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Effective dose and image quality for different patient sizes during AP upper abdominal radiography: a phantom study

Abstract

Introduction: Undertaking medical imaging examinations on obese patients can present practical challenges. Choosing optimal imaging protocols can be difficult, especially when promoting the ALARA principle. The aim of this study was to assess the effects of increasing body part thickness on image quality (IQ) and effective dose (ED) during upper abdominal radiography. A secondary aim was to determine the optimum exposure settings for larger sized patients.

Methods: Underweight, standard, overweight and obese abdomen sizes were simulated using an anthropomorphic upper abdomen phantom, without and with additional fat layers (6, 10 and 16 cm). Phantoms were imaged using a variety of tube potentials (70-110 kVp), automatic exposure control (AEC) and a source-to-image distance of 120 cm. IQ was assessed visually using a relative visual grading analysis (VGA) method. Radiation dose was evaluated by calculating the ED using the Monte Carlo PCXMC 2.0 computer program.

Results: IQ values showed a statistical reduction ($p=0.006$) with increasing phantom size across all examined tube potentials. The highest IQ scores (3.3, 2.8, 2.5 and 2.2, respectively) were obtained at 70 / 75 kVp for all phantom thicknesses. As tube potential increased the IQ was also shown to decrease. ED showed a statistically significant increase ($p<0.001$) with increasing phantom thicknesses.

Conclusion: Higher EDs were evident when applying lower tube potentials. Using an AEC with high tube potentials (105 / 110 kVp) can lead to a considerable decrease in ED with acceptable IQ when undertaking upper abdomen radiography on patients with large body part thicknesses.

Implication for practice: Applying higher values of tube potentials for patients who have a thicker abdomen can lead to decreased ED

Keywords: abdominal radiography, obesity, image quality, radiation dose, effective dose, optimization.

Introduction:

There have been continuing concerns regarding the increase in radiation exposure of patients undergoing medical imaging examinations. According to several studies low-dose radiation from radiography may increase risk of cancer as well as have hereditary and stochastic effect [1–3]. When a patient has acute abdominal pain, abdominal radiography (AXR) is commonly requested by healthcare professionals. Despite their frequency, there is much disagreement in the literature about the value of AXR [4–8]. In a review of 277 patients with five common acute abdominal diseases, Lee et al. reported the identification of relevant radiological findings in 48% of cases [4]. They subsequently recommended AXR for all instances of stomach pain [4]. In a second analysis of 249 patients with diverse types of abdominal pain, Lee discovered that AXRs were helpful in 42% of cases.

Practical challenges frequently arise when imaging overweight and obese patients, increases in radiation dose and lower image quality (IQ) can result [9]. Problems can result from the additional X-ray beam attenuation, greater quantities of scatter radiation and longer exposure times (increase in motion artifacts) [9–11]. In addition to clinical indications, the weight and body part diameter of a patient are important considerations when choosing the correct imaging protocol. Practitioners need research-based recommendations when selecting the pre-acquisition and post-acquisition imaging settings [12].

Standard imaging techniques for different radiographic examinations have been defined by the Commission of the European Communities (CEC). In addition, several optimization studies have focused only on average sized patients [13–15]. Therefore, this research is aimed to help determine the optimum imaging techniques that may be utilized for imaging larger size patients whilst providing an acceptable diagnostic IQ with the minimum amount of radiation (ALARA). This study sought to 1) evaluate how body part thickness affects IQ and effective dose (ED) during AXR. 2) to provide suggestions on the recommended '*optimised*' parameters that could be used when undertaking AXR on larger sized patients.

Methods

Imaging equipment and technique

A PH-5 CT adult anthropomorphic abdomen phantom (PH-5 CT Abdomen Phantom, Kyoto Kagaku Company, Japan) was utilized to evaluate IQ (**Figs. 1A & 1B**) this phantom has the following measurements: the x and y-axis diameter of the phantom are 26 and 18 cm, respectively, and the circumference of the phantom is approximately 79 cm[16]. A supine position (anterior posterior [AP] projection) was used for phantom imaging, a set collimation field was employed, and the beam was centered in the middle of the phantom. Various slabs of animal fat were placed on the anterior surface of the phantom to simulate different body part thicknesses (**Figs. 2A & 2B**). The distribution of adipose tissue in the human body does not typically correspond to the fat being positioned anteriorly. However, the procedure for incorporating fat as reported in this study was a simplification of the "apples" and "pears" fat distributions more frequently seen in adult body types [17]. Accordingly, the fat simulation used in this investigation used the extra body fat primarily distributed in the anterior body structures. Animal fat can accurately simulate abdominal fat since it has a tissue density close to human fat [18]. During this study, the simulated body size categories included patients ranging in size from underweight (without added fat) to obese (**Table 1**). The chosen imaging parameters were based on those published in the literature and local clinical practice[19,20]. In total 36 abdomen radiographs were obtained. Nine images for each phantom size with tube potentials ranging from 70 to 110 (5 kVp intervals). The mAs and kerma air product (KAP) values are summarized in **Table 2.**

Phantom radiographs were acquired using a digital X-ray unit (Wolveson X-ray Ltd, Willenhall, UK) which was equipped with a kerma area product (KAP) meter, a stationary anti-scatter grid (10:1 ratio, 40 lines/cm frequency) and 3 mm Al inherent filtration using the two outer and center AEC. The X-ray equipment included an Aero DR detector (Konica Minolta Medical Imaging USA INC, Wayne, NJ) with a 1994 by 2430-pixel matrix (175μm pixel pitch). Lighting within the viewing room was maintained at constant levels (30-40 lux) and dimmed during the IQ assessments in accordance with European Guidelines on Quality Criteria for Diagnostic Radiographic Images [21].

Table 1. Categories of body part thickness used in this study.			
Body size	**Body Mass Index (BMI)**	**Additional fat layer (cm)**	**Total AP abdomen thickness (cm)**
Underweight	14	0	18
Standard size	21	6	24
Overweight	28	10	28
Obese	37	16	34

Table 2: Summarize the mAs and KAP values for different phantom sizes.

kVp	**Underweight**		**Standard**		**Overweight**		**Obese**	
	mAs	KAP	mAs	KAP	mAs	KAP	mAs	KAP
70	9.4	269	26.0	740	49.0	1390	100.0	2765
75	7.2	233	18.9	616	34.0	1122	69.0	2235
80	5.4	201	13.9	516	24.0	920	48.0	1805
85	4.5	178	10.3	439	18.0	769	35.0	1476
90	3.6	155	8.1	375	13.5	642	25.0	1213
95	2.7	135	6.3	320	10.3	538	19.3	1000
100	2.2	126	5.4	290	8.5	484	15.3	887
105	2.2	118	4.5	267	7.2	440	12.6	795
110	1.8	112	4.0	249	5.8	402	10.3	716

Image quality evaluation

A relative visual grading assessment (VGA) approach was used to assess IQ by comparing two images simultaneously using clinically validated software created by Hogg and Blindell [22]. This technique resulted in the display of two images side by side, one serving as the reference image and the other as the experimental image being assessed. Three radiographers with more than five years' of experience were asked to rate the resultant radiographs using a 5-point Likert scale in accordance with the criteria illustrated in **Figure 3** [23]. Using the Likert scale score sheet the participants decided whether the IQ was: much worse (score of 1), slightly worse (score of 2), equal to (score of 3), slightly better (score of 4), or much better than (score of 5) that of the reference image. Scores were averaged for each image and could range from 1to 5. A score of 3 represented equal IQ to that of the reference image. A score of more than 3 meant enhanced IQ, while a score of less than 3 indicated a decline in IQ. The scores for each image were then averaged across all radiographers. Criteria used for IQ evaluation was based on the CEC guidelines [13]. and the reference image (acquired at 75 kVp, no additional fat).

All observers were blinded to the acquisition conditions and parameters used. Greyscale Digital Imaging and Communications in Medicine (DICOM) calibration was performed on monitors prior to the start of the study. Images were displayed to observers on two 5 megapixel DOME E5 (NDSsi, Santa Rosa, CA) monitors (2048 by 2560 pixels)[24].

Radiation dose measurement

KAP values were measured while conducting the phantom imaging. The verification of these measurements was performed during routine quality control checks of the X-ray unit which were performed periodically. For each phantom image, the ED estimates were made using the recorded KAP values and the Monte Carlo program PCXMC 2.0 (STUK, Radiation and Nuclear Safety Authority, Helsinki, Finland). Within the simulations, the phantom's weight was changed by one kilogram for every additional cm of fat thickness (or 0.96 additional centimeters of AP diameter). This equation was based work by Miyatake [25], which assumed a linear relationship between increasing waist size and body weight [26,27]. Additionally, it was demonstrated that the position of internal organs would not change as phantom size increased and that they would just be hidden by layers of additional adipose tissue [28]. In order to overcome the problem that PCXMC could overestimate the effective dose, the number of the simulated photons was increased to 10^6 which has been recommended in previous studies in order to lower the error by 1% [29,30].

Statistical analysis

The mean IQ and ED values for each phantom size were determined. Normality of the data were investigated using the Shapiro-Wilk test. A one-way ANOVA test was utilized to compare the IQ and ED values for the various phantom thicknesses (18, 22, 26 and 32 cm). This test provides an indication of statistical significance when comparing >2 variables. If significance arose, post hoc t-tests with Bonferroni correction were subsequently utilized. An inter-class correlation (ICC) coefficient was employed to evaluate inter-observer variability [31,32]. The statistical software SPSS Version 26.0 (IBM Inc, Armonk, NY) was used to conduct the statistical analysis. P values of <0.05 was used to indicate statistical significance.

Results

For the IQ evaluation, the observers' agreement was very good (ICC = 0.83; 95% CI 0.71-0.91). **Figures. 4** & **5** illustrate the ED and IQ values across the four phantom thicknesses. Across the studied kVp range the mean± SD ED, for underweight, standard, overweight, and obese phantom sizes, were 0.03±0.00, 0.07±0.01, 0.13±0.04, and 0.25±0.08 mSv, respectively. The mean± SD IQ values, for the underweight, standard, overweight, and obese phantom sizes, were 2.5±0.6, 2.1±0.5, 1.8±0.5 and 1.7±0.4, respectively. The one-way ANOVA demonstrated that there were statistically significant differences in the ED values between the various phantom thicknesses ($p<0.001$). Significant differences were found between underweight and overweight ($p<0.001$) and underweight and obese ($p<0.001$) phantom sizes. Moreover, there was a significant difference in ED between standard and obese ($p<0.001$), overweight and obese ($p<0.001$). Similar to this, there was a statistically significant difference in IQ scores between the various body part thicknesses ($p=0.006$). Post hoc t-tests revealed significant differences between underweight and overweight ($p=0.028$), underweight and obese ($p=0.007$) phantom sizes. Adding 6, 10, and 16 cm fat increased ED values by 80, 125 and 157 %, respectively and lowered IQ by 19, 34 and 41%, respectively.

Discussion

IQ and ED for adult supine abdominal radiographs were evaluated in relation to the effects of body part thickness under a variety of exposure conditions. Our results indicate that when imaging larger patients, standard techniques are in need of optimization.

According to the findings of this study, using higher tube potentials (105 and 110 kVp) for the various body part thicknesses resulted in significant reductions in ED while still achieving sufficient IQ for diagnosis. **Figure 4** demonstrates that ED decreases with increasing tube potential (kVp) values for the same phantom size. However, IQ decreases with increasing tube potential (**Figure 5**) and the highest IQ scores were observed at lowest tube potentials. This was contrary to standard clinical practice where radiographers often increase exposure settings, particularly the tube potential, when imaging larger patients to obtain higher-quality images. An explanation for the trends seen in our study is that lower energy photons (lower tube potentials) have a higher probability of being attenuated when compared to higher energy photons (higher tube potentials). This results in improved subject contrast for the image and an overall increase in IQ when photon energy is decreased. On the other hand, it was found that phantom size had an impact on both IQ and ED. IQ decreased with an increase in phantom size, whilst ED showed the opposite tendency.

To the best of the authors' knowledge, only two studies [33,34] have investigated how body part thickness affects IQ and radiation exposure during AXR. However, the types of the phantom, image detector, IQ evaluation method and radiation dose metric are different from our study.

In a study by Gatt et al.[34] IQ and radiation dose (KAP values) were investigated for different body part thicknesses (20, 25, 30 and 35 cm) during AXR. Signal to noise ratio (SNR), contrast to noise ratio (CNR) and an absolute visual grading analysis (VGA) approach were used for IQ evaluation. This study showed that as part thickness increase, KAP values increase and IQ declined. The highest IQ values were found at lower tube potentials (80 kVp), while 110 and 120 kVp were considered the optimum settings for producing adequate IQ with the lowest amount of radiation. Similar findings were observed within our research. However, the radiation dose was evaluated by calculating the ED which represents the stochastic health risk to the whole body, which is the probability of cancer induction and genetic effects when using of low levels of ionizing radiation. Moreover, we believe that our research has certain methodological advantages over the work by Gatt et al.[34] A relative VGA method was used in our work as opposed to the absolute VGA method used in the study by Gatt et al.[34] Using a relative VGA method is justified because it is expected to be less biased and more sensitive in detecting minute differences in IQ because of the presence of a reference image.

Kawashima et al. [33] examined the impact of increasing body part thicknesses on low contrast detail (LCD) detectability during AXR by using a CDRAD 2.0 phantom with four different polymethyl methacrylate (PMMA) slabs (10 , 15, 20 and 25 cm thickness). They found that as phantom thickness increased, LCD detectability decreased and vice versa. However, only one exposure at 80 kVp was used to image each phantom thickness, and other tube potentials were not considered. Additionally, the association between phantom size and LCD detectability values could not be adequately examined over a variety of clinically relevant acquisition parameters. Our research findings are equivalent to those of Kawashima et al.[33] and Gatt et al.[34] despite differences in the imaging protocols, types of phantom and types of IQ evaluation method.

Limitations

Our study does have several limitations, the use of only one kind of imaging system (digital radiography); however, future research may test different DR systems. The only acquisition parameter examined was tube potential, and more research is needed to fully understand the impact of source to image distance (SID), additional filtration, and grid ratio. Due to the lack of anatomical and pathological variety, using an anthropomorphic phantom is not a true representation of typical variations in the human body. Visceral fat, which is located between the organs, was not taken into consideration throughout our phantom modification nor dose modeling. The assessment of IQ was only subjective and did not include radiologists. The layers of fat were added to the anterior part of the phantom only, this would not represent the reality of fat accumulation between organs. A. further point is the absence of additional posterior fat, this could have affected our data collection in terms of the generation of scatter and could have been accounted for. A final consideration is the analysis of Likert scale IQ responses. Many different approaches have been described in the literature. Such differences could yield variations in interpretation and should be considered when reviewing our work. Trends in both IQ and ED have followed theoretical explanations. As with many optimization studies, the exact threshold for diagnostic IQ has not been definition and work in this area should continue, albeit it would be likely that there are a range of thresholds for different clinical indications.

Conclusion

In conclusion, IQ values declined significant as body part thickness increased, and the highest IQ values were found for lower tube potentials (70 and 75 kVp). ED values increased as phantom thickness increased and with lower tube potentials. Study data would support the application of higher tube potentials when imaging patients at increased body size and this would support the ALARA principle.

Conflict of interest

The authors have no conflict of interest.

Author statement

First author: Drafting the work or revising it critically

Second author: acquisition, analysis, or interpretation of data for the work

Third author: Drafting the work or revising it critically

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Figure 1. Photograph of the adult anthropomorphic abdomen phantom (A); the + on the image indicates the central ray location and the resultant radiograph (B).

Figure 2. Photograph describing the experimental setup of the phantom (A) and animal fat layers used for simulating different phantom sizes (B).

Figure 3. Description of the criteria utilised for the IQ evaluation.

Figure 4. ED values for various phantom thicknesses (18, 22, 26 and 32 cm) using a variety of tube potentials.

Figure 5. IQ values for various phantom thicknesses (18, 22, 26 and 32 cm) using a variety of tube potentials.