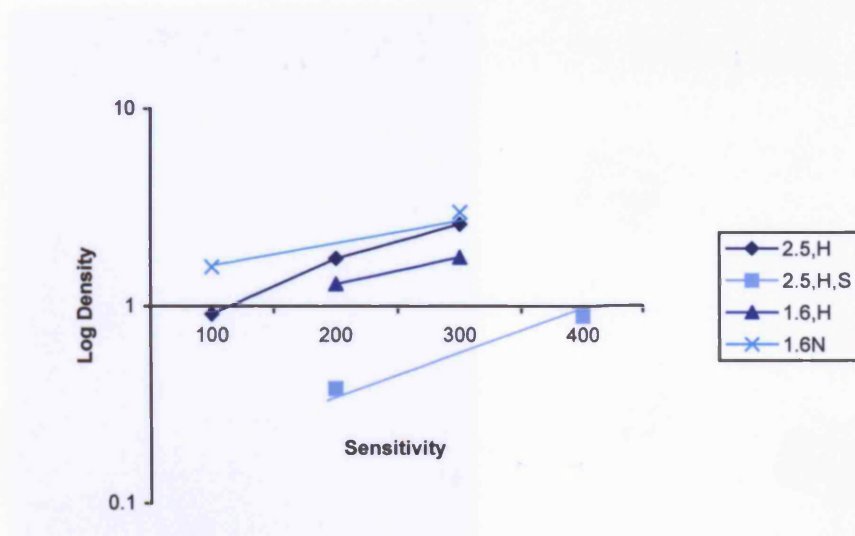
**Table 9.6-2: Relationship between S and mAs (semi-auto read mode)
63kVp, no scattering object**

Image	mAs	Sensitivity	Mean Density
AM	1.0	113	0.956
BM	1.6	76	0.958
CM	2.0	58	0.952
DM	2.5	52	0.956
EM	3.2	41	0.962
FM	1.0	115	0.934
GM	1.6	76	0.932
HM	2.0	58	0.940
IM	2.5	52	0.944
JM	3.2	41	0.952

**Table 9.6-3: Relationship between S and mAs (semi-auto read mode)
63kVp, 11cm scattering object**

Image	mAs	Sensitivity	Mean Density
AT	1.0	565	0.92
BT	1.6	391	0.92
CT	2.0	333	0.92
DT	2.5	277	0.92
ET	3.2	225	0.93
FT	3.6	205	0.93
GT	4.0	187	0.94
HT	4.5	167	0.94

Figure 9.6-1: Relationship between sensitivity and density (fixed read mode)



2.5 = 2.5mAs 1.6 = 1.6mAs H = (the same) high resolution imaging plate, N = (the same) standard resolution imaging plate, S = scattering object

Figure 9.6-2: Effects of kVp and mAs on sensitivity and density (semi-auto read mode)

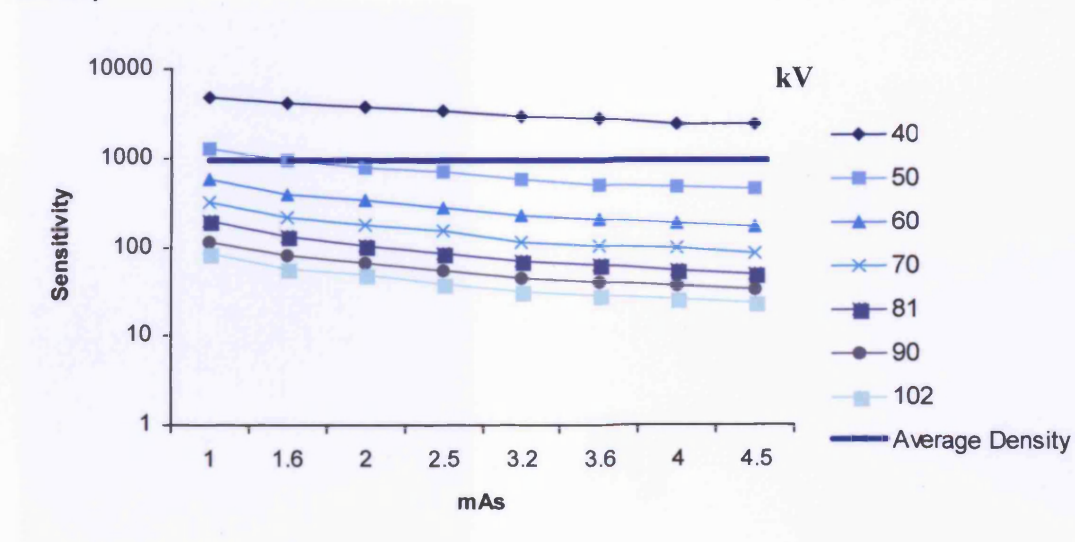


Figure 9.6-3: Leeds TO.10 test object 60KVp/1mAs

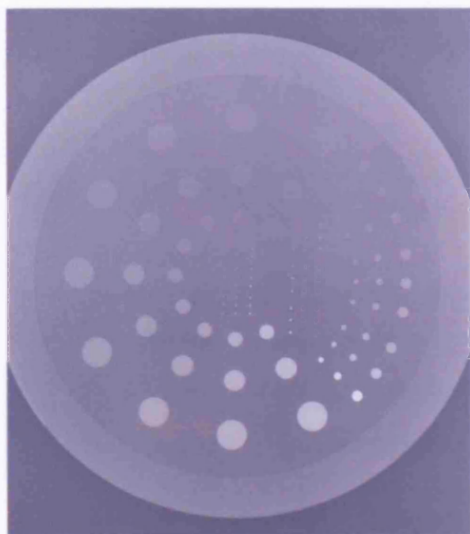
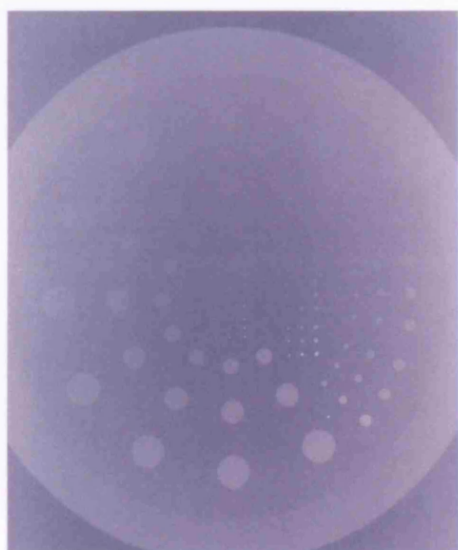


Figure 9.6-4: Leeds TO.10 test object 60KVp/1mAs (plus 11cm scattering object)



Chapter 10

The Phantom Studies: Leeds TO.16 Test Object

Oral Presentation

- *Safety issues in digital imaging in paediatric work*
UKRC, Manchester, June 2005
- *Optimisation of image quality in NAI*
ICH / GOSH Grand Round, March 2003

10.1 Abstract

Aim To determine those exposure parameters beyond which either there is no improvement in detail detectability, or maximum detail detectability is achieved.

Materials and Methods Exposures were made at varying mAs and kVp of the Leeds TO.16 test object on a 24cm x 30cm Fuji imaging plate (the TO.16 is larger than the TO.10). Images were developed on a Fuji 5000R CR system on semi-auto mode and contrast setting on “test”. Images were randomised and coded. Four observers read the images under standardised conditions, and for each contrast recorded the number of details visible. Half values were permitted. Detection indices for all exposures and each observer were calculated.

Results There was moderate inter and poor intra observer reliability. Detection indices increased with increasing exposure, however even at exposures of 80kVp and 6mAs, all details could not be visualised.

Conclusions It is likely that with higher exposures than used in this study, more details will be rendered visible. However in patients, such doses would exceed National Radiation Protection Board (NRPB) levels. It is necessary to repeat this study on post mortem cases using acceptable exposure parameters.

10.2 *Introduction*

Studies using the TO.10 test object revealed that even with a scattering object and low exposures, almost all details could be visualised.

The Leeds TO.16 test object was therefore purchased (RCR pump-priming fund – *Appendix I*, page 269). This test object was specifically designed for the assessment of CR systems.

It had previously been shown (*Chapter 9* page 171), that given constant reading conditions, changes in detail detectability by a single observer would be due to changes in imaging parameters and not changes in film density. The purpose of the study outlined in this chapter was to determine those parameters at which all details could be visualised by all observers. The ultimate aim was to apply these parameters to post mortem radiographs and to compare image quality and diagnostic accuracy with those of post mortem radiographs obtained at standard parameters.

10.3 *Materials and Methods*

Exposures of the TO.16 test object were made using the same x-ray equipment as in the previous study (Siemens Optilix; nominal focal spot size fine/broad = 0.6/1mm, inherent tube filtration 1.5mm Al and additional filtration 0.1mm Cu). The 1.6mm Cu plate provided with the test object was used for additional filtration. Exposures were made onto a 24cm x 30cm Fuji standard resolution imaging plate.

Exposures were made at 2, 4 and 6mAs for 50, 60, 70 and 80kVp. Some exposures were repeated with identical parameters to assess intraobserver reliability.

Images were coded and randomised.

Four observers blinded to the exposure parameters read the images under standardised conditions. The number of details of each size detected was recorded on a scoring sheet prepared for the purpose. Half values were permitted. Observers were shown the diagram of the test object (*Appendix IV*, page 272) to ensure that they filled out the scoring sheets correctly.

Detection indices were calculated according to the formula on page 89, and detection index diagrams constructed at the various exposure levels for each observer.

Cohen's kappa was calculated as a measure of inter and intra observer reliability using Stata/SE8.2 software.

10.4 Results

Appendix VII (page 275) is the completed data sheet for Observer 1.

Calculated detection indices (H_T) for each observer at 60kVp and 4mAs are shown in *Table 10.6-1* (page 188). *Figures 10.6-1* and *10.6-2* (page 189) show detection index diagrams based on the results obtained at 50kVp/2mAs and 80kVp/6mAs.

Subjective assessment of the curves suggests insignificant differences amongst the four observers, with H_T increasing directly with exposure.

Interobserver reliability was moderate ($Kappa = 0.49$). Intraobserver reliability was poor (*Table 10.6-2*, page 188).

Figure 10.6-3 (page 190) is an exposure of the TO.16 at 60kVp and 2mAs. Compare with *Figures 9.6-3* and *9.6-4* (page 181). These show exposures of the TO.10 test object at 60kVp and 1mAs with and without a scattering object.

Even at the highest exposure (80kVp and 6mAs) some details of the Leeds TO.16 were not visualised.

10.5 Conclusions

The observers who participated in this trial did not feel that the Leeds TO.16 test object was wholly objective. All complained that in some instances it was difficult to be sure that they could really see a detail, or whether it was “visible” just because they knew from the diagram that it “should be” there. This was reflected in the poor to fair intraobserver reliability scores obtained.

This indicates that use of the Leeds TO.16 test object may not produce consistent results. Even if this was not the case, objective means of assessing differences in H_T at different exposure levels are currently unavailable.

In the absence of an objective means of assessing the detection index diagrams, it is difficult to comment meaningfully on the results. It is certainly true that the detection index increased with exposure, but how significant is the difference between 50kVp/2mAs and 80kVp/6mAs (for example)?

Use of the Leeds test objects is not wholly objective. This is related to the intrinsic non-random design of the placement of the contrast details.

Even at an exposure of 80kVp/6mAs all details could not be visualised. Higher exposures were not made; such doses in patients would certainly exceed NRPB levels. It will be necessary to perform a wider range of exposures on the post mortem cases than initially proposed.

10.6 Tables and Figures

Table 10.6-1: Detection indices (H_T) for Observers 1 – 4 (60kVp/4mAs)

Row	Root Area	H_{T1A}	H_{T1B}	H_{T2A}	H_{T2B}	H_{T3A}	H_{T3B}	H_{T4A}	H_{T4B}
A	9.830	5.98	5.01	8.55	4.31	5.98	4.31	7.02	5.01
B	7.000	7.04	8.40	12.00	8.40	1.13	7.04	9.85	8.40
C	4.960	9.93	9.93	16.94	11.86	11.86	9.93	11.86	11.86
D	3.540	11.97	8.00	23.74	16.62	11.97	16.62	11.97	11.97
E	2.480	11.42	11.42	11.42	23.72	11.42	19.86	11.42	17.09
F	1.770	9.26	12.81	16.00	23.94	16.00	23.94	16.00	23.94
G	1.240	13.22	10.20	22.85	10.20	15.27	22.85	22.85	12.22
H	0.886	14.27	14.27	21.38	14.27	21.38	21.38	21.38	17.10
J	0.620	17.70	17.70	30.55	20.39	20.39	20.39	20.39	20.39
K	0.443	11.64	15.05	15.05	15.05	11.64	15.05	11.64	15.05
L	0.310	7.81	11.69	7.81	11.69	7.81	11.69	7.81	11.69
M	0.221	8.09	10.96	8.09	10.96	8.09	10.96	8.09	10.96

H_T = Detection index

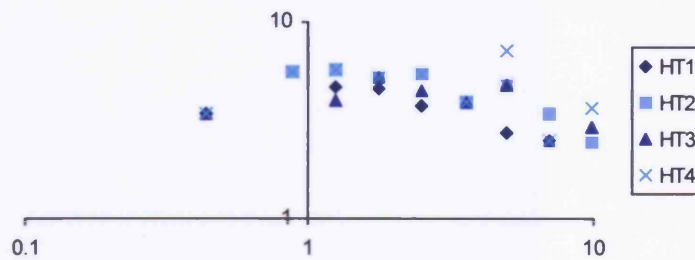
1 = Observer 1, 2 = Observer 2 etc

A = 1st reading, B = 2nd reading

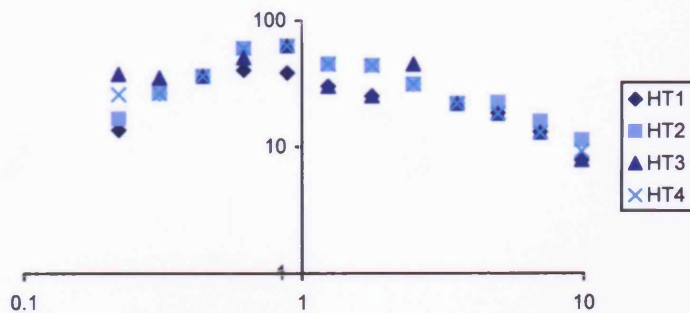
Table 10.6-2: Intraobserver reliability (Leeds TO.16 detection indices)

Observer	Kappa Score	Interpretation
1	0.31	Fair
2	0.08	Poor
3	0.15	Poor
4	0.23	Fair

**Figure 10.6-1: Detection index diagram Observers 1 – 4
50 kVp/2mAs (1st reading)**

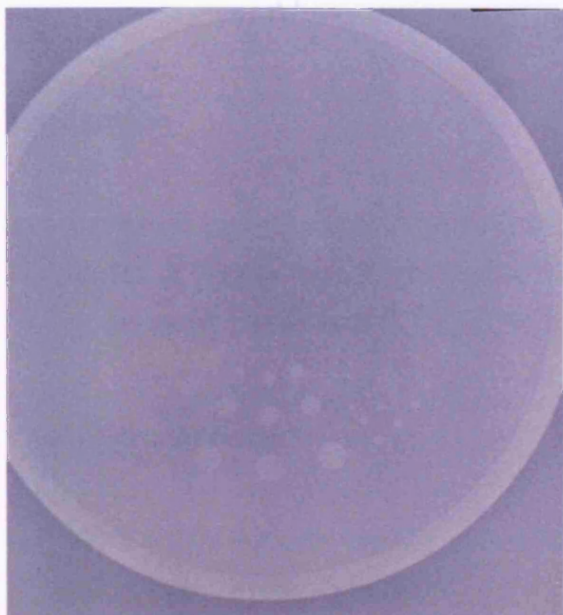


**Figure 10.6-2: Detection index diagram Observers 1 - 4
80kVp/6mAs**



Notice the difference in scale along the Y-axis (detection index – H_T) between the two figures. As expected, the higher exposure resulted in higher H_T for all observers. Note also the reduced interobserver variability at higher doses. However there is no subjective means of calculating the significance between differences, or (for a given exposure) of deciding what level of H_T is required to meet the clinical task (in this case visualisation of the subtle fractures of NAI).

Figure 10.6-3: Leeds TO.16 test object 60KVp/2mAs



See also *Figures 9.6-3 and 9.6-4* (page 181), which show exposures of the TO.10 test object (with and without an 11cm scattering object) at 60kVp and 1mAs.

Chapter 11

Dose Requirements for Digital Skull Radiographs in Infants

Publication

- *Optimal exposure parameters for digital radiography of the infant skull: A pilot study*
Offiah AC, Grehan J, Hall CM, Todd-Pokropek A
Accepted Clinical Radiology July 2005

Oral Presentations

- *Safety issues in digital imaging in paediatric work*
UKRC, Manchester, June 2005
- *Optimal exposure parameters for digital radiography of the infant skull: A pilot study*
BSPR Annual Conference, Leicester, November 2004

11.1 Abstract

Purpose: To determine optimal exposure parameters when performing digital skull radiographs in infants with suspected non-accidental injury (NAI).

Method: Anteroposterior and lateral post mortem skull radiographs of six consecutive infants with suspected NAI were made at six exposure levels for each projection. Entrance surface doses ranged from 75 μ Gy to 351 μ Gy. Exposures were made with a Fuji 5000R computed radiography system onto a standard resolution imaging plate. In three patients exposures were repeated using a high resolution imaging plate. Hard copy images with an edge-enhancement factor of 0.5 were produced. Six observers assessed and scored the radiographs from 1 = poor to 5 = excellent for visualisation of five criteria. The criteria scored included outer table of skull vault, inner table of skull vault, suture margins, vascular markings and soft tissues of the scalp. Radiographs were then ranked in order of overall image quality. Film density and sensitivity values were recorded.

Results: Current parameters give an average entrance surface dose of 253 μ Gy and 246 μ Gy for anteroposterior and lateral radiographs respectively. The study demonstrated no perceived improvement in image quality above an entrance surface dose of 200 μ Gy (80% of current dose) or by the use of a high resolution imaging plate.

Conclusion: The potential exists to reduce radiation exposure in infants. A study has commenced to determine the effects of dose reduction on diagnostic accuracy in suspected NAI.

11.2 Introduction

Barnhard touched upon the subjectivity associated with determining the quality of an image when he wrote, "... image quality is in the eye of the beholder..." [BARN1982]. Despite this subjectivity, image quality must be optimised, perhaps for the clinical indication, and certainly for the imaging modality.

In an attempt to standardise image quality throughout Europe, the Commission of European Communities (CEC) published guidelines for both adult and paediatric radiographic imaging [CEC1996, EUR1996]. These guidelines have proved useful for optimising image quality [MACC1995, ALME2000]. However it has been concluded by authors of two paediatric papers that if they are also to be used for the assessment of clinical image quality, then modification of these criteria is required [COOK2001A, OFFI2003A].

With the advent of digital imaging, studies have been performed comparing image quality of digital with conventional film-screen systems. It has been shown that digital systems have lower spatial, but improved contrast resolution when compared to film-screen systems [COWE1993].

Image quality is related to radiation dose. Particularly in the paediatric population it is necessary to adhere to the ALARA (as low as reasonably achievable) principle. Computed radiography (CR) systems have a wider dynamic range than film-screen systems. This, in addition to the post-processing capabilities has led to much expectation of a substantial reduction in radiation dose with the implementation of CR. Several studies have demonstrated possible dose reductions ranging from 25% to 60% with no significant impairment in the diagnostic performance of observers [PROK1990, JONS1996, SIEF1996, HUFT1998]. Of particular relevance is the study by Hufton et al in 900 children [HUFT1998]. These authors suggest that with CR it is possible to reduce dose by at least 33% for chest radiographs and 60% for other examinations in departments using conventional film of speed 400 or less, while maintaining comparable image quality.

Other authors are more cautious, believing that the dose benefits of CR are overstated [LIND1996, BRAG1997, JAME2001, PEER2002]. Some of these authors suggest that significant dose reductions can be achieved for certain clinical indications (such as

scoliosis assessment), while higher doses are necessary for more subtle abnormalities (such as wrist fractures) [LIND1996, PEER2002].

High quality images are required for the diagnosis of suspected NAI even at the risk of increased radiation dose to the infant and child [ACR2001]. It has previously been shown that in the United Kingdom (UK) there is considerable variation in the projections obtained for skeletal surveys in suspected NAI. There is also much variability in the quality of radiographs, with skull radiographs generally being of poor quality [OFFI2003B].

In the radiology department at GOSH, current exposures with a CR system are higher than previous exposures using a film-screen system. The aim is to optimise parameters for the digital imaging of NAI. Initial results with the Leeds TO.16 phantom [LEEDSTO] were difficult to interpret as the minimum spatial and contrast resolution required for digital radiographs in this clinical setting are not known. Furthermore, the phantom was felt to be too sensitive for the purpose – not all objects could be visualised even at exposures above recommended NRPB levels (*Chapter 10* page 182).

The aim of this pilot study was to document the potential for dose reduction in computed radiography (CR) of the infant skeletal system, concentrating on radiographs of the skull.

11.3 Materials and Methods

Case selection and image processing

Six consecutive infants undergoing post mortem skeletal surveys for suspected NAI were prospectively recruited. In addition to the routine skeletal survey, each patient had anteroposterior (AP) and lateral radiographs of the skull at various exposures (*Figures 11.6-1 to 11.6-6*, pages 207 – 209). Routine departmental exposure levels for AP and lateral skull radiographs in children less than a year of age are 65kV and 4mAs. Exposure parameters for this study were selected to give entrance surface doses of approximately 35%, 45%, 70%, 75%, 100% and 120% of this reference level. All radiographs were obtained using the same x-ray machine (Wolverson Comet; nominal focal spot size fine/broad = 0.6/1mm, inherent tube filtration 1mmAl, additional filtration 1.5mmAl).

Images were processed on a Fuji 5000R CR system using a standard resolution imaging plate. In three patients (Patients 2*, 3* and 4*, *Table 11.6-1*, page 203) exposures were repeated using a high resolution imaging plate.

All images were processed in auto read mode. In one patient (Patient 1*, *Table 11.6-1*, page 203) the images were also processed in fixed read mode with a sensitivity value (S) of 200.

Radiographs were printed with an edge-enhancement of 0.5.

The six radiographs of each patient (for a given projection, read mode and imaging plate combination) were coded, shuffled and placed in a single packet. This gave 20 film packets, each containing six AP or lateral skull radiographs of the same patient. There was therefore a total of 60 AP and 60 lateral skull radiographs.

Bitemporal and occipitofrontal diameters were measured and used to calculate entrance surface doses. Entrance surface doses and sensitivity values were documented for each exposure. Film density (at the centre of the film) was measured for each radiograph using a Victoreen 07-423 dual reference densitometer.

Image interpretation

All twenty packets were presented independently to six post-fellowship radiologists.

These included two consultants, one clinical research fellow (three years post certification for completion of specialist training), two paediatric radiology fellows (one offered and the other seeking a consultant post) and one year five radiology registrar with an interest in paediatric radiology.

Observers interpreted the images under routine clinical conditions, and were given no time limitations.

Images within each packet were individually scored according to the standardised form illustrated in *Appendix IX* (page 278). The scoring system adopted included five criteria. Several criteria were scored, as differences in exposure might affect one criterion and not another. Observers assessed and scored the images depending on how well they could visualise each of the criteria. Scores ranged from 1 (poor) to 5 (excellent). Observers then ranked the images based on overall image quality.

A year later, Observers 1, 4 and 6 repeated the readings for two of the film packets.

Statistical analysis

Each criterion was analysed separately. The Stata/SE8.2 statistical software package was used. The average individual and pooled observer scores for all patients were calculated for each exposure level. Analysis of variance was performed to determine relationships between patient age (divided into age groups; less than 1 week, 1 to 4 weeks, 4 – 12 weeks, 12 – 36 weeks and 36 – 52 weeks) and entrance surface dose. Student's paired t test was performed to determine differences in density based on imaging plate resolution, exposure and read mode and to determine significance of differences in quality scores and measured film density. Kendall's rank correlation was performed to detect the significance of relationships between image rank (based on quality) and radiation exposure. Cohen's Kappa was calculated as an indication of inter and intra observer reliability. Interpretation of Kappa scores was based on that given by Tudor et al [TUDO1997]. Multivariate linear regression analysis was performed to determine relationships between quality scores and entrance surface dose. Using the ANOVA tools (Stata/SE8.2) the statistical analysis goes some way into taking account of the interdependence of the variables caused as a result of multiple observations by multiple observers. The nominal level of significance was set at 5%.

11.4 Results

Entrance surface dose

Patient age ranged from 1 to 60 weeks with a mean of 26 weeks. Bitemporal skull diameters ranged from 4.3cm to 9cm and anteroposterior diameters from 6cm to 18.5cm. Entrance surface doses ranged from 75 μ Gy to 351 μ Gy with a mean of 178 μ Gy and a median of 164 μ Gy. Patient age was not related to entrance surface dose ($p = 0.34$). Sensitivity values were inversely related to radiation dose, and (for a given exposure) were lower for the standard compared to the high resolution imaging plate (*Figure 11.6-7*, page 210).

Film density

The density of individual radiographs processed in auto read mode was significantly lower for high resolution compared to standard resolution imaging plates ($p < 0.001$), but was not affected by radiation dose or skull diameter. Measured density of the (control) radiographs processed in fixed read mode was significantly higher than that of radiographs processed in auto read mode ($p = 0.001$). *Table 11.6-2* (page 203) gives a summary of the measured (objective) densities of the radiographs. *Figures 11.6-1 to 11.6-6* (pages 207 – 209) illustrate the visual (subjective) effects of dose and image processing on radiographic density and mottle.

Fulfilment of criteria

Fulfilment of criteria increased significantly ($p = 0.001$) with increasing radiation dose to a maximum of 200 μ Gy. At this dose the image quality scores reached a plateau. Above a dose of 300 μ Gy, there was a (non-significant) downward trend in quality scores. These results were true for the quality scores of pooled observers (*Figure 11.6-8*, page 211) and for all individual observers except Observer 3 for whom there was no relationship between fulfilment of criteria and radiation exposure.

Ranked image quality

For pooled observers, there was a significant positive relationship between ranking (based on a subjective assessment of overall image quality) and radiation dose ($p < 0.001$). This was also true for all individual observers except Observer 3. For this observer, there was in fact a slight (insignificant) negative relationship between rank and radiation dose (*Table 11.6-3*, page 204).

Imaging plate

The average quality scores for standard and high resolution imaging plates are compared in *Table 11.6-4* (page 204). Images exposed onto a standard resolution plate had a tendency towards higher scores than those exposed onto a high resolution plate.

Observer reliability

Kappa scores are summarised in *Tables 11.6-5* and *11.6-6* (page 205). Observer 3's ranking results were in contrast to results of the other observers. Kappa scores for interobserver reliability were therefore calculated with and without the results of this observer.

Intraobserver variability a year after initial interpretation tended to be fair or moderate.

11.5 Discussion

In this paper the results of a pilot study to determine the effects of various exposure parameters on the quality of skull radiographs have been reported. The potential for a 20% reduction in exposure has been demonstrated.

Frontal and lateral skull radiographs were selected because of the findings of a previous study [OFFI2003B]. This study, on the quality of skeletal surveys performed in the UK for suspected NAI, revealed these to be the projections most likely to be of poor quality, whether performed with film-screen or digital systems.

Compared to adults, children are at twice the risk of developing delayed complications of radiation exposure for the same effective dose [MUIR1993]. Increasing emphasis is being placed on optimisation of radiographic parameters while still adhering to the ALARA principle [WRAI1995, COOK2001B]. This is particularly important with the recent advent of digital imaging systems [FREE1995, BOSM2001, MARS2001B]. In cases of NAI, the child undergoes a full skeletal survey consisting of a minimum of 17 radiographs [ACR2001, BSPR2004]. Further views of suspicious areas, and (in certain instances) delayed radiographs may be obtained. The total effective radiation dose of a skeletal survey may therefore be significant. It is accepted that the high quality of radiographs needed in the setting of NAI justifies increased radiation dose [ACR2001]. The need for optimisation of imaging parameters in this clinical setting is clear.

Unlike traditional film-screen radiography, CR systems (in auto read mode) produce images of almost constant density regardless of the choice of radiographic parameters. However the extent of dose reduction is limited by the degree of quantum mottle [JAME2001]. In this study, a near constancy of density was confirmed in the 108 skull radiographs obtained in auto read mode. The perceived differences in image quality were therefore due to the degree of quantum mottle on the radiographs (*Figures 11.6-1 to 11.6-4, pages 207 and 208*).

Assessment of image quality may be objective (based on physical parameters such as the characteristic curve and modulation transfer factor) or subjective (based either on phantom studies of spatial and contrast resolution, or on the quality criterion concept [MARS2001A, JESS2001]). In this study, quality was assessed based on a modification of the CEC quality criteria [EUR1996] (*Table 11.6-7, page 206*). The CEC criteria that depended purely on patient positioning were omitted. Visualisation of inner was separated from visualisation of outer skull vault. Similarly visualisation of vascular

channels was separated from visualisation of trabeculae. The visualisation of soft tissues was included. And finally the same criteria were maintained for the lateral, as for the anteroposterior projection.

Almen measured radiation dose for a variety of paediatric film-screen investigations [ALME2004]. For pelvic radiographs she showed a range of entrance surface doses of 90 μ Gy to 1,700 μ Gy with a plateau at 400 μ Gy above which there was no perceptible improvement in image quality. Similarly, in this study, it was shown that improvement in perceived image quality of skull radiographs reached a plateau at 200 μ Gy.

A number of studies have been performed to determine the magnitude of dose reduction achievable with computed compared to film-screen radiography. Dose reductions with CR can be as high as 95% depending on the clinical indication [JONS1996, HUFT1998, LIND1996, HONE1994]. The CEC has not published diagnostic reference levels for infant skull radiographs. Levels cited for children five years of age are 1500 μ Gy and 1000 μ Gy for anteroposterior and lateral skull radiographs respectively [EUR1996]. In the radiology department at GOSH, parameters used for film-screen imaging of skull radiographs in infants were 60kV and 3.2 mAs. The degree of quantum mottle when these parameters were employed with the new CR system (1998) was felt to be unacceptable, and these exposure parameters were subsequently increased to current levels of 65kV and 4mAs. For the patients recruited in this study, the average entrance surface dose at these parameters was 253 μ Gy and 246 μ Gy for anteroposterior and lateral radiographs respectively. However multivariate linear regression analysis revealed no increase in image quality above a dose of 200 μ Gy (80% of current reference level) for individual quality criteria. Observers ranked the 75% exposure images below the 100% images 80% of the time, and although there was a slight trend in favour of the higher exposure, there was no significant difference in fulfilment of individual quality criteria between the two. The implication is that lower doses (75% - 80% of those currently in use) might suffice for imaging of the infant skull.

It is interesting that no differences in quality between the 75% and 100% images were detected, as the 75% exposure levels represent those used with the former film-screen system (60kV, 3.2mAs). With the advent of the CR system, these parameters were rejected as depicting excess quantum mottle. The possibility is raised that increased familiarity with CR images has rendered observers more tolerant of its imperfections.

The current maximum spatial resolution achievable with CR systems (and standard resolution imaging plates is 5lp/mm, compared to 10 – 15lp/mm for film-screen systems [ARTZ1997]. The spatial resolution of the imaging plates used in this study was 5lp/mm and 10lp/mm for standard and high resolution imaging plates respectively. *Figure 11.6-7* (page 210) demonstrates that when using high resolution imaging plates, higher exposure factors are required to achieve the same (low) degree of quantum mottle compared to standard resolution imaging plates. The use of high resolution imaging plates has been recommended for radiographs of the hands, wrists, elbows, ankles and feet but not for the skull [FREE1995]. Certainly the results of this study would indicate that there is no role for high resolution imaging plates in imaging of the infant skull. It should be noted that the study design was such that no direct comparisons were made between radiographs obtained with the two imaging plates. Thus while quality scores did not differ, direct ranking of images obtained on the two plates was not performed.

It has been shown that in cases of suspected NAI, when reading from a monitor (soft copy), digital image quality is significantly better, and diagnostic accuracy is at least as good as when reading from printed radiographs (hard copy) [OFFI2005]. In this pilot study, hard copy radiographs were used. Manipulation of images (e.g. brightness, grey-scale, magnification etc) is an advantage of soft compared to hard copy interpretation of radiographs. This may allow further reduction in radiation exposure not demonstrated by the study methodology.

Interobserver reliability was good for five of the six observers. One observer (Observer 3) showed significant variation when compared to the others. At completion of the study it was established that this observer did in fact score and rank the images in accordance with the study protocol. No explanation can be given for Observer 3's results; however they highlight the subjective nature of quality assessment. A more objective method, such as the method described by Bosmans et al [BOSM2001] may be preferable.

In this pilot study, patient numbers were relatively small, and the effect of dose on the detection of pathology (e.g. skull fractures, soft tissue swelling etc) was not an objective. However the results suggest that there is scope for at least a 20% dose reduction in radiographs of the infant skull, particularly when the clinical indication does not require fine detail (e.g. diagnosis of constitutional disorders of bone).

A study has been started to determine the magnitude of dose reduction achievable without compromise to diagnostic accuracy in infants with suspected NAI.

11.6 Tables and Figures

Table 11.6-1: Image processing

Patient	Imaging Plate Resolution	System Read Mode
1	Standard	Auto
1*	Standard	Fixed
2	Standard	Auto
2*	High	Auto
3	Standard	Auto
3*	High	Auto
4	Standard	Auto
4*	High	Auto
5	Standard	Auto
6	Standard	Auto

* Patients previously imaged with different parameters

Table 11.6-2: Average radiographic densities^a

Image Processing (n)	Mean Density	Minimum Density	Maximum Density	Standard Deviation	95% Confidence Interval	
Auto, standard resolution (72)	-0.02	-0.09	0.09	0.04	-0.03	-0.01
Auto, high resolution (36)	-0.12	-0.15	-0.09	0.02	-0.13	-0.12
Fixed, standard resolution (12)	1.19	-0.23	2.21	0.84	0.66	1.73

a. Measured in the centre of each radiograph with a Victoreen 07-423 dual reference densitometer

**Table 11.6-3: Kendall's rank correlation (standard resolution imaging plate)
Comparing image rank with radiation exposure**

Observer	Projection			
	Anteroposterior		Lateral	
	Kendall's Tau	p	Kendall's Tau	p
1	0.71	<0.0001	0.69	<0.0001
2	0.36	0.0038	0.24	0.0494
3	-0.02	0.8898	-0.03	0.8139
4	0.66	<0.0001	0.59	<0.0001
5	0.59	<0.0001	0.42	0.0007
6	0.51	<0.0001	0.59	<0.0001
Pooled	0.62	<0.0001	0.58	<0.0001

Table 11.6-4: Average quality scores

Criterion	Anteroposterior projection			Lateral projection		
	SR	HR	p ^a	SR	HR	p
Outer table of skull vault	3.76 (3.57 – 3.95) ^b	3.64 (3.43 – 3.84)	0.19	3.92 (3.74 – 4.09)	3.8 (3.65 – 4.04)	0.44
Inner table of skull vault	3.84 (3.66 – 4.03)	3.79 (3.61 – 3.97)	0.49	4.04 (3.84 – 4.23)	3.83 (3.70 – 4.01)	0.05
Suture margins	3.10 (2.91 – 3.30)	2.88 (2.68 – 3.08)	0.02	3.32 (3.13 – 3.52)	3.28 (3.08 – 3.48)	0.65
Vascular	2.88 (2.69 – 3.07)	2.68 (2.47 – 2.88)	0.03	2.90 (2.70 – 3.10)	2.89 (2.69 – 3.09)	0.92
Markings	3.25 (3.05 – 3.45)	3.12 (2.90 – 3.34)	0.20	3.67 (3.47 – 3.86)	3.61 (3.38 – 3.84)	0.70

SR = standard resolution imaging plate

HR = high resolution imaging plate

a. p values from paired t test

b. Mean (95% confidence interval)

Table 11.6-5: Interobserver reliability

Projection	Interpretation (Kappa score)	
	Including Observer 3	Excluding Observer 3
Anteroposterior	Fair (0.37)	Moderate (0.46)
Lateral	Fair (0.38)	Moderate (0.48)

Table 11.6-6: Intraobserver reliability ^a

Criterion	Interpretation (Kappa score)		
	Observer 1	Observer 4	Observer 6
Outer table of skull vault	Excellent (0.84)	Moderate (0.51)	Excellent (0.83)
Inner table of skull vault	Moderate (0.56)	Moderate (0.51)	Good (0.79)
Suture margins	Fair (0.31)	Fair (0.37)	Moderate (0.45)
Vascular markings	Fair (0.32)	Fair (0.35)	Moderate (0.44)
Soft tissues	Moderate (0.40)	Fair (0.39)	Good (0.62)
Rank	Excellent (0.80)	Good (0.61)	Excellent (0.87)

a. The interval between reading sessions was 12 months

Table 11.6-7: The CEC quality criteria for radiographs of the skull [EUR1996]

Criterion	Anteroposterior / Posterolateral Projection	Lateral Projection
1.1	Symmetrical reproduction of the skull, particularly cranium, orbits and petrous bones	Visually sharp reproduction of the outer and inner tables of the entire cranial vault and the floor of the sella consistent with age
1.2	Projection of the upper margins of the petrous temporal bones into the lower half of the orbits in AP projection	Superimposition of the orbital roofs and the anterior part of the greater wings of the sphenoid bones
1.3	Reproduction of the paranasal sinuses and structure of the temporal bones consistent with age	Visually sharp reproduction of the vascular channels and the trabecular structures consistent with age
1.4	Visually sharp reproduction of the outer and inner tables of the entire cranial vault consistent with age	Reproduction of the sutures and fontanelles consistent with age
1.5	Visualisation of the lambdoid and sagittal sutures	-

Figure 11.6-1: Lateral skull radiograph (Patient 2)
Standard resolution imaging plate, 35% exposure, and auto read mode



Figure 11.6-2: Lateral skull radiograph (Patient 2)
Standard resolution imaging plate, 120% exposure, and auto read mode

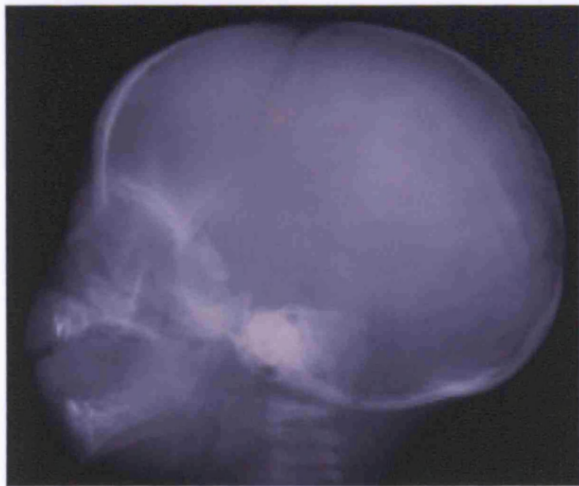
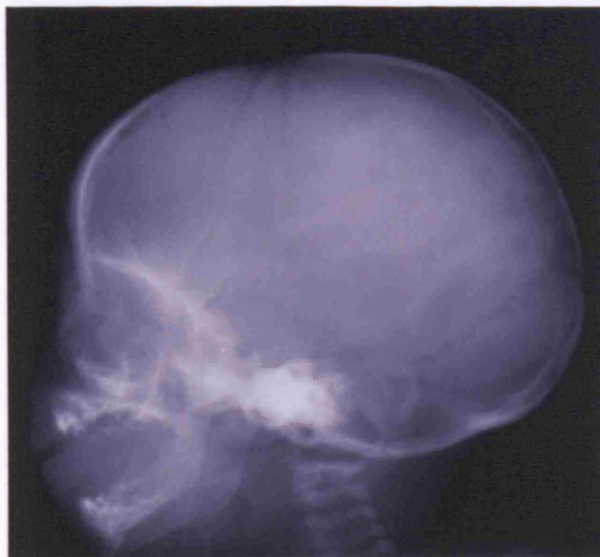


Figure 11.6-3: Lateral skull radiograph (Patient 2)
Standard resolution imaging plate, 100% exposure, and auto read mode



Figure 11.6-4: Lateral skull radiograph (Patient 2*)
High resolution imaging plate, 100% exposure, and auto read mode

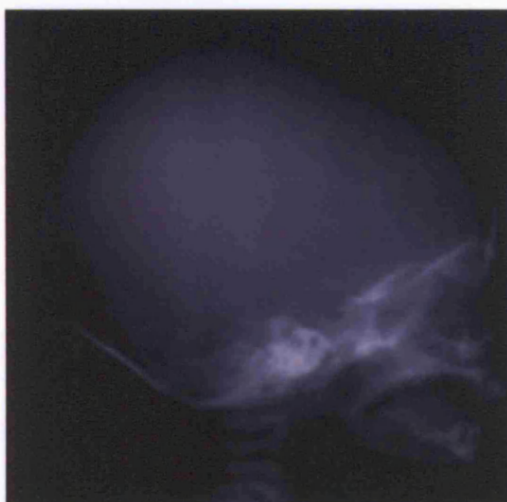


For a given exposure, there is more quantum mottle with the high than with the standard resolution imaging plate. So, when compared to standard resolution, high resolution plates require a higher dose in order to achieve the same (low) degree of quantum mottle.

Figure 11.6-5: Lateral skull radiograph (Patient 1*)
Standard resolution, 35% exposure, and fixed read mode

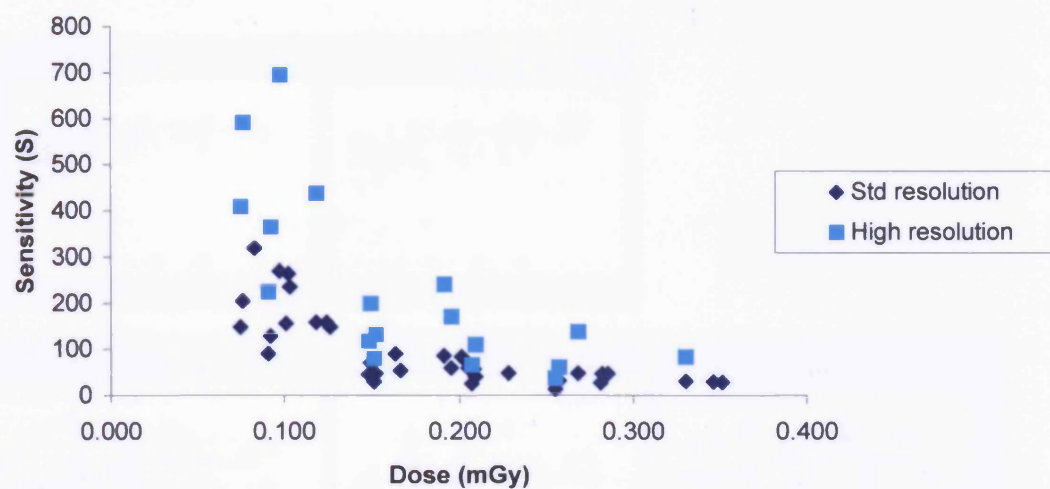


Figure 11.6-6: Lateral skull radiograph (Patient 1*)
Standard resolution, 75% exposure, and fixed read mode



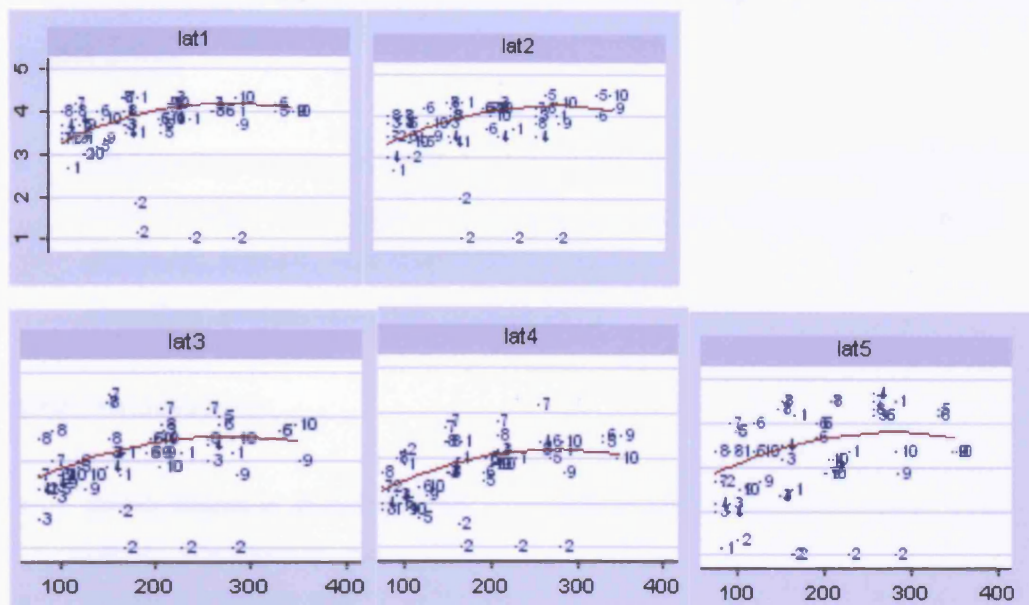
In fixed read mode, digital systems respond in the same way as conventional film-screen systems; increasing the exposure parameters leads to increasingly overexposed and non-diagnostic radiographs.

Figure 11.6-7: Sensitivity values and radiation dose



Sensitivity was inversely related to radiation dose. For a given dose, sensitivity values were lower for standard compared to high resolution imaging plates.

Figure 11.6-8: Relationship between quality and entrance surface dose for lateral skull radiographs (standard resolution imaging plates)



Lat1 = Lateral projection, Criterion 1; Lat2 = Lateral projection, Criterion 2 etc

Vertical axis represents quality scores from 1 (poor) to 5 (excellent)

Horizontal axis represents entrance surface dose (μGy)

Numbers represent individual film packets. The radiographs in Packet 2 (Patient 1*) were developed in fixed read mode, explaining the constantly low scores (See also Figures 11.6-5 and 11.6-6, page 209).

Average observer quality scores have been calculated for each radiograph and each criterion. Quality scores begin to plateau at an entrance surface dose of $200\mu\text{Gy}$ and show a slight (but insignificant) downward trend at $300\mu\text{Gy}$.

Similar curves were obtained for anteroposterior projections and for high resolution imaging plates.

Chapter 12

Digital Image Display in NAI: A ROC Study

Publication

- *Diagnostic accuracy of fracture detection in suspected non-accidental injury:
Effect of edge-enhancement and digital display on observer performance*
Offiah AC, Moon L, Hall CM, Todd-Pokropek A
Accepted Clinical Radiology August 2005

Oral Presentations

- *Safety issues in digital imaging in paediatric work*
UKRC, Manchester, June 2005
- *Digital imaging in NAI: A ROC study*
Radiological Society of North America, 90th Scientific Assembly and Annual Meeting,
Chicago, December 2004
- *Digital image display in NAI: A ROC study*
BSPR Annual Conference, Leicester, November 2004

12.1 Abstract

Purpose: To compare the effect of varying degrees of edge-enhancement and method of digital image display on fracture detection in suspected non-accidental injury (NAI).

Materials and Methods: 50 radiographs exposed as part of post mortem skeletal surveys in 13 children with suspected NAI were selected. Images were obtained using a Fuji 5000R computed radiography system. Hard copies were printed with edge-enhancement factors 0, 0.5 and 1.2. Images (edge-enhancement 0.5) were also displayed on a 1K² monitor. Six observers independently evaluated all 200 images for the presence of abnormality. Observers also scored each image for visualisation of soft tissues, visualisation of trabecular markings and overall image quality. The paired student's t test and location ROC analysis were used to compare quality scores and diagnostic accuracy of each display method. Individual and pooled true positive rates (sensitivity) were determined. For the purposes of ROC analysis, histology was taken as the gold standard.

Results: There was no difference in duration of hard and soft copy reading sessions ($p = 0.76$). Following image manipulation soft copy radiographs scored significantly better for image quality than hard copy ($p < 0.0001$). Pooled observer sensitivity (at a false positive rate of 10%) was below 50% for all display methods. Diagnostic accuracy varied significantly between observers. Diagnostic accuracy of individual observers was not affected by display modality.

Conclusion: In suspected NAI, diagnostic accuracy of fracture detection is generally low. Diagnostic accuracy appears to be affected more by observer related factors than by the method of digital image display.

12.2 Introduction

The purpose of this study was to evaluate the effect of 1) soft compared to hard copy display and 2) varying degrees of edge-enhancement on reporting times, subjective assessment of image quality and diagnostic accuracy of observers in suspected non-accidental injury (NAI).

In the assessment of image quality, it is crucial to answer the question, “How well does the imaging system perform?” The American College of Radiology (ACR) recommend that a high resolution imaging system producing high quality images is used for detection of the subtle fractures of NAI, even if this means increased radiation dose to the patient [ACR2001].

Digital images have lower spatial resolution compared to film-screen systems. However a potential advantage of computed radiography (CR) over conventional film-screen imaging lies in the post-processing abilities available with the former. When used optimally, post-processing improves the visualisation of pathology and allows the display of the full object irradiated range while improving local contrast [FRIJ1998]. Techniques include non-linear grey-scale enhancement, non-linear unsharp masking (edge-enhancement) and single or dual exposure energy subtraction [KANT1997]. Edge-enhancement emphasises the edges and contrast of a lesion, compensating for the lower spatial resolution of CR compared to film-screen systems [OEST1989].

In musculoskeletal imaging, studies exist both in support of [WILS1994] and against [PROK1990, LIND1996] the use of edge-enhancement. The study in support of edge-enhancement did not consider abnormal radiographs, and the authors suggested that more extensive studies of proven injuries were required [WILS1994]. Two studies conclude that the use of edge-enhancement either enhances physiological trabecular irregularities [PROK1990] or produces artefacts at the borders of cortical bone [LIND1996]. In both instances appearances may then be misdiagnosed as cortical defects or periosteal reaction. Finally, another group [KAJI1995] were unable to demonstrate any significant advantage of edge-enhancement in the detection of skeletal fractures, although they reported that it did improve the detection of “small fractures” (sic).

Similar uncertainty exists when comparing interpretation from a monitor (soft copy) with traditional printed x-ray films (hard copy). For instance some authors have shown that soft copy images perform as well as or better than hard copy digital images

[WILS1994, REIN1996]. Another study revealed no significant difference in fracture detection between the two modes of image display [KAJI1995]. While a more recent study showed significant reduction in the detection of subtle abnormalities from a variety of radiographs (including 62 skeletal radiographs) when viewed as soft compared to hard copy [ENG2000]. If true, this last result would have significant implications for image presentation in suspected NAI (given that most radiology departments plan to become “filmless” if they are not already).

Fractures of NAI are often more subtle than those following accidental trauma. What are the effects of 1) soft compared to hard copy display and 2) varying degrees of edge-enhancement on diagnostic accuracy in suspected NAI?

12.3 Materials and Methods

Routine patient referral and management at authors' institute

A Coroner refers children who have died under suspicious circumstances to the authors' institution for post mortem histopathological investigation. The aim is to elucidate a cause of death. All such children have a skeletal survey as their initial investigation (*Table 12.6-1*, page 225). In all cases, prior to the post mortem histopathological examination, a single radiologist – a professor of paediatric radiology – issues a formal report. Histopathology is performed according to national guidelines [RCP2002] by a professor of paediatric forensic pathology. Specimen radiography (additional radiographs of resected ribs or long bones) is performed when the radiologist is uncertain about the nature of an observation, and when on gross inspection the histopathologist is suspicious of injuries not initially identified by the radiologist. Histology is performed on all sites of definite or suspected injury. At the authors' institute, the post mortem is performed within hours of the skeletal survey.

This is the cohort of patients from which radiographs for this study were selected.

Image acquisition

All images were obtained from one of two rooms - Room 1 (Siemens Optilix; nominal focal spot size fine/broad = 0.6/1mm, inherent tube filtration 1.5mm Al, additional filtration 0.1mm Cu) and Room 2 (Wolverson Comet; nominal focal spot size fine/broad = 0.6/1mm, inherent tube filtration 1mmAl, additional filtration 1.5mmAl). Radiographs were performed between June 2001 and May 2003. During this time no changes were made to departmental imaging parameters (*Table 12.6-1*, page 225). All radiographs were obtained using a Fuji 5000R CR system onto a single sided standard resolution imaging plate (5lp/mm), and were processed in auto read mode. The installed CR system has a matrix of 2K².

Observer details

Six radiologists independently interpreted the images during four separate reporting sessions (a total of 24 sessions). Observers consisted of three consultants, one clinical research fellow and two paediatric radiology fellows (year

five training in radiology). One fellow had already secured a consultant post. The other two fellows were both eligible for consultant posts. All observers were familiar (at least six months) with the picture archiving and communications (PACS) station used within the Department. Observers were blinded to the degree of edge-enhancement used for individual radiographs and to histopathological findings. They were however aware of the clinical indication of suspected NAI.

Image preparation and interpretation

50 radiographs (covering all anatomical sites) from 13 infants and children were selected and prepared by a paediatric radiology fellow (LM) in her 6th year of training. This fellow did not participate as an observer in the study.

Laser-printed hard copies were made of all radiographs at three levels of edge-enhancement – 0, 0.5 and 1.2. The radiographs were then assigned to one of three packets so that each packet had a total of 50 radiographs of varying edge-enhancement. No packet contained more than one identical radiograph of any given patient. Patient details and date of image acquisition were eliminated from all radiographs. Order of packet interpretation varied for individual observers. A magnifying lens (magnification factor x 2) was made available to each observer. This is a normal adjunct to hard copy viewing of NAI cases.

Following the completion of hard copy interpretation, all radiographs were viewed as soft copy images from a 1K² monitor with the standard departmental edge-enhancement factor of 0.5. Observers were permitted to use all post-processing tools available including magnification and grey-scale-enhancement. The monitor from which viewing occurred, allowed the achievement of maximum image resolution when the magnifying tool was used.

At each session observers were given standardised response sheets and required to assess overall image quality, visualisation of soft tissues and visualisation of bony trabecular markings. Scores were marked on a continuous centimetre scale ranging from 1 (poor) to 5 (excellent). For soft copy images, overall quality was assessed prior to use of any available tools. However visualisation of soft tissues and trabecular markings were scored after image manipulation.

Finally observers were asked to indicate the presence and location of any abnormality (e.g. soft tissue swelling, periosteal reaction, fracture etc), and to score their level of confidence for that abnormality on a continuous scale ranging from 1

(low) to 5 (high). If no abnormality was detected, then that section of the form was left blank (confidence level = 0).

Instruction sheets were available at each reporting session.

Prior to the study, all observers had one practise session, results of which were not analysed.

The duration of each reporting session (three hard and one soft copy per observer) was recorded.

Statistics

Power calculation

It has been shown that for adequate statistical power to be achieved, similar numbers of cases are required with ROC analysis as with other, more traditional measurements of diagnostic accuracy [METZ1986].

A literature search did not reveal values for diagnostic accuracy for the detection of individual fractures in NAI.

Fractures in NAI can be extremely subtle, and a radiologist who is not an expert in the field (as the majority of observers in this study) might have a relatively low sensitivity. Similarly, there are several normal variants that may mimic injuries seen in NAI. A general radiologist might therefore be expected to also have a relatively low specificity. With the above in mind, it was assumed that observers might correctly identify any individual bone as being normal or abnormal 60% of the time. From the questionnaires that were prepared by LM, a total of 628 bones were identified which could reasonably be commented upon by the observers. For any given observer, assuming a diagnostic accuracy of 0.6, a two-tailed alpha of 0.05, and a power of 80%, the study would detect as significant, an increase in diagnostic accuracy of 0.08 or more for one display modality over another (Stata/SE8.2 software). If, in reality an observer had a diagnostic accuracy higher than 0.6, then the power of the study to detect a change of 0.08 would increase above 80% for that observer. Conversely, if diagnostic accuracy was lower than 0.6, the power of the study would be less than 80%, or a change of more than 0.08 would be required in order to be detected.

Statistical analysis

Using Stata/SE8.2 software, a paired t test was performed to assess the significance of display method on average reporting times of pooled observers.

To compare observer preferences for display techniques, the average scores for overall image quality, visualisation of soft tissues and visualisation of trabecular markings as assigned by individual and pooled observers was calculated. Paired t tests were then performed again using the Stata/SE8.2 software. Prior to the t tests, ANOVA (Stata/SE8.2) showed no effect from intraobserver and intersubject correlations, thus justifying the use of the paired t tests.

In order to compare diagnostic accuracy between observers and display method, location ROC analysis was performed. ROC analysis and calculation of the significance of differences in the area under the ROC curves (A_z) was performed with the University of Chicago ROCFIT statistical package. Histopathological findings were taken as the gold standard, with each bone (e.g. each rib on a chest radiograph) being scored separately. Data obtained from the ROC analysis was used to determine true positive rates (sensitivity) at specificity values of 85%, 90% and 95% for individual and pooled observers.

The nominal level of significance was set at 5%.

12.4 Results

General

Patient age and the number and site of fractures is summarised in *Table 12.6-2* (pages 226 and 227).

Table 12.6-3 (page 228) shows which fractures (confirmed by histology), individual observers detected for each display modality. *Figure 12.6-1* (page 231) illustrates metaphyseal spurs of the distal femur) mistaken for a fracture by observers, but shown at histology to be normal.

Reading sessions were conducted over four months. Intervals between each session ranged from 14 to 58 days with a mean of 24.8 days.

The interval between Observer 1's initial reports and participation in the study ranged from three months (for four of the fifty radiographs) up to twenty-three months, with a mean of eleven months.

All children presented with unexplained or sudden death. The diagnosis of NAI was made on the basis of the presence of skeletal and/or extra skeletal injury that could not be explained by the available history. Amongst the 13 children, the diagnosis was NAI (8), possible NAI (1) or sudden infant death syndrome (4) and none had any other on-going disease process. Case presentation was such that there were no metaphyseal fractures (as confirmed by histopathological examination). However there were cases of distal femoral and proximal tibial metaphyseal spurs (*Table 12.6-2*, pages 226 and 227, patients 2 and 11, and *Figure 12.6-1*, page 231).

For all 50 radiographs, a total of 731 individual observations were made. This gave 4,386 observations (six observers in the study) for each of the four display modalities, and a grand total of 17,544 observations.

Reading times

Table 12.6-4 (page 229) summarises the session times for each observer. Although there was some variation between observers, soft copy reporting sessions were on average one minute shorter than hard copy sessions (i.e. one second shorter per image). This difference was not significant ($p = 0.76$).

Image quality

The individual and average quality scores for the four display methods are summarised in *Table 12.6-5* (page 229). There was no significant difference between overall image quality of soft and hard copy radiographs ($p = 0.096$). However (following image manipulation with the post-processing tools of the work station,) the soft copy images scored significantly higher than all three hard copy groups. This was true for both visualisation of trabecular markings and visualisation of soft tissues (*Table 12.6-5*).

Diagnostic accuracy

There was significant interobserver variability in diagnostic accuracy as measured by the area under the ROC curve (A_z).

Table 12.6-6 (page 230) and *Figures 12.6-2 to 12.6-4* (page 232) summarise the A_z . Data from Observer 4 was degenerate (empty cells in the data matrix [DORF1995]), so it was not possible to plot an individual curve for this observer. For the remaining five observers, no single display method scored consistently highest or lowest. Soft-copy scored second highest for all observers except Observer 5, for whom it scored third.

Table 12.6-7 (page 230) compares predicted sensitivity (mean, 95% CI) at specificity values of 85%, 90% and 95% for soft and hard copy (edge-enhancement 0.5) display modalities.

Figures 12.6-5 to 12.6-8 (pages 233 and 234) illustrate two of the 13 chest radiographs that were included in the study. The figures show how varying degrees of edge-enhancement may lead to either false positive or true positive observations.

12.5 Discussion

This study was designed to determine the effects of soft and hard copy image display and of varying degrees of edge-enhancement on observer performance in cases of suspected NAI. It has been shown that there is no significant difference in diagnostic accuracy of 1K² and 2K² monitors [OCON1998B]. Therefore in this study, for soft copy interpretation, a 1K² monitor was used, as this is the standard resolution of monitors within the authors' department.

Measured parameters included session times, image quality and diagnostic accuracy.

No significant difference was shown between duration of soft and hard copy reporting sessions. Franken et al [FRAN1992] reported increases in reporting times with the introduction of soft copy reporting. All observers in this study were familiar with the PACS station, which might therefore have saved time. This is supported by the work of Bryan et al [BRYA1998] and other authors [KHED1991, RAZA1992] who have had results consistent with those reported here.

Regarding image quality, soft copy images scored slightly (but not significantly) worse than hard copy images for overall quality. However, following image manipulation, soft copy radiographs scored significantly better for visualisation of soft tissues and trabecular markings. This concurs with a previous study [REIN1996]. This finding has implications in the context of NAI, in which the presence and extent of soft tissue swelling is used as an adjunct in determining the age of a fracture. When reporting from a digital workstation, the radiologist would do well to take advantage of the available post-processing tools.

There were two main variables that might affect diagnostic accuracy; namely observer experience and image display modality.

Eng et al [ENG2000] demonstrated marked interobserver differences related to the training level and specialty of the observers. In this study, observers were either consultants or eligible to apply for consultant posts. Except for two observers (1 and 2), diagnostic accuracy was relatively low. Observer 1 was the most experienced radiologist, and furthermore is an expert in the field of NAI. This observer was the professor of radiology responsible for the initial reports issued for the purposes of post mortem histopathological examination. Observer 1 did significantly better than less experienced junior colleagues. Observer 1 played no

role in the selection and preparation of radiographs included in the study. The average interval between this observer's initial reports and participation in the study was eleven months. Furthermore, during the study, radiographs were reviewed in random order and as independent anonymous anatomical sites (rather than completed skeletal surveys of individual patients). Therefore it is more likely that the improved results of this observer are related to years of experience rather than to the introduction of bias as a result of image recall.

It has been shown [ROCK1995] that in ROC studies, the more subtle the cases, the greater the interobserver variation. Many of the fractures included in this study were subtle, such as the scapula fracture illustrated in *Figures 12.6-7 and 12.6-8* (page 234). The subtlety of cases, although reflecting normal practise, may have contributed to the significant differences in the area under the ROC curves.

Generally, diagnostic accuracy of the (relatively senior) observers participating in this study was low. However, regardless of observer experience, there was no significant difference in diagnostic accuracy between hard copy radiographs of varying edge-enhancement or between hard and soft copy radiographs with edge-enhancement 0.5. Kaji et al [KAJI1995] were also unable to demonstrate any benefit of edge-enhancement for the detection of skeletal injury. Training of observers rather than image display should be emphasised.

The diagnosis of NAI ultimately depends not only on identification of fractures, but also on dating the fractures, elucidating a mechanism of injury and interpreting the findings in light of the clinical history. In any study comparing diagnostic accuracy of image display techniques, these may act as confounding factors. This study concentrated purely on the detection of injury, and not on reaching a final diagnosis of NAI. In this way, the study differs from that of Youmens et al [YOUM1998] in which observers were asked to make a diagnosis of NAI based on findings from entire skeletal surveys of 20 patients with confirmed NAI, and 20 control patients. This may explain their relatively high diagnostic accuracy (mean sensitivity values for three observers were 80% and 63% for film-screen and digitised radiographs respectively) compared to that reported here (mean sensitivity of 46% at a specificity of 90% for all display modalities and six observers).

In NAI, more than one fracture may be present on the same radiograph (e.g. multiple rib fractures plus a proximal humeral metaphyseal fracture on a chest radiograph). Furthermore it is the multiplicity of fractures (of different age) that

helps the radiologist to reach the diagnosis of inflicted injury. For this reason it was felt appropriate to perform location ROC analysis (LROC) which requires not only that an abnormality be identified, but also that the site of that abnormality be stated. In addition LROC allows for the presence of more than one abnormality on the same radiograph [CHAK1989, CHAK1990].

Any study of the diagnostic accuracy of a test requires an external gold standard, which will provide the “diagnostic truth” by which such a test can be compared. In NAI there is no perfect gold standard. For instance there will always be a problem with those fractures that are missed by both radiologists and histopathologists (false negatives). In this study, the results of histopathological examination (in conjunction with the initial radiological reports of an expert witness in NAI) were used as the gold standard. Where histopathology differed from radiology, the histopathological finding was taken as the measure of truth.

The study concentrated on the effects of image display and post-processing of digital radiographs on diagnostic accuracy in suspected NAI. Post mortem cases were used in order to have a non-radiological gold standard. Whether there is a difference in diagnostic accuracy from radiographs obtained on living or dead infants is debatable. However once the radiographs have been obtained, there is no reason why the effects of image display and post-processing on quality and diagnostic accuracy should differ. For this reason, it should be possible to extrapolate the findings (from the study group of post mortem cases,) to surviving cases of NAI. The exception may be in the chest. This is because the effect of unaerated (dead infants) compared to aerated (live infants) lungs on image quality and detection of rib fractures is not known, although fracture detection rate is likely to be lower in the latter group.

To conclude, the interpretation of CR images in cases of suspected NAI is difficult, with diagnostic accuracy being significantly related to observer experience. Radiologists do particularly badly in detecting acute rib fractures. Although the generally low diagnostic accuracy in this clinical setting is not significantly affected by display modality, because of superior image quality, soft copy would appear to be the most suitable method of image display. Dedicated training, close supervision and collaboration of radiologists involved in these cases is advised.

12.6 Tables and Figures

Table 12.6-1: Imaging parameters for skeletal surveys in those under five years

Projection /Age:	KV		mAs		FFD		Grid	
	< 1	1 – 5	< 1	1 - 5	< 1	1 - 5	< 1	1 - 5
AP skull	58 – 65	60 – 65	2.5 – 4.0	6.4 – 8.0	100	100	No	Yes
Lateral skull	58 – 65	60 – 65	2.5 – 3.2	5.0 – 7.0	100	100	No	Yes
AP Chest	60 – 65	65 – 70	2.0 – 2.5	2.0 – 3.2	180	180	No	No
Abdomen / Pelvis	58 – 63	60 – 65	1.3 – 2.5	1.6 – 4.0	100	100	No	No
Lateral whole spine	60 – 65	65 – 70	2.0 – 4.0	3.0 – 6.0	100	100	No	No
Upper limbs	50 – 55	50 – 55	1.5 – 2.5	1.5 – 3.0	100	100	No	No
Hands	50 – 55	50 – 55	1.5 – 2.0	1.5 – 2.0	76	76	No	No
Lower limbs	50 – 55	55 – 58	1.5 – 2.5	1.8 – 3.2	100	100	No	No
Feet	50 – 55	50 – 55	1.5 – 2.0	1.8 – 2.5	100	100	No	No

FFD = film focus distance

Table 12.6-2: Number and site of fractures (Patients 1 – 7)

Patient (Age, Months) [Weight, Kg]	Date of Skeletal Survey	Projection	Findings		
			Skeletal Survey	Specimen Radiography	Histopathology Gross and / or Microscopy
1 (1) [2.4]	07/06/01	AP skull	N	X	N
		Lat skull	N	X	N
		Chest (ribs)	N	# 4 adjacent ribs	# L 3 – 6 ant acute
2 (1) [2.9]	07/11/02	Lower limbs	# R distal femoral metaphysis	# R distal femoral metaphysis	N
		Chest	N	X	N
3 (1) [4.2]	19/11/02	AP skull	L parietal #	X	L parietal #
		Lat skull	Parietal #	X	L parietal #
		Lat spine	N	X	N
		Chest (ribs)	N	# L 2 - 8	# L 2 – 7 post healing
		Upper limbs	N	X	N
4 (2) [4.2]	27/11/02	Hands	N	X	N
		Lower limbs	N	X	N
		Feet	N	X	N
		Chest (ribs)	# L 6 – 8 post	# L 6 – 8 post	# L 6 – 8 post 3 weeks
		AP skull	N	X	N
5 (2) [4.5]	03/01/02	Lat skull	N	X	N
		Chest (ribs)	# R 4 – 7 MAL, 9 – 11 post # L 6 MAL, 10 – 12 post	# R 3 – 7 MAL, # R 10 costochondral # R 10 – 12 post # L 4 – 6, 8 ant, 6 – 8 post	# R 3 – 7 MAL acute # R 10, 11 MAL 2 weeks # R 10 costochondral # L 6 – 8 post 2 weeks
		Lower limbs	N	X	N
		AP skull	L parietal # R parietal #	X	Complex biparietal #
		Lat skull	Complex parietal #	X	Complex biparietal #
6 (3) [5.5]	11/06/02	Lat spine	N	X	N
		Chest	N	X	N
		L arm	N	X	N
		Hands	N	X	N
		Lower limbs	N	X	N
		Feet	N	X	N
		AP skull	N	X	N
7 (3) [5.6]	23/10/01	Chest (ribs)	# L 4 – 6 MAL	X	# L 4 – 6 healing

= fracture

Ant = anterior; AP = anteroposterior Post = posterior; Lat = lateral; MAL = mid axillary line

L = left; R = right

N = normal

X = not performed

Table 12.6-2contd.: Number and site of fractures (Patients 8 - 13)

Patient (Age, Months) [Weight, Kg]	Date of Skeletal Survey	Projection	Findings		
			Skeletal Survey	Specimen Radiography	Histopathology Gross and / or microscopy
8 (4) [5.1]	06/06/02	Lat skull	L parietal #	X	N
		Chest	N	X	N
		Abdomen / pelvis	N	X	N
9 (4) [6.8]	22/11/02	AP skull	N	X	N
		Lat skull	N	X	N
		Chest	N	X	N
		Lower limbs	N	X	N
		AP skull	N	X	N
10 (8) [6.6]	07/02/03	Lat skull	N	X	N
		Chest	N	X	N
		Abdomen / pelvis	N	X	N
		AP skull	N	X	N
11 (9) [5.1]	18/07/02	Lat skull	N	X	N
		Chest	N	X	N
		Lat spine	N	X	N
		Chest	N	X	N
12 (9) [10.8]	31/07/01	R arm	Soft tissue swelling	X	N
		Lower limbs	Bilateral # proximal tibial metaphyses	Bilateral # proximal tibial metaphyses	N
		Feet	N	X	N
		Chest	# Lateral border L scapula	# Lateral border L scapula	# Lateral border L scapula
		Upper limbs	# Lateral border L scapula Periosteal reaction L forearm	# Lateral border L scapula Periosteal reaction L forearm	# Lateral border L scapula No abnormality of forearm
13 (5 years) [*]	11/09/02	Abdomen / pelvis	N	X	N

= fracture

Ant = anterior; AP = anteroposterior; Post = posterior; Lat = lateral; MAL = mid axillary line

L = left; R = right

N = normal

X = not performed

* Patient 13's weight is not known

Table 12.6-3: Fracture Detection by Individual Observers

Patient	Fracture (confirmed by histology)	Observers who detected fracture			
		0	0.5	1.2	PACS
1	Anterior L rib 3*	-	-	-	-
	Anterior L rib 4*	-	-	-	-
	Anterior L rib 5*	-	-	-	-
	Anterior L rib 6*	-	-	-	-
2	L parietal (AP)	All	All	All	All
	L parietal (lateral)	All	All	1, 2, 4, 5, 6	All
3	Posterior L rib 2*	-	-	-	-
	Posterior L rib 3*	-	-	-	-
	Posterior L rib 4*	-	-	-	-
	Posterior L rib 5*	-	-	-	-
	Posterior L rib 6*	-	-	-	-
	Posterior L rib 7*	-	-	-	-
4	Posterior L rib 6	1 – 4, 6	1, 2, 4	All	All
	Posterior L rib 7	1 – 4, 6	1, 2, 4 – 6	All	All
	Posterior L rib 8	1 – 4, 6	1, 2, 4 – 6	All	All
5	Axillary R rib 3*	-	-	-	-
	Axillary R rib 4*	-	-	-	-
	Axillary R rib 5*	-	-	-	-
	Axillary R rib 6*	-	1	1	1, 2
	Axillary R rib 7*	1	1	1	1, 2
	Axillary R rib 10*	-	-	-	-
	Axillary R rib 11*	-	-	-	-
	Anterior R rib 10*	-	-	-	-
	Posterior L 6*	-	-	-	-
	Posterior L 7*	-	-	-	-
	Posterior L 8*	-	-	-	-
	Biparietal (AP)	All	All	1 – 5	All
	Biparietal (lateral)	All	All	All	All
7	Axillary L rib 4	All	1, 3 – 6	1 – 4, 6	1, 3 – 6
	Axillary L rib 5	All	1, 3 – 6	1 – 4, 6	1, 3 – 6
	Axillary L rib 6	All	1, 3 – 6	1 – 4, 6	1, 3 – 6
12	L scapular (arm)	1, 4	1	1	1, 4
	L scapular (chest)	1	1	1, 4	1

* = Rib fractures 2 weeks old or less.

- = None. Radiologists were not able to reliably detect acute rib fractures. Results support the need for follow-up chest radiographs in 10 to 14 days.

Table 12.6-4: Average duration of session times

Observer	Time (minutes)	
	Hard Copy (Average of Three Sessions)	Monitor
1	61	45
2	39	50
3	90	80
4	45	43
5	83	90
6	48	50
Mean (95% CI)	61 (39 – 83)	60 (39 – 81)

Table 12.6- 5: Image Quality scores (average for all observers)

Display	Score					
Modality	Overall Image Quality ^a		Visualisation of Trabecular Markings ^b		Visualisation of Soft Tissues ^b	
	Mean	SD	Mean	SD	Mean	SD
0	3.68	0.77	3.60	0.79	3.82	0.88
0.5	3.72	0.72	3.70	0.76	3.82	0.86
1.2	3.63	0.79	3.70	0.75	3.69	0.95
Monitor	3.57	0.86	4.10	0.80	4.34	0.77
p value ^c	= 0.096		< 0.0001		< 0.0001	

a. Scored before image manipulation (for soft-copy radiographs)

b. Scored after image manipulation (for soft-copy radiographs)

c. Comparing soft- and hard-copy radiographs (edge enhancement = 0.5)

Table 12.6-6: Area under the ROC curve (A_z) for each observer and each display modality

Observer	Edge-Enhancement			
	0	0.5	1.2	Monitor
1	.895	.960	.772	.957
2	.871	.846	.954	.952
3	.710	.498	.526	.538
4 ^a	-	-	-	-
5	.533	.709	.898	.600
6	.668	.345	.525	.623

a. Degenerate data [DORF1995]

Table 12.6-7: Predicted sensitivity rates at 85%, 90% and 95% specificity

Observer	Specificity					
	85%		90%		95%	
	Monitor	Film (0.5)	Monitor	Film (0.5)	Monitor	Film (0.5)
1	0.86	0.97	0.80	0.93	0.67	0.81
2	0.82	0.57	0.76	0.47	0.66	0.33
3	0.49	0.33	0.45	0.30	0.40	0.26
4 ^a	-	-	-	-	-	-
5	0.40	0.75	0.37	0.67	0.33	0.52
6	0.44	0.26	0.38	0.24	0.30	0.22
Pooled ^b	0.53	0.50	0.48	0.44	0.40	0.36
	(0.43 – 0.64) ^c	(0.39 – 0.60)	(0.39 – 0.59)	(0.35 – 0.54)	(0.32 – 0.47)	(0.29 – 0.43)

a. Degenerate data [DORF1995]

b. Including Observer 4

c. 95% confidence interval

Figure 12.6-1: Metaphyseal spurs on AP radiograph of the knee



This radiograph demonstrates metaphyseal spurs of the distal femur (short arrows) and proximal tibia (long arrow). On initial imaging these were diagnosed by the expert witness (Observer 1) as metaphyseal fractures. Histopathology excluded the presence of fractures. During the study, this normal variant (of the distal femur) was misdiagnosed as a metaphyseal fracture (corner appearance) in 9 out of 24 observations (at least once by four out of six observers, but not by Observer 1). The proximal tibial spur was not mistaken as a fracture by any of the observers.

Figure 12.6-2: ROC curves Observer 1 (most paediatric radiology experience), all display modalities

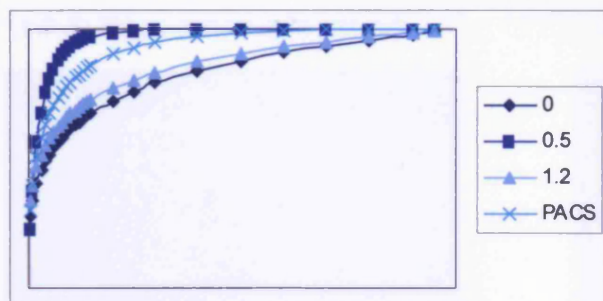


Figure 12.6-3: ROC curves Observer 3 (least paediatric radiology experience), all display modalities

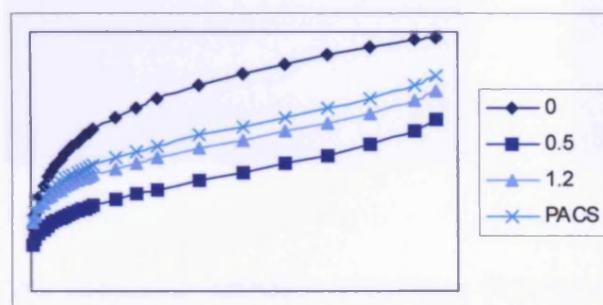
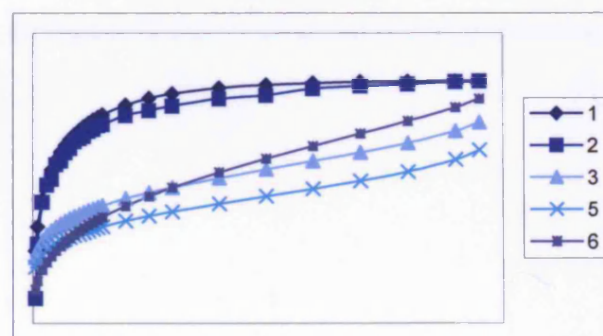


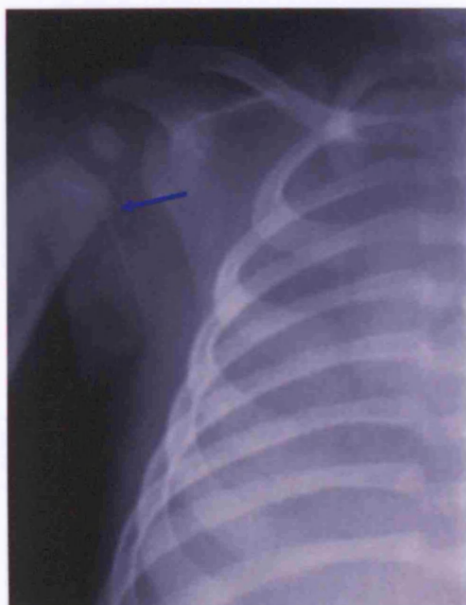
Figure 12.6-4: ROC curves Observers 1 – 3, 5, 6 (PACS only) ^a



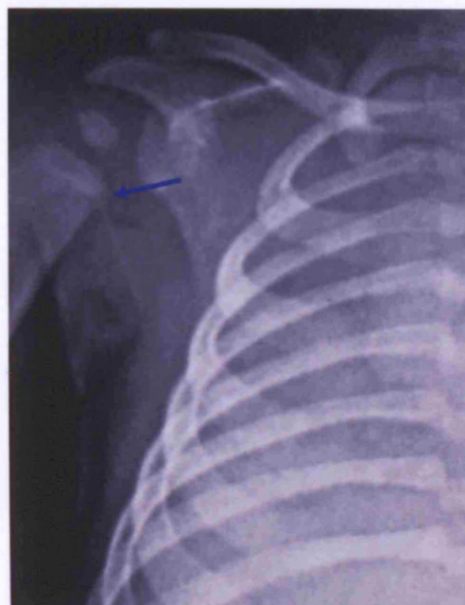
a. Data from Observer 4 was degenerate [DORF1995]

Figures 12.6-5 and 12.6-6: False positive effect of edge-enhancement

12.6-5: Edge-enhancement = 0



12.6-6: Edge-enhancement = 1.2

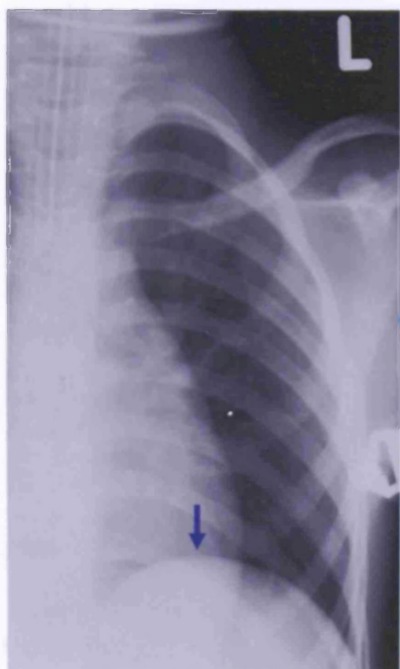


The increasing definition of margins (“hardening” of the radiograph) with increasing edge-enhancement is well illustrated. Note the increased prominence of the radiolucent line caused by metaphyseal beaking in the right proximal humerus (arrows).

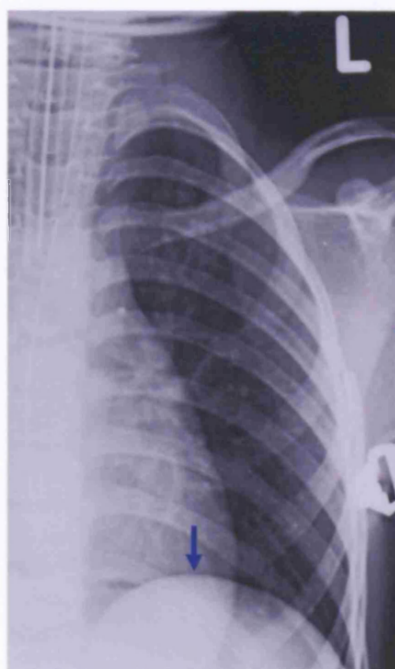
Several observers misdiagnosed a fracture from *Figure 12.6-5*, having called it normal on *Figure 12.6-6*. In other words, edge enhancement had a false positive effect.

Figures 12.6-7 and 12.6-8: True positive effect of edge-enhancement

12.6-7: Edge-Enhancement = 0



12.6-8: Edge-Enhancement = 1.2



Note the increasing crispness e.g. of the left diaphragm (navy arrows), the apparent increase in lung markings, and particularly the increased visualisation of the left scapular fracture (turquoise arrows) with increasing edge-enhancement. Only two observers identified this fracture. Edge-enhancement had a true positive effect; one of the two observers only identified the fracture once – interpreting from film, edge enhancement 1.2 (*Figure 12.6-8*).

Section D

Results Roundup

Chapter 14

Summary and Conclusions

14.1 Summary

This thesis is titled “Optimisation of the digital radiographic imaging of suspected non-accidental injury”. There is no gold standard for the confirmation of a diagnosis of non-accidental injury (NAI). The diagnosis is therefore one of exclusion and inference. If there is no gold standard, how then is it possible to confidently state that optimal imaging has been achieved? The answer is that emphasis was placed on the optimal representation of soft tissue and bony injuries, such that any suitably trained individual would be expected to detect them. The interpretation of the mechanisms and aetiology of these injuries was not addressed.

Physical abuse (NAI) most commonly occurs in children under two years of age who cannot verbalise their pain. Furthermore, the injuries may not be associated with any visible external bruising. The onus is therefore on radiology departments to provide images of sufficient quality to allow unequivocal depiction of all of the child’s injuries.

Factors affecting image quality are related

- To the imaging system: Is the degree of contrast and spatial resolution adequate for the task at hand?
- To radiographic parameters: Have adequate images been obtained in terms of projection and number? Have the optimum exposure parameters been employed? Has the child been properly positioned? Is the degree of collimation satisfactory? Are there artefacts obscuring areas of interest? Is the labelling of radiographs (name, date of birth, side marker etc) correct and complete?
- To image display: Should the images be printed or viewed on a monitor? What is the role of edge-enhancement in digital radiography? What is the level of ambient light? What is the strength and colour of light emanating from the viewing box? Are there shutters to exclude superfluous light? Is a magnifying glass available?
- To observer factors: What is the level of radiological competence of the individual? Has the observer specific experience of the condition being questioned? How good is their visual acuity? How familiar are they with the imaging and viewing system?

This list is not exhaustive; nevertheless it is apparent that there are many variables, any of which may affect image quality and/or fracture detection.

In this thesis, an attempt has been made to address the second and third issues, namely optimisation of factors related to radiographic parameters and image display.

Following a literature search, several null hypotheses were postulated. Subsequently, studies were designed to test the validity of the null hypotheses. The results that led to these hypotheses being either accepted or discarded are summarised below.

1. The CEC criteria are not appropriate for the objective assessment of the quality of skeletal surveys

In the first study (Chapter 7, page 137), two observers independently assessed 286 paediatric lateral spine radiographs according to the CEC criteria for this projection (Table 7.6-2, page 151). Before image analysis, there were several detailed discussions regarding the interpretation of these criteria. Prior to the study proper, the observers also scored several radiographs together, in order to identify possible sources of confusion. Despite this, interobserver reliability was moderate or better in only six out of 14 comparisons. This suggests that there is considerable room for interpretation of the CEC criteria (certainly for the lateral spine radiograph).

The study also revealed other limitations of the CEC criteria, namely that they do not allow for mitigating factors such as the presence of artefact, over-collimation, patient motion and pathology (for example) for failure of fulfilling a given criterion. Finally there was no mention of the number of vertebrae that had to meet the requirements in order to consider a given criterion fulfilled.

The CEC criteria were developed for the optimisation of radiographic parameters. They therefore do not address important issues related to skeletal surveys in NAI. Such issues include the number and projection of radiographs obtained; the presence of all relevant child details; the need for the signature of at least one radiographer performing the survey to be clearly visible on the radiograph etc.

It was concluded firstly that the CEC criteria would require modification if they were to be used as a tool for determining clinical image quality. The second conclusion was that a more simplified tool was required if interobserver variability was to be improved. The third and final conclusion was that there was a need to develop an objective means of quality assessment of skeletal surveys performed for non-accidental injury.

The first null hypothesis was accepted.

2. *Image quality of computed radiography systems is neither inferior nor superior to that of traditional film-screen systems.*

This second hypothesis was also tested in the study outlined in Chapter 7 (page 137). Individual results for the two observers demonstrated that both visually sharp reproduction of cortex and trabecular markings (spatial resolution) and reproduction of adjacent soft tissues (contrast resolution) were significantly related to imaging modality. Traditional film-screen radiographs scored better for spatial resolution, while digital images scored better for contrast resolution. Although only 50% of film-screen radiographs and 56% of digital radiographs fulfilled at least six of the seven CEC criteria, 99% of all radiographs were diagnostic. This highlights the fact that while image quality scores may be helpful both for optimisation of radiographic parameters and for audit purposes, they do not necessarily impact on the clinical diagnosis and management of the patient.

The radiographs in this study were performed for the diagnosis of skeletal dysplasias and rheumatological conditions. For this purpose differences in image quality were probably of no clinical significance. However, the fact that spatial resolution was reduced with the digital system was a source of concern in the context of fracture detection in suspected NAI. The need to optimise the quality of digital radiographs (in order to take advantage of its increased contrast resolution, and compensate for its reduced spatial resolution when compared to film-screen radiography) was underlined. The second null hypothesis was rejected.

3. *There is no significant variability in the quality of images obtained in the United Kingdom (UK) and therefore*
4. *There is no need to standardise the radiographic imaging of this condition in the UK*

The CEC criteria were shown to be unsuitable for determining clinical image quality, particularly in the case of NAI. Therefore a scoring system was developed to test the above null hypotheses. Using this scoring system, the results of a prospective review of skeletal surveys performed in the United Kingdom were more than a little alarming. 10% of the surveys performed were “babygrams”; one or two radiographs of the whole child. These are inadequate for the diagnosis of NAI and should not be performed.

Furthermore, of the 50 patients reviewed, there were 37 different skeletal surveys. Image quality was variable, and worst for anteroposterior and lateral skull radiographs, which tended to be overexposed. Only 22% of radiographs included the initials or signature of the attendant radiographer(s). Of the 35% of radiographs in which there was significant artefact, the presence of the hand(s) of the assistant holding the child in position was identified in approximately one third (32%). No radiograph scored the maximum of 15 points.

The study demonstrated significant variability in the quality of skeletal surveys performed in the UK for suspected NAI, and highlighted the need for the prompt development of a national protocol.

Null hypotheses 3 and 4 were rejected.

5. *There is no direct relationship between radiation exposure and image quality (as determined by the detection rate of abnormality e.g. fractures). Therefore increasing exposure will have no effect on image quality or on diagnostic accuracy*

The ideal test of this null hypothesis required that radiographs demonstrate pathology (e.g. a fracture). In the event, a suitable number of pathological radiographs were not obtained within the time scale of the ethical approval obtained for the PhD. Therefore image quality, rather than diagnostic accuracy was assessed. The assumption was that if observers could not detect improvements in image quality above a given exposure level, then correspondingly, there would be no improvement in diagnostic accuracy above this level.

A survey of radiographs obtained in the UK had shown that skull radiographs were generally of the poorest quality, tending to be overexposed. Anteroposterior and lateral skull radiographs were therefore chosen to test this fifth hypothesis.

Results showed that current radiographic parameters at GOSH give an average entrance surface dose to infants of 253 μ Gy and 246 μ Gy for anteroposterior and lateral radiographs respectively. However there was no perceived improvement in subjective image quality above a dose of 200 μ Gy (80% of current doses). The potential therefore exists to reduce current departmental radiation exposures.

Although subjective image quality and not diagnostic accuracy was assessed, the study results allowed the above null hypothesis to be rejected. Had it stated, "Above a

certain level, there is no direct relationship...” then given the study results, the null hypothesis would have been accepted.

6. *Edge-enhancement is a post-processing capability of digital imaging systems that has no effect on diagnostic accuracy or image quality*
7. *There is no difference in diagnostic accuracy whether interpreting radiographs from a monitor (soft copy) or from printed film (hard copy)*
8. *There is no difference in image quality of soft and hard copy image display modalities*

To test these last three null hypotheses, a ROC study was performed. The results of this study showed that there was no difference in either diagnostic accuracy or image quality for various degrees of edge-enhancement. Null hypothesis 6 was accepted. Alarming low sensitivities (as low as 24% at a false positive rate of 10%) were demonstrated by the study. Diagnostic accuracy was not however affected by soft or hard copy image display. Null hypothesis 7 was therefore also accepted. The lack of effect of image display modality on the low diagnostic accuracy of observers may reflect the subtle nature of the injuries seen in NAI.

Although there was no effect on diagnostic accuracy, soft copy radiographs scored significantly better than hard copy radiographs for image quality. Null hypothesis 8 was rejected. This effect on image quality was only apparent following manipulation of the image with the workstation tools. The observer would do well to make use of these post-processing tools.

14.2 Future Studies

1. *There is a discernable difference in image quality of film-screen and digital radiographs. Does this have an effect on diagnostic accuracy in cases of NAI?*

It is likely that the improved contrast resolution of digital systems compensates for the reduced spatial resolution. Many departments (including that at GOSH) have fully installed digital systems and are now entirely “filmless”. Even should the above study be performed, it is unlikely that the results would have significant impact in this “digital era”. The suggested study should have been performed prior to or during the purchasing process. Efforts should now be concentrated on optimisation of digital systems.

2. *A repeat survey of the variability of surveys in the UK*

Given the implications of a wrong diagnosis as well as the degree of public and media interest in the subject, the current variability in skeletal surveys is unacceptable. Following publication of the study in Chapter 7 (page 137) and oral presentation of the study in Chapter 12 (page 212), the BSPR standard is no longer “Draft”. Increased awareness by radiologists of the “definitive” standard is essential. Following this, a timely repeat of the national study would be advisable.

3. *How does dose reduction affect diagnostic accuracy in suspected NAI?*

While phantom studies are useful for optimisation of the physical parameters of an imaging system and for quality assurance, it is difficult to extrapolate results to the clinical setting. However Bosmans et al [BOSM2001] have proposed a method whereby an exposure of a phantom is made, and the raw data from this multiplied with the raw data from clinical radiographs. The image of the phantom is located over sites of interest (e.g. a fracture) allowing spatial and contrast resolution to be quantified. Not only does this allow an objective assessment, but it also disposes of the need to conduct complicated and time-consuming ROC studies.

There is clearly scope for dose reduction in digital imaging of the infant skull; however it is uncertain how this will affect diagnostic accuracy in cases of suspected NAI. It

would be interesting to conduct such a study using the method described by Bosmans et al above [BOSM2001]. This might allow the publication of optimum exposure parameters for all radiographs performed as part of skeletal surveys in NAI.

4. *Should oblique chest radiographs be routinely performed as part of the skeletal survey?*

The BSPR guidelines stipulate oblique radiographs of the chest (for the detection of rib fractures) as a routine. However this is based on the results of only one study [KLEI1996A]. From November 2003, oblique radiographs have been performed on children presenting to the radiology department at Great Ormond Street Hospital. An observer study has commenced to determine the effect these projections have on the detection of rib fractures in suspected NAI.

14.3 Conclusions

- There is a need to standardise the radiographic imaging of suspected NAI in the UK.
- A 20% reduction in current departmental exposure levels is possible with no discernable subjective difference in the quality of skull radiographs. Given the adverse effects of radiation, and considering that one infant will have a minimum of 17 radiographs as part of their routine skeletal survey, this is a significant finding. It is highly desirable to determine the effects of such dose reductions on diagnostic accuracy.
- Diagnostic accuracy for the detection of fractures in suspected NAI is rather low amongst relatively senior specialist registrars and junior consultants in paediatric radiology. More emphasis should be placed on training, supervision and collaboration of radiologists in this area.
- In the clinical setting of suspected NAI, it is beneficial to display digital images as soft copy. The observer would do well to take advantage of the post-processing tools that are available on the (digital) workstation.

While an attempt has been made to optimise the digital imaging of suspected NAI, there is still much that needs to be done, not least in terms of the recognition and diagnosis of NAI. It is to be hoped that recent events and their outcomes as reported by the media, will not have deterred academics and clinicians from pursuing careers (and research) in non-accidental injury.

May it continue to be as in the GOSH motto

“The child first, and always”.

Section E

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Section F

Appendices

Appendix I: Royal College of Radiologists' grant approval

THE ROYAL COLLEGE OF RADIOLOGISTS



Dr Amaka Offiah
Dept of Radiology
Great Ormond Street Hospital

26th October 2001

Dear Dr Offiah

RE: CLINICAL RADIOLOGY PUMP-PRIMING GRANTS 2001

I refer to your recent application for a grant entitled "Computed radiography in paediatric skeletal surveys for non-accidental injury (NAI): setting a standard". As you are aware, there is only a limited amount of funding available and the total value of applications received considerably exceeded the available budget. All the applications received were of a very high standard and carefully considered by an independent adjudication panel.

However, I am delighted to be able to inform you that your application was one of those approved for funding and a grant of £6,254.48 has been agreed. The names of the successful applicants will be shown on the College web site shortly.

I enclose a copy of the conditions of award. I would be grateful if you would confirm your own and your Trust's acceptance of the grant on the basis required by the conditions. We will then arrange for a cheque to be issued to the Department or Trust Fund you specify.

With kind regards,

Yours sincerely

Dean
Faculty of Clinical Radiology

Enc

Appendix II: The CEC criteria for the lateral segmental spine radiograph

SEGMENTAL SPINE

LATERAL PROJECTION

1. DIAGNOSTIC REQUIREMENTS

Image criteria

- 1.1. Reproduction as a single line of the upper and lower plate surfaces in the centre of the beam
- 1.2. Full superimposition of the posterior margins of the vertebral bodies
- 1.3. Reproduction of the pedicles and the intervertebral foramina
- 1.4. Visualisation of the posterior articular processes
- 1.5. Reproduction of the spinous processes consistent with age
- 1.6. Visually sharp reproduction of the cortex and trabecular structures consistent with age
- 1.7. Reproduction of the adjacent soft tissues

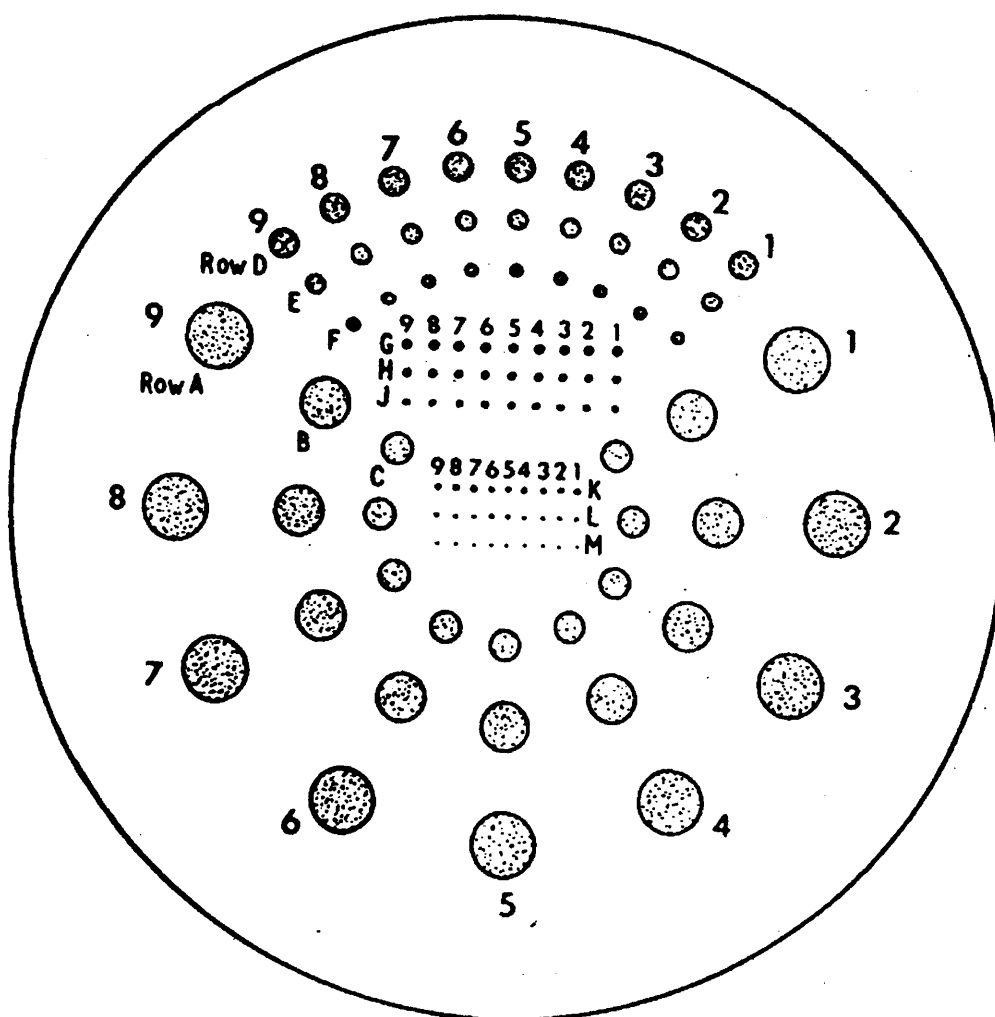
2. CRITERIA FOR RADIATION DOSE TO THE PATIENT

Entrance surface dose for standard five year old patient: no values as yet available

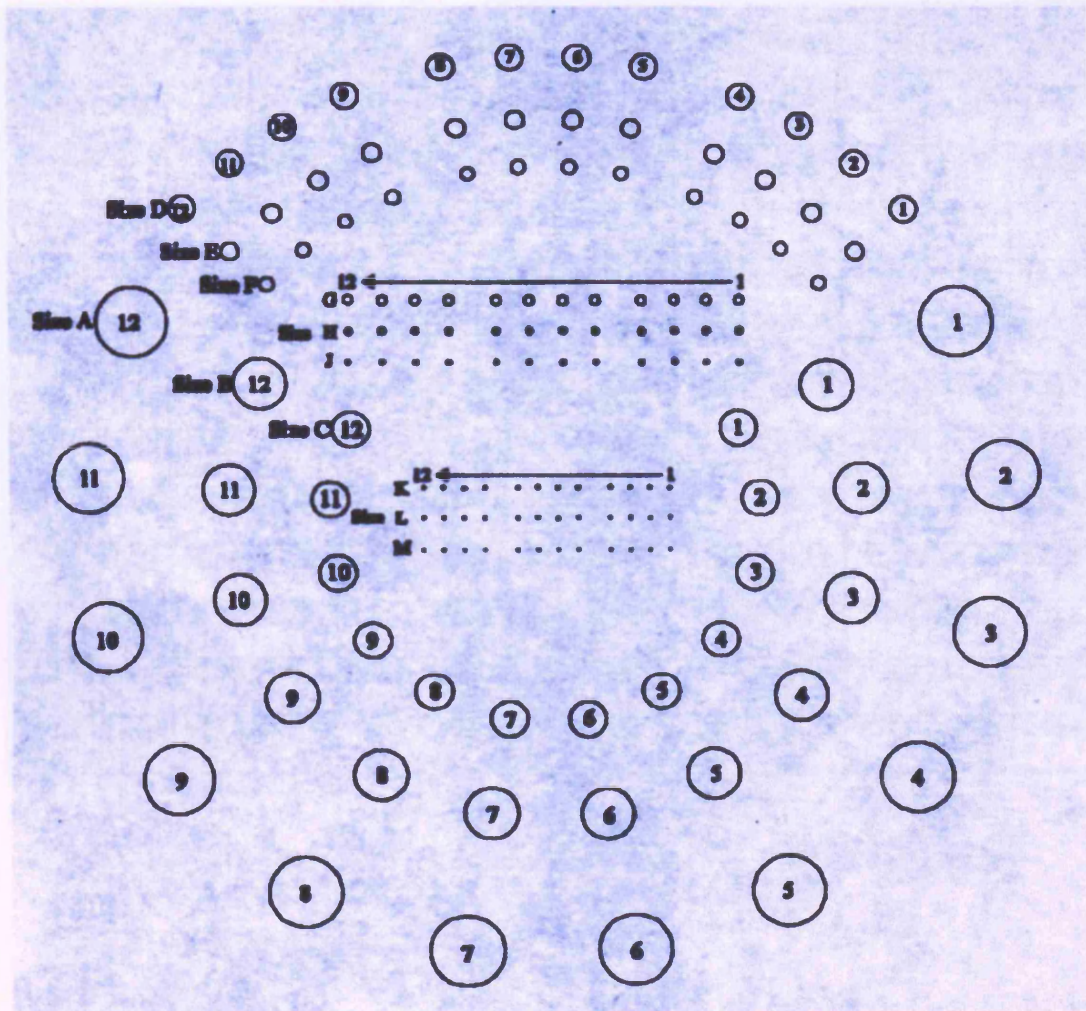
3. EXAMPLE OF GOOD RADIOGRAPHIC TECHNIQUE

- 3.0. Patient position : supine or upright
- 3.1. Radiographic device : table, grid table or vertical stand with stationary or moving grid, depending on age
- 3.2. Nominal focal spot value : 0.6 (≤ 1.3)
- 3.3. Additional filtration : up to 1 mm Al + 0.1 or 0.2 mm Cu (or equivalent)
- 3.4. Anti-scatter grid : $r = 8$; 40/cm no grid for infants <6 months of age
- 3.5. Screen film system : nominal speed class 400 - 800
- 3.6. FFD : 115 (100 - 150) cm
- 3.7. Radiographic voltage : 65 - 90 kV
- 3.8. Automatic exposure control : chamber selected - central
- 3.9. Exposure time : < 100 ms
- 3.10. Protective shielding : gonad capsules should be employed for male patients

Appendix III: The Leeds TO.10 TCDD test object



Appendix IV: The Leeds TO.16 TCDD test object



Appendix V: The Leeds TO.16 detection index values at 75KVp

Detail	A	B	C	D	E	F	G	H	J	K	L	M
A ½ mm	9.83	7.00	4.96	3.64	2.48	1.77	1.24	0.886	0.620	0.443	0.310	0.221
Count												
1	1.912	2.685	3.790	4.076	5.819	8.153	7.906	11.07	15.81	5.286	4.925	4.897
2	2.874	4.036	5.695	5.310	7.579	10.62	11.64	16.29	23.27	7.575	7.555	6.908
3	3.607	5.066	7.149	7.980	11.39	15.96	15.16	21.22	30.32	11.76	10.82	10.60
4	5.411	7.600	10.72	10.02	14.30	20.03	22.78	31.88	45.56	16.85	16.80	15.18
5	7.480	10.50	14.82	15.03	21.45	30.05	28.60	40.02	57.20	22.13	24.07	23.57
6	10.71	15.04	21.22	20.77	29.65	41.54	42.90	60.04	85.79	32.57	31.63	33.77
7	13.38	18.80	26.53	29.74	42.44	59.47	59.30	82.99	118.6	42.43	46.55	44.36
8	17.54	24.63	34.76	37.17	53.06	74.34	84.89	118.8	169.8	63.77	60.64	65.29
9	26.77	37.59	53.06	48.70	69.52	97.41	106.1	148.5	212.2	80.05	91.12	85.05
10	39.13	54.95	77.54	74.34	106.1	148.7	139.0	194.6	278.1	120.1	114.4	127.8
11	53.54	75.19	106.1	108.6	155.1	217.3	212.2	297.0	424.4	166.0	171.6	160.5
12	72.66	102.0	144.0	148.7	212.2	297.4	310.2	434.1	620.3	237.6	237.2	240.7

Appendix VI: The Leeds TO.16 x-ray contrast values at 75KVp

Detail	A	B	C	D	E	F	G	H	J	K	L	M
Size mm	11.1	7.9	5.6	4.0	2.8	2.0	1.4	1.0	0.7	0.5	0.35	0.25
Count	.0532	.0532	.0532	.0693	.0693	.0693	.1020	.1020	.1020	.427	.655	.924
1	.0532	.0532	.0532	.0693	.0693	.0693	.1020	.1020	.1020	.427	.655	.924
2	.0354	.0354	.0354	.0532	.0532	.0532	.0693	.0693	.0693	.298	.427	.655
3	.0282	.0282	.0282	.0354	.0354	.0354	.0532	.0532	.0532	.192	.298	.427
4	.0188	.0188	.0188	.0282	.0282	.0282	.0354	.0354	.0354	.134	.192	.298
5	.0136	.0136	.0136	.0188	.0188	.0188	.0282	.0282	.0282	.102	.134	.192
6	.0095	.0095	.0095	.0136	.0136	.0136	.0188	.0188	.0188	.0693	.102	.134
7	.0076	.0076	.0076	.0095	.0095	.0095	.0136	.0136	.0136	.0532	.0693	.102
8	.0058	.0058	.0058	.0076	.0076	.0076	.0095	.0095	.0095	.0354	.0532	.0693
9	.0038	.0038	.0038	.0058	.0058	.0058	.0076	.0076	.0076	.0282	.0354	.0532
10	.0026	.0026	.0026	.0038	.0038	.0038	.0058	.0058	.0058	.0188	.0282	.0354
11	.0019	.0019	.0019	.0026	.0026	.0026	.0038	.0038	.0038	.0136	.0188	.0282
12	.0014	.0014	.0014	.0019	.0019	.0019	.0026	.0026	.0026	.0095	.0136	.0188

Appendix VII: TO.16 data sheet – Results Observer 1 (Chapter 10, page 182)

Reference ↓	A	B	C	D	E	F	G	H	J	K	L	M
M1	3	2 ¹ / ₂	2	3	2	1 ¹ / ₂	1 ¹ / ₂	—	—	1	—	—
T2	5	4 ¹ / ₂	4 ¹ / ₂	5	4	2 ¹ / ₂	3 ¹ / ₂	3	2 ¹ / ₂	4	3	5
G1	5	4 ¹ / ₂	4 ¹ / ₂	4 ¹ / ₂	4 ¹ / ₂	4	4 ¹ / ₂	4	3	4	4	3
OB	6 ¹ / ₂	6	5	5 ¹ / ₂	5	4	5	4 ¹ / ₂	2 ¹ / ₂	5	4	4
J8	5	5 ¹ / ₂	5 ¹ / ₂	6	6	4 ¹ / ₂	5	4 ¹ / ₂	3 ¹ / ₂	6	5	3 ¹ / ₂
Y7	4	3 ¹ / ₂	3 ¹ / ₂	3 ¹ / ₂	3 ¹ / ₂	3	3	3	1	3	2	3
Z3	4 ¹ / ₂	5	4 ¹ / ₂	4	4	3 ¹ / ₂	3	3	2 ¹ / ₂	5	4	4
C6	4	4 ¹ / ₂	4	4	4	3	4	3	2 ¹ / ₂	4	4	3
R2	5 ¹ / ₂	5	4	5	4 ¹ / ₂	4	4	3	2 ¹ / ₂	4 ¹ / ₂	4	3 ¹ / ₂
I7	3	3 ¹ / ₂	3 ¹ / ₂	3	2	1 ¹ / ₂	2	2	—	2	—	1
P6	6	5 ¹ / ₂	4 ¹ / ₂	5 ¹ / ₂	4	4	4	4	3 ¹ / ₂	5	4	3 ¹ / ₂
W4	5	5	5	5 ¹ / ₂	5 ¹ / ₂	4 ¹ / ₂	4	3 ¹ / ₂	3 ¹ / ₂	4 ¹ / ₂	4	4
O5	6	5 ¹ / ₂	5	6	5 ¹ / ₂	4	4 ¹ / ₂	4	3	5 ¹ / ₂	4	4
L9	5	5	5	6	5	4	5 ¹ / ₂	4	2 ¹ / ₂	4	4	4
S1	6	5	5	4	4	3 ¹ / ₂	3	3	2	4	3	3
Q4	2 ¹ / ₂	2 ¹ / ₂	2 ¹ / ₂	3 ¹ / ₂	3	1 ¹ / ₂	1	—	—	1	1	—
A7	3 ¹ / ₂	3 ¹ / ₂	3 ¹ / ₂	4	3 ¹ / ₂	3	3	3	1	4	3	2 ¹ / ₂
NF	4	3	2	3	2	2	3	3	1	2	2	1
X3	6	5	4	5	4 ¹ / ₂	4	4	4	2	4	3	4

Appendix VIII: Local research ethics committee approval

Institute of Child Health
and Great Ormond Street Hospital for Children NHS Trust
UNIVERSITY COLLEGE LONDON



5 February 2002

Dr A Offiah
Clinical Research Fellow
Radiology/Physics
GOS

Dear Dr Offiah,

01RP08 Computed radiography (CR) in Paediatric skeletal surveys for non-accidental injury (NAI): setting a standard

Notification of ethical approval

The above research has been given ethical approval after review by the Great Ormond Street Hospital for Children NHS Trust / Institute of Child Health Research Ethics Committee subject to the following conditions.

1. Your research must commence within twelve months of the date of this letter and ethical approval is given for a period of 24 months from the commencement of the project. If you wish to start the research more than twelve months from the date of this letter or extend the duration of your approval you should seek Chairman's approval.
2. You must seek Chairman's approval for proposed amendments to the research for which this approval has been given. Ethical approval is specific to this project and must not be treated as applicable to research of a similar nature, eg. using the same procedure(s) or medicinal product(s). Each research project is reviewed separately and if there are significant changes to the research protocol, for example in response to a grant giving body's requirements you should seek confirmation of continued ethical approval.
3. Researchers are reminded that REC approval does not imply approval by the GOS Trust. Researchers should confirm with the R&D office that all necessary permissions have been obtained before proceeding.



4. It is your responsibility to notify the Committee immediately of any information which would raise questions about the safety and continued conduct of the research.
5. On completion of the research, you must submit a report of your findings to the Research Ethics Committee.

Yours sincerely

Administrator to the Research Ethics Committee

Cc:

**Appendix IX: Standardised scoring sheet, dose requirements study
(Chapter 11, page 191)**

Packet Number 18

Observer ACO

Film Code	Fulfillment of Criterion					Rank
	i	ii	iii	iv	v	
CRIOSTOIR	1	1	1	1	1	D
AEDAN	1	1	1	1	1	E
PROINNSAIS	1	1	1	1	1	F
EOGAN	2	2	2	2	1	C
UILLIM	4	4	4	3	2	A
ITE	3	3	3	2	3	B

Criteria:

- Visualisation of outer table of skull vault
- Visualisation of inner table of skull vault
- Visualisation of suture margins
- Visualisation of vascular markings
- Visualisation of soft tissues of the scalp

Score each criterion as follows:

- 1 = Poor
- 2 = Adequate
- 3 = Good
- 4 = Very good
- 5 = Excellent

Compare and Rank all 6 radiographs as follows:

Alphabetically from A to F, with A = best and F = worst radiograph in terms of overall quality.

Thank you.

Appendix X: Standardised scoring sheet, ROC study (Chapter 12, page 212)

IMAGE NO. 44 **PACKET NO. B** **OBSERVER NO.**

How well could you see the soft tissues?
(1=poor, 5=excellent)

1					5
---	--	--	--	--	---

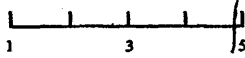
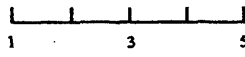
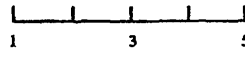
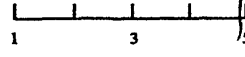
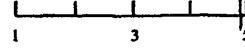
How well could you see the bony trabecular pattern?
(1=poor, 5=excellent)

1					5
---	--	--	--	--	---

What is your impression of the overall quality of the film?
(1=poor, 5=excellent)

1					5
---	--	--	--	--	---

SITE OF FRACTURES:

Bone	Precise site of fracture (e.g. post, lat, ant)	Level of confidence (1=low, 5=high)
Left scapula	lateral border	
Left clavicle		
Left humerus		
Left radius	periosteal reaction distally	
Left ulna	" on radial side	

Appendix XI: Observer instruction sheet, ROC study (Chapter 12, page 212)

Observer no: AC Date: 4/6/3 Start time: 8.35am Finish time: 9.20am Packet: B

Computed Radiography for the Diagnosis of Fractures in NAI: A receiver – Operating Characteristic Study

Instructions for Observers

Please work systematically through the films in the packet provided – you will find it easier if you do this in numerical order.

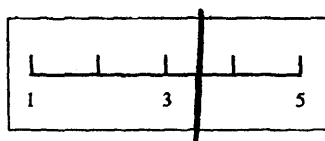
For every film, we would like you to make the following observations by marking the scale (1=unacceptable, 5=excellent) :

- How well could you assess the soft tissues?
- How well could you assess the bony trabecular pattern?
- ~~- What was your overall impression of the quality of the film?~~

For the films on which you detect a bony abnormality:

- Please write on the associated observation sheet the site of the bony abnormality.
- For each abnormality, mark on the scale your level of confidence in this observation (1=not confident, 5=very confident).
- Where you do not see a fracture, you can leave this part completely blank (less work!!)

Please note that in each case, when marking your observations on the scale, you can make a stroke at any point along the scale, eg.



Thanks for your help with this study!