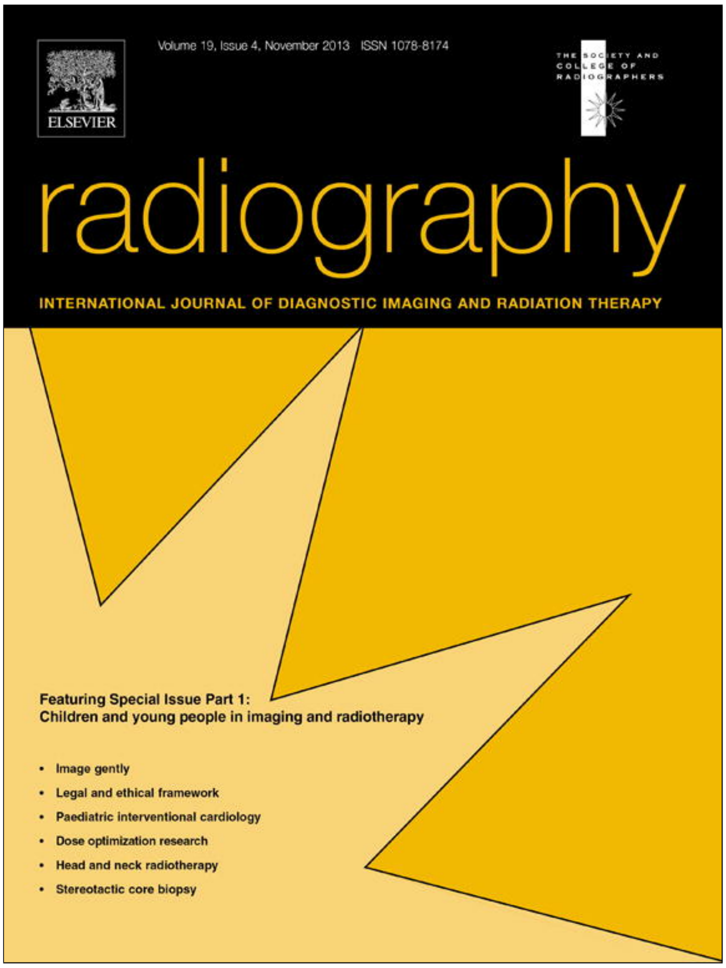
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Radiation dose optimization research: Exposure technique approaches in CR imaging – A literature review

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ABSTRACT

The purpose of this paper is to review the literature on exposure technique approaches in Computed Radiography (CR) imaging as a means of radiation dose optimization in CR imaging. Specifically the review assessed three approaches: optimization of kVp; optimization of mAs; and optimization of the Exposure Indicator (EI) in practice. Only papers dating back to 2005 were described in this review.

The major themes, patterns, and common findings from the literature reviewed showed that important features are related to radiation dose management strategies for digital radiography include identification of the EI as a dose control mechanism and as a "surrogate for dose management". In addition the use of the EI has been viewed as an opportunity for dose optimization. Furthermore optimization research has focussed mainly on optimizing the kVp in CR imaging as a means of implementing the ALARA philosophy, and studies have concentrated on mainly chest imaging using different CR systems such as those commercially available from Fuji, Agfa, Kodak, and Konica-Minolta. These studies have produced "conflicting results". In addition, a common pattern was the use of automatic exposure control (AEC) and the measurement of constant effective dose, and the use of a dose-area product (DAP) meter.

Introduction

The problem of dose creep in Computed Radiography (CR) has been described by several authors in the recent literature[1–6] In review, dose creep refers to "the risk of increasing patient dose, possibly without being aware of it … or an increase in exposure over time when using digital systems with manual tube settings".[5] In a similar vein, Cohen et al.[3] explain that dose creep is an "unintended excessive exposure and subsequent unnecessary patient radiation exposure …"3.

For diagnostic imaging workers using digital systems, this is a significant problem, and has resulted in a number of activities/publications to ensure that users have a clear understanding of the dose-image quality relationship. For example, the International Commission on Radiological Protection (ICRP) provides a seminal report (Publication 93) on *"Managing Patient Dose in Digital Radiology"*[7]; the Society for Pediatric Radiology (SPR), the American Association of Physicists in Medicine (AAPM), the American College of Radiology (ACR), and the American Society of Radiologic Technologists (ASRT) have formed the Alliance for Radiation Safety in Pediatric Imaging (Image Gently) in an effort to educate users on dose issues when imaging children.[4] Furthermore, Schaefer-Prokop and Neitzel[8] have provided a comprehensive review of some 75 papers appearing before 2006 that examine the relationship between dose and image quality in digital projection radiography. In this review, the authors emphasize that users understand the physical aspects of digital detectors, the EI as a control mechanism, and other technical parameters as methods of controlling dose creep, when attempting to optimize the imaging system. Such optimization is the very essence of radiation protection of patients, and it is one of the cardinal principles of the radiation protection framework of the ICRP.

The goal of radiation protection is, therefore, to minimize the probability of stochastic risks and to prevent the occurrence of deterministic effects. To achieve this goal, the ICRP (2007) has developed a framework that is guided by the same three principles described in its 1991 recommendations. These principles relate to justification, optimization, and dose limitation.[9] While justification refers to the fact that every exposure a patient receives must have a positive net benefit associated with it, optimization is intended to ensure that all exposures be kept as low as reasonably achievable

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(ALARA) without compromising the diagnostic quality of the examination. Dose limits on the other hand, are outlined in ICRP Publication 60[10]

The ICRP[9] in Publication 73: *Radiological Protection and Safety in Medicine* notes that there are two levels of optimization, one that deals with the design and construction of equipment and the other that addresses optimization during daily operation. While the former looks at designing equipment to comply with radiation protection standards, the latter examines the procedural and operational practices during the conduct of an x-ray examination, that play an important role in reducing the dose to patients while maintaining image quality. This is the central tenet of the ALARA philosophy.

Two of the „continuous iterations" of the principle of optimization of the ICRP as noted by Matthews and Brennan[11] are:

1. Identification of options for implementing ALARA principle
2. Selection of the most appropriate option for implementation of the ALARA principle

Strategies for radiation dose management in digital radiography, including CR, have been identified and reviewed by several authors[2,7,8,12,13,15–17] and many of the papers address directly the 2 iterations above.

In two recent papers, one examining the dose and image quality balance[15] and the other on optimizing digital radiography of the pediatric patient.[14] The authors first outline the various methods for dose-image quality optimization. Willis[14] describes four broad approaches including technical methods to reduce dose, operational approaches to improving image quality, operational techniques for controlling patient radiation dose, and reform in clinical practice to optimize dose and image quality. Schaefer-Prokop and Neitzel[15] on the other hand review dose requirements and image quality with respect to 14 items. First, they begin with a fundamental discussion of ALARA and image quality classes (high, medium, and low), followed by a reviewing of various strategies for dose containment. Subsequently, they outline the optimization of tube voltage and beam filtration approach; the use of scattered radiation grids; optimizing image processing; image noise; speed-class systems; and the use of the EI as a "surrogate for dose-management".[15]

In summary, both reviews identify clinical and operational approaches for optimizing patient dose and image quality in digital radiography (CR/DR). While the technical approaches to dose reduction focus on radiographic exposure technique factors, detection efficiency, anti-scatter grids, source-to-image receptor distance (SID), beam collimation, filtration, and the EI for example, operational approaches to improving image quality "is affected by decisions made by the radiographer while performing the examination".[14] In addition, operational approaches for controlling patient dose include the use of the automatic exposure control (AEC) device, use of manual techniques, avoiding the use of grids, increasing the SID, paying attention to the EI feedback, collimation and reprocessing images rather than repeating the examination.[14]

More recently Seibert and Morin[2] note that there is an opportunity for dose optimization using the EI associated with the standardization of the EI for digital radiography.

Purpose of this review

The purpose of this paper is to review the literature on exposure technique approaches in CR Imaging as a means of radiation dose optimization in CR imaging. Specifically the review will assess the degree of research conducted to evaluate the use of kVp and mAs and associated Exposure Indicators (EIs) in optimization of the digital imaging system.

Methodology

The methodology or search strategy used in this review of the literature consists of a systematic search of several databases for the health sciences, including Biomedical Central, Biomedical Reference Collection, the Cumulative Index to Nursing and Allied Health Literature (CINAHL) with full text, MEDLINE and PubMed (the National Library of.

Medicine"s free search service). Additionally, the following key terms were used in the initial scan of the databases:

- CR kVp
- CR mAs
- Exposure Indicator in CR
- CR radiation dose
- CR exposure creep
- Dose optimization
- Dose-image quality optimization in CR

An initial scan of PubMed (with citations from MEDLINE and additional life sciences journals) revealed several articles on CR physics and technology and a few papers on image quality and radiation dose, dose optimization. These articles are from major journals: *Radiology*, *Physics in Medicine and Biology*, *Medical Physics*, *Journal of Digital Imaging*, and *Radiation Protection*. Furthermore, a few review articles and reports were found from the American Association of Physicists in Medicine (AAPM) and the International Commission on Radiological Protection (ICRP).

The focus of the literature search was subsequently centered mainly on several scholarly (peer-reviewed) journals such as *Radiation Protection Dosimetry*, *Radiology*, *American Journal of Roentgenology*, *British Journal of Radiology*, *European Journal of Radiology*, *Radiography*, *Journal of Medical Imaging and Radiation Sciences*, *Radiologic Technology*, and *Medical Physics*. The results of this phase of the search revealed that the literature is replete with articles relevant to the use of kV in optimization of the digital imaging system.

The final phase of the search strategy focussed on articles for inclusion in this literature review. It was decided to include mostly articles that date back to 2005. A few seminal papers were older and included in the citations used here. A structured review of selected papers on the use of exposure technique factors in CR was conducted. This was based on the following format; author, purpose of the study/research question/objectives, methodology, and results. Key issues were identified and summarized to generate a statement of the conclusion(s) drawn. In this regard, it is important to note that a number of quotations have been used so as not to detract from the authors" original meaning.

Optimization research: exposure technique approaches in CR imaging

The use of the most appropriate exposure technique factors (mAs and kVp) is the basis for the production of a diagnostic image, as well as factors that play a significant role in determining the dose to the patient.

The selection of the most appropriate exposure technique factors is one of the fundamental options for implementing the ALARA principle during routine daily operation of the CR imaging system.

Optimization of kVp in CR imaging research

During the transition from film-based radiography to digital radiography, exposure technique factors used for film-based radiography have been assumed to be appropriate for use in digital radiography.[18] An important consideration in this respect is that the response of the CR detector to the beam energies used in diagnostic radiology is simply different than that of a conventional film-screen detector.[19] The typical CR detector phosphor BaFBr/I (barium fluorobromide/iodide) has a k-edge at approximately 37 keV, while that of a typical rare-earth film-screen detector such as Gd_2O_2S has a k-edge of about 50 keV. Moore et al. suggest therefore "that lower tube voltages relative to those used for film-screen should be used for CR".[19] The significance of this point is that departments should consider optimization of the kVp when using CR systems. In this regard, the literature is replete with studies focusing on optimization of the tube voltage (kV) using different CR imaging systems and different body parts to the extent that these studies have produced "conflicting results".[19,20]

An early review of the influence of kVp on image quality in chest images using CR technology was published in 2004.[18] In this paper, the authors reviewed the literature prior to 2004 on optimizing kVp for chest examinations, since it is the most frequent examination conducted in radiology departments. The structures in the chest such as the lungs and mediastinum as well as fine structures (nodules for example) pose a radiation attenuation challenge.

This challenge was reviewed by McEntee et al.[18] who identified about ten studies dealing with kVp optimization in CR, using beam energies ranging from 60 kVp to 125 kVp for chest radiography. The conclusions drawn from the review of these studies are as follows:

- "CR systems produce better image quality at beam energies below 100 kVp compared with higher beam energies, and the E (effective dose) does not increase significantly. The dose to the gonads of both the male and the female will be reduced as a result of the decrease in tube potential".[18]
- "Further research on the topic is required".[18]

Following the year 2004, several studies on optimizing tube potential in digital radiography appeared in the literature from 2005 to 2010. This literature review narrowed the search to CR studies (rather than flat-panel DR studies) and found eight CR studies as outlined in Table 1.

Studies in 2005

Hansson et al.[21] conducted a study to investigate the optimum tube voltage for neonatal chests using a Fuji FCR 5000 (Fuji Photo Film, Tokyo, Japan) CR imaging system using a living rabbit as a phantom (Table 2). Images were obtained at nine kVp settings ranging from 40 kVp to 90 kVp and at mAs values to ensure a constant effective dose at all kVp settings. Both standard and high resolution IPs were used and six images were produced for each kVp setting for each IP type. While the mAs settings for the standard IP corresponded to 50, 100, and 200% of the effective dose, they were 100, 200, and 400% for the high resolution (HR) IP. A total of 52 images were collected. For image viewing, the monitor was calibrated and all images were processed using processing parameters at 70 kVp. Furthermore, gradation processing controlled by Fuji"s GA (contrast) and GS (brightness) were adjusted to obtain the proper luminance.

This study employed an absolute Visual Grading Analysis (VGA) procedure to assess image quality using ten observers to rate the reproduction of anatomical structures on a 4-point graded ordinal scale using the Commission of European Communities (CEC) quality criteria for pediatric chest radiography. In addition, a validation study was also conducted using neonatal images from Sahlgrenska University Hospital. These images were collected at 70 kVp and were compared with the rabbit phantom images obtained at 90 kVp, using a relative VGA study, meaning that image pairs were collected and assessed (standard IPs were used for the validation study). Structures on the evaluated images were compared with those in a reference image, using a 5-point graded scale. Based on the results, the authors conclude that "although tube voltages $\leq$70 kVp are common in radiography of neonates, a high tube voltage such as 90 kVp seems to be a good alternative in digital radiography. Based on the results of the phantom study, the use of standard imaging plates gives better image quality than the use of HR imaging plates, particularly at low levels".[21]

In another study published in 2005 by Tingberg and Sjöström[22] (see Table 1), the researchers goal was to determine the optimization of a Fuji FCR AC-3CS/ID CR system, with respect to kVp for chest and pelvis, at a constant effective dose, using anthropomorphic phantoms of the chest and pelvis. While images of the pelvis were obtained with tube voltages ranging from 50 to 102 kVp and corresponding mAs settings ranging from 112 to 8 mAs (mAs settings were adjusted to ensure the same effective dose) chest images were obtained with tube voltages from 70 to 150 kVp with corresponding mAs settings ranging from 32 to 4 mAs and adjusted to ensure constant effective dose. Six observers evaluated all chest and pelvis images on image quality criteria established by the CEC using a VGA procedure.

The results of this study showed the following:

1. VGA scores were higher at low kVp settings for both chest and pelvis images, meaning that clinical image quality improves at lower tube voltages

Table 1
Elements of eight CR studies on optimization of the tube potential from 2005 to 2010.

Year	Author	Title of the article	Journal
2005	Tingberg A. & Sjöström D.	Optimization of image plate radiography with respect to tube voltage	*Radiation Protection Dosimetry*, *114*(1–3), 286–293
2005	Hansson J. et al.	An optimization strategy in a digital environment applied to neonatal chest imaging	*Radiation Protection Dosimetry*, 114(1–3), 278–285
2005	Honey I.D. et al.	Investigation of optimum energies for chest imaging using film-screen and computed radiography	*British Journal of Radiology*, *78*(929), 422–427
2005	Brindhaban A. et al.	Effect of x-ray tube potential on image quality for lumbar spine CR examinations	*Australasian Physical & Engineering Sciences in Medicine*, *28*(4), 216–222
2006	Sandborg M. et al.	Comparison of clinical and physical measures of image quality in chest and pelvis CR at different tube voltages	*Medical Physics*, *33*(11), 4169–4175
2008	Moore C.S. et al.	Investigation of optimum x-ray beam tube voltage and filtration for chest radiography with a CR system	*British Journal of Radiology*, *81*, 771–777
2008	Bumbare L et al.	Quality of the CR Image acquired with decreased doses	*NBC Proceedings* (20); 1–4
2010	Egbe N.O. et al.	A simple phantom study of the effects of dose reduction (by kV increment) below current dose levels on CR chest image quality	*Radiography*, *16*(4), 327–332

Table 2
A summary of the major elements of optimization studies of kVp in CR studies from 2005 to 2011.

Author	Year	Anatomy	Type of study and CR system	kVp settings	Evaluation methodology	Conclusions
Hansson et al.	2005	• Neonatal chest	• Fuji FCR 5000, Std and Hi Res IPs • Optimization of kVp	• 40–90 kVp	• Validation study using a rabbit model • Absolute VGA • 10 observers • Constant effective dose at all kVp settings	• High kVp such as 90 kVp for diagnostic radiography • Std IPs give better image quality at low doses
Tingberg & Sjöström	2005	• Chest and pelvis anthropo-morphic phantoms	• Optimization of kVp • Fuji FCR AC-3CD/ID system	• Pelvis at 50–102 kVp (112–8 mAs) • Chest at 70–150 kVp (32–4 mAs)	• VGA study • Constant effective dose • 6 observers • CEC quality criteria	• VGAS higher at low kVp for both chest and pelvis • Reduced kVp produced improved image quality of the chest and pelvis compared to 120 kVp and 70 kVp chest and pelvis respectively used for FS radiography
Honey et al.	2005	• Lumbar spine	• Optimization of kVp • Kodak Direct View CR 900 system • Fuji FCR 9000 system	• 80, 92, and 105 kVp for Kodak unit • 81 to 94 to 104 kVp for the Fuji CR unit	• Image Scores (IS) • ESD measured with survey meter • 9 observers	• Doses can be reduced by 25–50% without affecting image quality
Sandborg et al.	2006	• Chest and pelvis anthropo-morphic phantoms	• Correlation of physical image quality (SNR) without clinical image quality • Fuji FCR AC-3 system • Std IP	• 70–150 kVp for chest • 50–102 kVp for pelvis • Reference kVp Chest – 125 Pelvis – 70	• VGA • CEC quality criteria • 6 observers • mAs adjusted to provide constant effective dose	• Optimum kVp lower than FS (i.e., 125 kVp for chest and 70 kVp for pelvis) • Physical image quality measures can be derived that correlate with clinical VGA image quality descriptor
Mooreet al.	2008	• Chest anthropo-morphic phantom	• Optimization of kVp • Agfa 75.0 CR system	• 60, 80, 90, and 120 kVp	• SNR • Air kerma dose measure • Number of observers not mentioned	• Optimization of kVp depends on the anatomical region • 60 kVp for lungs, 80–125 kVp for heart, and 60–90 kVp for diaphragm
Burnbure et al.	2008	• Plexiglass phantom and Test Plate (EIR-1)	• AEC exposure timing compared to manual exposure timing • Kodak Direct View CR 500 system	• AEC mode 40 kVp/23.7 mAs 50 kVp/6.34 mAs 60 kVp/2.79 mAs 70 kVp/1.59 mAs 80 kVp/0.98 mAs 90 kVp/0.59 mAs • Manual mode 40 kVp/16 mAs 50 kVp/4 mAs 60 kVp/1.6 mAs 70 kVp/1.0 mAs 80 kVp/0.63 mAs 90 kVp/0.5 mAs	• Image quality assessed with visualization of line pairs per mm and contrast (optical density) • Air kerma (DAP measure) • Number of observers not mentioned	• Compared to AEC manual mode of exposure timing resulted in a dose reduction of 40–75% while maintaining good image quality
Egbe et al.	2010	• Chest	• Optimization of kVp • Kodak Direct View CR 800 system	• 102, 117, 133, and 150 kVp	• AEC used • ESD (mGy) measured ESD (mGy) measured at each kVp setting • Simulated lesions for clarity and detectability • 4 medical physicists as observers	• Clarity and detectability worsen as dose was reduced below a reference dose of 0.17 mGy (no image manipulation) • For clarity, significant difference seen at 0.04 mGy • Image manipulation resulted in parallel image quality • Significant differences in clarity and detectability seen at 0.10 mGy • No difference in clarity and detectability seen in mediastinum area at all doses with and without image manipulation • Clarity and detectability of simulated lesions depend on whether contrast enhancement techniques are used

Table 2 (*continued*)

Author	Year	Anatomy	Type of study and CR system	kVp settings	Evaluation methodology	Conclusions
Walker	2011	• Pelvis (phantom)	• Optimization of kVp • Konica-Minolta Regius 170 CR system	• 60, 70, 81, and 90 kVp at 6 different mAs settings for each kVp increment • 24 images at each kVp setting	• Image quality score on a 5-point scale • DAP dose measurement (mGy/m^2) • UNFORS dosimeter used to measure Entrance and Exit doses	• Poor and high image quality scores associated with low and high mAs respectively for same kVp settings • High 'S' numbers at lower doses and vice versa • Results followed the 15% rule, that is, if the kVp is increased by 10%, the mAs is reduced by one-half to produce equivalent quality

2. Statistical analysis using the Newman–Keuls test to show significant differences reveal that:
   a. For chest images, there were differences between the 70 kVp and 141 kVp settings ($p = 0.033$) at 5% level; and at the 10% level between 70 kVp and 133 kVp ($p = 0.054$) and at 70 kVp and 150 kVp ($p = 0.061$)
   b. For the pelvis images, there was no significance between small changes in kVp (60–63); however, for large changes between 50 and 60 kVp, there was a significant difference ($p < 0.05$)

The authors conclude that for the CR system, clinical image quality of the chest and pelvis can be improved when the tube voltage is reduced "compared with standard settings (125 kVp and 70 kVp for chest and pelvis respectively) which were used for screen-film radiography previously".[22]

In yet another study published in 2005 by Honey et al.[23] (see Table 1) the researchers "objectives were to determine the optimum tube potential for chest imaging using CR, and to assess the comparative image quality for FS and CR as a function of tube voltage".[23] Using a contrast-detail detection phantom (CDRAD), images were obtained using both FS radiography on an Agfa CR system at 75 kVp, 90 kVp, and 125 kVp at different detector doses, from about 0.5 μGy to 20 μGy. Two observers evaluated hard copy images using a masked light viewing box to score threshold contrast indices. These indices were then used to calculate a visibility index (VI). The authors summarize their results and conclusion as follows:

> *"The improvements in VIs obtained using CR at 75 kVp and 90 kVp were found to be statistically significant compared to 125 kVp at matched dose levels. The relative performance of FS and CR varies as a function of energy, owing to the different k-edges of each system when changing from FS to CR. The use of lower tube potentials may allow image quality to be maintained whilst reducing effective dose. A tube voltage of 90 kVp is indicated by this work, but may require clinical verification".*[23]

The final study published in 2005 is one by Brindhaban et al.[24] (see Table 1). The purpose of this study was to examine optimization of the tube potential for the lumbar spine using two different CR systems; the Fuji FCR 9000 and the Kodak Direct View CR 900 systems. Images of a pelvis-lumbar spine phantom including L2 to L5 with a thickness of 23.5 cm and weighing 73.6 kg were obtained at different kVp settings. For the Fuji system, the kVp values increased from 81 to 94 to 104, as opposed to 80, 92, and 105 for the Kodak CR system. Exposures were measured with a Victoreen Model 660 survey meter containing a 5.6 cm diameter ionization chamber.

Nine observers (five radiologists, one medical physicist, and three radiographers with more than 15 years of clinical experience) evaluated image quality using the CEC quality criteria to assess visibility of anatomical structures on a 5-point scale. Mean image scores (IS) were computed for the nine observers. The dose was measured with backscatter included for each of the techniques used to produce the images. Three images were recorded for each tube voltage-mAs combination, and the entrance surface dose (ESD) was calculated.

The results showed that doses can be reduced by 25–50% without affecting image quality by increasing the kVp and reducing the mAs (using the 15% rule). The authors conclude that "the optimization of the balance between image quality and patient dose can be achieved by exploring changes in exposure factors used in CR".[24]

Studies in 2006

In 2006, a study by Sandborg et al.[25] (see Table 1) was conducted to investigate the correlation between physical measures of image quality such as SNR, for example, and clinical image quality. Additionally, another goal of this study was to explore a range of tube voltages for chest and pelvic CR examinations in an effort to optimize the kVp.

The researchers used a computer model of the imaging system and an anthropomorphic phantom for both chest and pelvis examinations. The tube voltage for the chest and pelvis (both in the AP position) ranged from 70 kVp to 150 kVp and 50 kVp to 102 kVp respectively. The reference tube voltage for the chest and pelvis was 125 kVp and 70 kVp respectively. Ten different kVp values were used for each examination, while the mAs was adjusted to produce a constant effective dose.

Both chest and pelvis examinations were conducted with the Fuji FCR AC-3 CR system using the standard IP coated with barium fluorochloride PSP. Images were evaluated by six experienced radiologists using the CEC image quality criteria. The images were displayed on a monitor and radiologists used the VGA procedure to score images on visibility of anatomical structures.

The results of this study demonstrate that for CR chest and pelvis examinations, optimum kVp values are lower compared to those employed in film-based radiography, that is, 125 kVp for the chest and 70 kVp for the pelvis. Furthermore, Sandborg et al.[25] (2006) concluded that "using an anthropomorphic phantom and a computer model of the imaging system, physical measures of image quality can be derived that correlate with clinical VGAS image quality descriptor".[25]

Studies in 2008

There were two studies found that were published in 2008. The first is one by Moore et al.19 who conducted a study to explore the optimization of kVp for chest examinations using an Agfa 75.0 CR system, with MD 4.0 IPs. Using a chest phantom, images were obtained at 60 kVp, 80 kVp, 90 kVp, and 120 kVp, and the air kerma dose data were measured, followed by a calculation of the contrast-to-noise ratio (CNR), with respect to the air kerma for each kVp setting.

Statistical analysis of the data obtained for defined chest anatomical structures (lung region, heart and spine region, and the diaphragm) showed that the optimum kVp depends on the specific anatomical region. The authors subsequently conclude that "tube voltages that maximize CNR" using the Agfa CR system are 60 kVp for the lungs; 80–125 kVp for the heart/spine; and 60–90 kVp for the diaphragm anatomical compartments.

The other study that appeared in 2008 is one by Bumbure et al.[26] who investigated optimization of the dose-image quality in a plexiglass phantom coupled with a test plate ("ETR-1") using a Kodak Direct View CR 500 system. Phantom images were obtained both with the AEC and manual timing modes. The air kerma (mGy m^2) was measured with a dose-area-product (DAP) meter.

In the AEC mode, the kVp and associated mAs values were 40 kVp and 23.7 mAs; 50 kVp and 6.34 mAs; 60 kVp and 2.79 mAs; 70 kVp and 1.59 mAs; 80 kVp and 0.98 mAs; and 90 kVp and 0.59 mAs. Images were obtained at each of these settings. In the manual mode of operation, images were obtained at 40 kVp and 16 mAs; 50 kVp and 4 mAs; 60 kVp and 1.6 mAs; 70 kVp and 1 mAs; 80 kVp and 0.63 mAs; and 90 kVp and 0.5 mAs.

Image quality was assessed on two parameters; the lateral resolution in line pairs/mm and the contrast. For the lateral resolution a defined region of the test object was used. Image contrast was calculated using optical density values. The authors did not describe the details of the number of observers used in the study.

The results showed that compared to the AEC mode, the manual mode of operation resulted in a dose reduction of *40–75% while maintaining "good" image quality.*

Studies in 2010

Only one study on optimization of the kVp in CR was found for the year 2010. This study was one by Egbe et al.[27] who conducted an image quality and dose optimization investigation in chest radiography using a Kodak Direct View CR 800 system. Images of a chest phantom were recorded at 102 kVp; 117 kVp; 133 kVp; and 150 kVp using the AEC operational mode. The ESD (mGy) was measured as well at each kVp setting, using four exposures per setting. All exposures were done in a single day, and IPs were processed within the first 30 min of exposure.

The assessment of image quality was done by four medical physicists who viewed 40 images of the lungs and 24 mediastinum-simulated lesion images per dose setting, on a calibrated monitor. The assessment lasted between 24 h to one week, and images were scored on clarity and detectability of simulated lesions seen on the images.

The results showed that clarity and detectability of simulated lesions became worse as the dose was reduced below a certain reference dose of 0.17 mGy, when images were not manipulated. At 0.06 mGy, the clarity in the lung area was significantly different and significant detectability changes were seen at 0.04 mGy. Furthermore, image manipulation resulted in parallel image quality changes. Significant differences in image clarity and detectability were observed at 0.10 mGy. There was no significant difference in image clarity and detectability in the mediastinum area at all doses, with and without image manipulation.

The authors conclude that image clarity and detectability of simulated lesions in the chest at different doses "may be dependent on whether or not contrast enhancement techniques are employed. There is also evidence to suggest that low dose images of the high density mediastinum can be enhanced with post processing, making exposure at high doses unnecessary".[27]

Studies in 2011

A more recent study is one by Walker[28] who investigated the relationship between exposure technique factors and image quality in an attempt to establish dose-image quality optimization using a Konica-Minolta Regius 170 CR system. Walker imaged a pelvis phantom using 60 kVp; 70 kVp; 81 kVp; and 90 kVp along with six different mAs settings for each of the kVp values used. The mAs was doubled at each kVp increment. In addition, the x-ray beam was collimated to show beam restriction along the four sides of the 35 cm $\times$ 43 cm IP. A hip processing algorithm was selected to process images of the pelvis using the Konica-Minolta workstation, for each of the 24 images obtained for all kVp settings.

The radiation dose was measured using a DAP meter in mGy m^2. Additionally, both entrance and exit doses were measured with a UNFORS dosimeter. All images were assessed on the Konica-Minolta CR workstation monitor without any image post processing such as windowing, and evaluated by one experienced radiographer. The images were given a quality score based on a 5-point scale where 1 indicates a poor image to 5 indicating excellent image quality. Images were also presented in a random order and assigned a letter of the alphabet which referred to an anonymized exposure value.

The results of this study indicate that while poor and high image quality scores were associated with low and high mAs values respectively, doubling the mAs resulted in a doubling of the surface doses. The author emphasized that despite the subjective nature of the image quality evaluation, the results demonstrate that higher mAs techniques produce better image quality that low mAs settings for the same kVp setting. Additionally, the author noted that the results follow the 15% kVp rule, meaning that if the kVp is increased by 10 kVp, the mAs must be reduced by one-half to produce equivalent image quality.

Optimization of mAs in CR imaging

It is clearly apparent from the above studies that "manipulation of the operating kVp cannot stand alone even with digital systems, and concomitant compensation of the applied mAs, together with adequate scatter control are necessary".[11] One of the fundamental concerns in digital imaging is the inverse relationship between mAs and image noise. As a result, optimization must consider the assessment of image quality with respect to the dose per image. Increasing the dose per image will decrease the noise, thus improving image quality.[29]

One of the benefits of digital radiography is the wide exposure latitude, meaning that images can be obtained with a wide range of detector doses from about 0.05 μGy to 300 μGy per image (Marshall, 2001). While this wide range can be advantageous to the operator, it can also allow the operator to use higher than necessary doses, as is evident in the phenomenon of exposure creep.[1,2]

Optimization should, therefore, assess image quality with respect to the dose per image.[29] A search of the literature revealed only one study (between 2005 and 2010) using such an approach, that is the lowest mAs possible "without excessive noise degradation of image quality"11 in optimizing the dose-image quality in CR imaging. This study is by Fauber[20] who investigated the "insufficient and excessive radiation exposure on CR image quality."

The goal of Fauber"s study was to reduce patient dose without compromising image quality and explore how the variation in the radiation quantity would influence the EI, radiographic contrast and resolution (detail). Using a Fuji XG-1 Smart CR system (Fujifilm, Tokyo, Japan) and a Fuji FCR 1-Shot Quality Control (QC) phantom

(Fuji Medical Systems, Stamford, CT). Five images were obtained for each of the following exposure groups: 1 mAs; 2 mAs; 4 mAs; 8 mAs (baseline value); 16 mAs; 32 mAs; 64 mAs; and 125 mAs. Fauber[20] explained that "the mAs value to achieve an optimal quality QC phantom image was ultimately decreased by 300% for the lowest mAs value and increased 400% for the highest mAs value".[20] The EI („S'' number for Fuji CR) for each of the five exposure groups were recorded. Images were then printed on film to measure the optical density (OD) using a densitometer and using the differences in OD to evaluate radiographic contrast. The resolution grid on the image of the phantom was used to assess resolution in terms of the number of line pairs.

The results of this study showed that:

1. "The EI is stable over a wide range of radiographic exposures above the optimal baseline value".[20]
2. The line pairs/mm were difficult to discriminate at low exposures compared to the baseline value of 8 mAs, and image mottle (noise) was pronounced at low exposures below the baseline value of 8 mAs.

The author concluded that the results of this study simply support the literature on dose optimization in digital radiography, in that diagnostic quality images can be produced with a wide range of exposures above or below an optimal level (8 mAs).

Optimization of the EI practice

Optimization of the EI is closely linked with optimization of exposure technique factors (kVp and mAs). In summary, the EI is a numerical parameter devised by CR manufacturers to provide the user with a visual cue as to the amount of exposure to the CR IP. It provides the technologist with an indication of whether the appropriate radiographic techniques are used for the examinations under study.

The exposure dependence, X, for the Fuji, Carestream, and the Agfa systems for example are: $200/S \propto X(\text{mR})$; $EI + 300 = 2X$; and $\lg M + 0.3 = a2X$ respectively, where „S'' is the sensitivity number, EI is the exposure index, and lgM is the log of the median of the histogram[2]. This means that for the Fuji S number for example, as the exposure increases, the S number decreases. For the Carestream CR system if the EI is increased by 300, then the exposure to the IP (detector) is doubled.

The EI is not the patient dose. Patient dose depends on several factors such as kVp, mAs, beam filtration, SID, body part being imaged, and collimation for example (reviewed earlier). The significance of the EI is that it is an important tool for QC purposes, appropriate use of the equipment, and "to optimize radiation dose on an exam-by-exam basis for appropriate patient care.[2]

In terms of using the EI as part of an optimization strategy in digital radiography, the literature is extremely sparse in this area of research. In the previous studies on optimizing kVp and mAs reviewed above, no attempts were made to explore the influence of the kVp and mAs on the EI values. Only one study published in 2002 by Peters and Brennan[30] found that specifically addressed the notion of an optimized EI as a dose management strategy via establishing an optimized mAs. In brief, the researchers found that the optimized mAs resulted in a significant decrease in the average EI (for the Kodak CR system) during mobile chest radiography, from 1840 to 1570 ($p < 0.001$). Furthermore, the optimized EI is "substantially lower than the manufacturer"s guidelines of 2000" and significantly lower than those used in clinical practice.[30] Additionally, the authors report that "although dose levels to the patient have not been directly measured, it is safe to assume that a strong correlation exists between higher exposure indices and higher patient dose" (p. 2385). In this respect, Fauber et al.[20] state that:

> "Further research is necessary to understand the significance of the exposure indicator and its relationship to exposure techniques and patient exposure"[20]

In 2007, Warren-Forward et al.[31] conducted a study to explore the use of the EI by radiographers in clinical practice, as well as exposure creep, and the relationship between EIs and radiation dose. The study was divided into two phases; a retrospective study and a phantom study, using the Kodak CR 800 and 850 systems. The only difference between the two systems as pointed out by the authors is that the 800 system reads less IPs/hour than the 850 CR system.

The retrospective study examined data (on patients older than 16 years of age) such as exam information, date, time of exam, as well as EIs for the PA chest and the lateral lumbar spine, from two hospitals, between 2004 and 2005. The phantom study employed a lung/chest phantom using several exposures at 125 kVp at 180 cm SID under AEC operation. An average of three EI values (1550) "was used to control all other exposure factors".[31] Subsequently, exposures of the phantom at 70–125 kVp were recorded making sure that the EI was maintained at 1550. The ESD was measured at these factors (70–125 kVp) using thermoluminescent dosimeters (TLDs) for every exposure. Three exposures were made and the mean was used for data analysis.

The results of the retrospective study showed that radiographers used EIs that were beyond the manufacturers recommended range of 1700–1900. While EIs of less than 1700 were observed for 25% of both examinations, exposure creep was clearly apparent over the 18-month period especially for the lateral lumbar spine at one hospital. The phantom study results clearly showed that "a small increase in the EI produced a large increase in the entrance surface dose … an EI of 2000 produced at 125 kVp can deliver the same patient dose as an EI of 1700 produced at 70 kVp, where the EI difference of 300 represents a doubling of the dose to the detector" (p. 31). In addition, the authors stated that "a reduction of as little as 10% of the manufacturer recommended range (1530–1700) can result in a dose saving of nearly 50% and this has shown that EIs produced at this range produce diagnostically acceptable images".[31] Furthermore, evaluation of the phantom images by four experienced radiographers indicated that higher contrast and less noise were characteristic of low kVp values, and all images were acceptable.

Conclusions

To minimize the probability of stochastic effects and prevent deterministic effects, the practice of radiology is guided by the radiation protection framework established by the ICRP. One of the important principles of this framework is that of optimization, meaning the use of as low as reasonably achievable (ALARA) dose without compromising the quality of the image. Optimization, therefore, involves strategies to manage the radiation dose to the patient.

This literature review addressed optimization research focusing specifically on exposure technique approaches in CR imaging. Three approaches were reviewed: optimization of kVp; optimization of mAs; and optimization of the EI in practice. Only papers dating back to 2005 were described in this section.

The major themes, patterns, and common findings from the literature reviewed are centered around dose management strategies; optimization research; The important features are as follows:

1. Dose management strategies for digital radiography include each of the following:
   - The EI has been identified as a dose control mechanism
   - The EI can be used as a "surrogate for dose management"
   - The use of the EI has been viewed as an opportunity for dose optimization
   - Operational techniques for controlling patient dose
   - Operational approaches to improving image quality
2. Optimization research has focused mainly on optimizing the kVp in CR imaging as a means of implementing the ALARA philosophy. These studies have concentrated on mainly chest imaging using different CR systems such as those commercially available from Fuji, Agfa, Kodak, and Konica-Minolta. These studies have produced "conflicting results".[19,20] In addition, a common pattern was the use of automatic exposure control (AEC) and the measurement of constant effective dose, and the use of a dose-area product (DAP) meter.

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