The validity and reliability of the exposure index as a metric for estimating the radiation dose to the patient.

Erenstein H.G. MSc [α, λ], Browne D. MSc [γ], Curtin S. PhD [β], Dwyer R.S. [δ], Higgins R.N. PhD [β], Hommel S.F. [α], Menzinga J. [α], Pires Jorge J.A. Msc [ε], Sauty M. [ε], Vries de. G drs [θ], England A. PhD [β]
α; Department of Medical Imaging and Radiation Therapy, Hanze University of Applied Sciences, Groningen, Netherlands
β; Directorate of Allied & Public Health, University of Salford, United Kingdom
γ; Radiographer at Tameside and Glossop Integrated Care Unit NHS Foundation Trust, United Kingdom
δ; Department of Medical Imaging and Radiation Sciences, University of Johannesburg, South Africa
ε; School of Health Sciences (HESAV), HES-SO University of Applied Sciences and Arts Western Switzerland
θ; Department of Medical Imaging and Radiation Therapy, Inholland University of Applied Sciences, Haarlem, Netherlands

λ; Corresponding author; h.erenstein@pl.hanze.nl, Petrus Driessenstraat 3, 9714 CA Groningen, Netherlands

ABSTRACT

Introduction: With the introduction of digital radiography, the feedback between image quality and over-exposure has been partly lost which in some cases has led to a steady increase in dose. Over the years the introduction of exposure index (EI) has been used to resolve this phenomenon referred to as 'dose creep'. Even though EI is often vendor specific it is always a related of the radiation exposure to the detector. Due to the nature of this relationship EI can also be used as a patient dose indicator, however this is not widely investigated in literature.

Methods: A total of 420 dose-area-product (DAP) and EI measurements were taken whilst varying kVp, mAs and body habitus on two different anthropomorphic phantoms (pelvis and chest). Using linear regression, the correlation between EI and DAP were examined. Additionally, two separate region of interest (ROI) placements / per phantom where examined in order to research any effect on EI.

Results: When dividing the data into subsets, a strong correlation between EI and DAP was shown with all R-squared values > 0.987. Comparison between the ROI placements showed a significant difference between EIs for both placements.

Conclusion: The relationship between EI and radiation dose is dependent on a wide variety of factors. EI can be used as a dose indicator but further research into the factors which influence EI is required before implementing EI as a dose indicator in practice.

Keywords: Exposure index; radiation dose; radiography

INTRODUCTION

Ever since the discovery of X-rays in 1895 by W.C. Röntgen the field of medical imaging has been in a state of constant development. Of these developments the switch from analogue to digital imaging has probably been the most impactful and has brought numerous benefits. Of these benefits the wide dynamic range of the detectors introduced a new option for dose reduction, but paradoxically introduced the concept of dose creep (1).

Due to the wide dynamic range of most digital detectors, modern systems are less likely to suffer from under- or over-exposure. An increase in radiation dose results in less noise and therefore a more ecstatically pleasing imaging, the initial introduction of digital systems was followed by a gradual increase in radiation dose, often referred to as 'dose creep'. To help resolve the issue of dose creep detector exposure indicators were introduced by vendors.

Even though the introduction of exposure indicators has been widespread, the use of vendor specific indicators has been shown to be confusing for practitioners (2). To battle these inconsistencies a push has been made for the development of a single Exposure Index (EI)(2). However, the use of EI as a patient dose indicator is still not recommended.

Traditionally, patient dose from general radiography imaging is often determined by using the dose area product (DAP) meter mounted directly under the diaphragm. However, the inherent dose dependent nature of the EI should have a relation with the DAP, which implies a possible more intricate use for the EI in radiation safety.

Several studies have shown the relationship between EI and the entrance surface dose (ESD) under varying circumstances such as exposure parameters, anatomy and body habitus (2,3). However, limited research had been performed in order to validate the EI in relation to the DAP under the combination of similar parameters.

The aim of this research project was to assess the validity and reliability of using EI to estimate the DAP, and therefore patient dose, when manipulating body habitus, exposure time product and tube potential.

METHODS

The study was conducted in the School of Health & Society at the University of Salford. A Wolverson Acroma Arco ceiling suspended general X-ray system (Arcoma, Annavägen, Sweden) with a retrofitted Konica Minolta DR unit (Konica Minolta Medical Imaging USA INC, Wayne, NJ, USA) was used, which included a Cesium Iodide (CsI) Aero image detector, was used for the data acquisition. The built-in DAP meter of the Wolverson X-ray unit was used for the acquisition and measurement of the DAP in $mGy.cm^2$ in order to estimate the patient ESD. Image acquisition was achieved using the Konica Minolta CS7 software version 1.22R01_011. All equipment used was part of a routine quality assurance test, that included checks on tube output, tube potential, time consistency, tube potential accuracy and linearity, all of which were within the expected tolerances.

The study was performed using two adult chest and pelvis anthropomorphic phantoms. The chest phantom used was the adult multipurpose chest phantom N1 'LUNGMAN', manufactured by Kyoto Kagaku. The pelvis phantom used was an adult lower sectional torso RS-113T manufactured by Radiology Support Devices. Both phantoms have an x-ray absorption very close to human tissues and are anatomical representable of the average human male as noted by both manufacturers. The chest and pelvis examinations were chosen as they are amongst the most frequently examined anatomical regions in general radiography(4). In addition, both require different exposure factors

which provides this research with an additional approach regarding the EI – DAP relation at different voltage and dose levels.
In order to assess the influence of body habitus on EI and DAP two different body habitus were simulated by adding animal fat to the anthropomorphic phantoms, following similar methods used in previous research (5). The thickness of additional fat was chosen to roughly simulate an overweight female as described by the NHS (6). This resulted in an addition of 2 cm to the chest phantom, and 10 cm of fat to the pelvis phantom.

Both phantoms were placed in AP position on the examination table with the image detector in the Bucky tray with a non-removable grid. The chest and pelvis phantoms were centered and collimated following the guidelines described by Clark's Radiographic Positioning.

Two millimeters of additional aluminum filtration were included for the chest acquisitions, and 1 mm Al with 0.1 mm Cu for the pelvis. This filtration was selected based on the clinical experience of the international research team conducting the experiment. In order to ensure stable exposures, the exposure time product was inputted manually, no automatic exposure control was used.

In addition to the effect of body habitus and exposure time product the influence of tube voltage (kVp) was investigated. These parameters were chosen because both tube voltage and exposure time product can have a significant influence on patient and detector dose. The exposure time product and voltage variations were chosen to assess the influence of these across a broad spectrum of acquisition parameters, as shown in **Table 1**. Patient habitus was included as its effect on EI has not been widely investigated. All the variations in tube voltage, exposure time product and body habitus resulted in 420 data points.

Table 1: Parameters used (variables used for DAP validation highlighted using *)

Pelvis		Chest	
Tube voltage (kVp)	Exposure time product (mAs)	Tube voltage (kVp)	Exposure time product (mAs)
55 *	10 *	90 *	0.8*
65	20	100	1.0
75 *	32 *	110 *	1.2 *
85	40	120	1.4
95 *	50 *	130 *	1.6 *
105			1.8
115			2.0

In order to minimize the influence of other parameters the collimation (as described), SID (120 cm), focus (large), grid and post-processing parameters were kept constant, all of which were chosen to represent clinical practice.

To validate the reliability of the DAP meter, five measurements were taken with low, medium and high exposures, for each of the anatomical areas (marked in **Table 1 using ***). The mean values and relative standard deviations were calculated in order to affirm the DAP reliability and validity.

EI measurements were performed using two region of interests (ROI), drawn using the DR workstation. The first measurement covered the entire irradiated area (**Figure 1A & 1C**) and the second covered a reproducible part of anatomy of both areas to ensure consistency (**Figure 1B & 1D**). This second set of measurements was acquired to investigate the influence of the ROI

placement on the resultant EI value. The chest included the entire lung fields for the second ROI measurement, whereas the pelvis was set to include both femoral heads and iliac fossa.

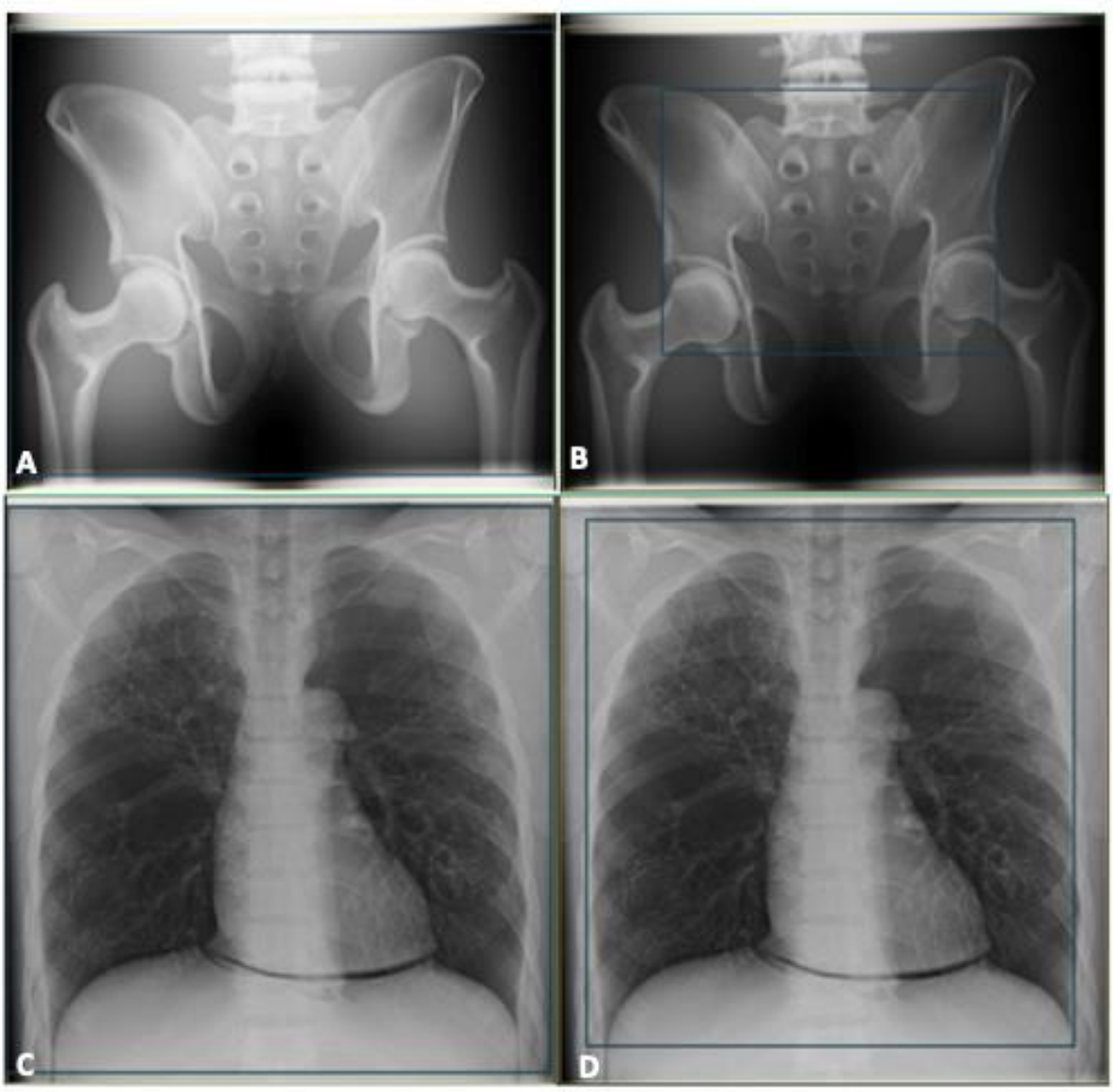

Figure 1: Different ROI placements, A & C show the ROI placed over the whole irradiated area, whilst B & D show the ROI places over the anatomic area.

The entire data set was analysed using SPSS Version 25.0 (IBM Inc, Armonk, NY). The significance between the different ROI placements was assessed using the Wilcoxon signed-rank test.

The correlation between EI and DAP for the entire data was calculated using linear regression expressed using R-squared. In addition to the whole dataset, several subsets were analysed (e.g. body habitus, anatomical region (chest & pelvis) and different tube voltages).

RESULTS

Before the data acquisition, DAP validation was performed for both the chest and pelvis phantom. Three exposures were tested, ranging from low to high exposures, for both the chest and pelvis as mentioned in Table 1. For the low chest exposures, the average DAP was 22.4 mGy.cm^2 with a

relative standard deviation of ± 2.5%. For the medium exposure of the chest, the average DAP was 55.4 mGy.cm² with a relative standard deviation of ± 1.0% and for the high exposure an average DAP of 102 mGy.cm² was measured with a relative standard deviation of ± 0.7%. Regarding the pelvis exposures the resulted average measured DAPs and relative standard deviations were 86.6 mGy.cm² (± 0.6%), 667 mGy.cm² (± 0.1%) and 1800 mGy.cm² (± 0.1%), respectively.

The total number of exposures resulted in a dataset consisting of 420 points consisting of DAP and both ROI placements. One deviating measurement (0.2% of the total measurements) was discovered in the pelvis dataset at 80 kVp and 10 mAs with an EI of 199.60 where other two of three exposure measurements are 120.1, this was most likely an error in notation but other causes could not be excluded. Because of the minor nature in relation to the complete dataset and the lack of a clear explanation it was not excluded.

A Wilcoxon-signed rank test between the two ROI placement situations showed a significant difference in EI between both sets ($P < 0.05$). As there was a significant difference separate regression analysis were performed for both datasets.

The regression of the whole dataset shows a R-squared of 0.506. When the set is divided between non-fat and fat it shows an R-squared of 0.866 for non-fat and R-squared of 0.411 for fat. Dividing the set into anatomical regions it shows an R-squared of 0.887 for the chest and an R-squared of 0.554 for the pelvis as shown in **Figure 2**.

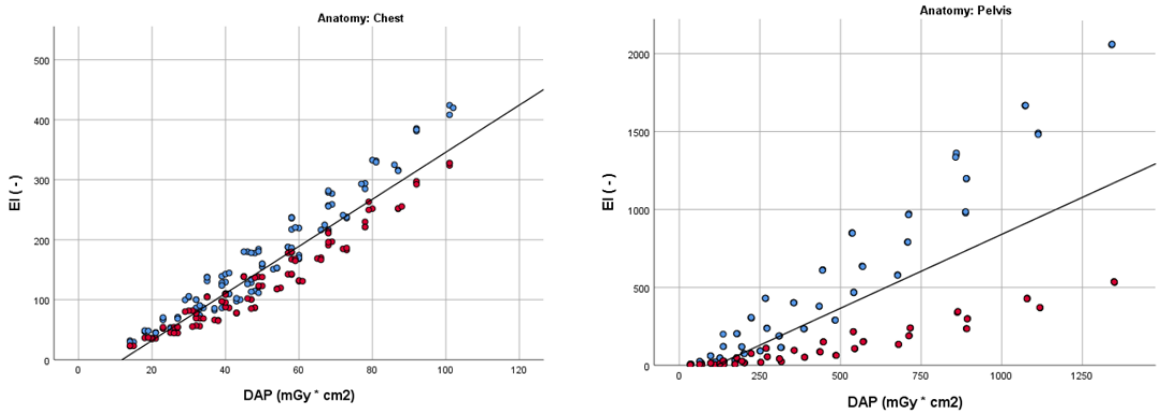

Figure 2: EI vs DAP for all data points on Chest (left, R-squared 0.887) and Pelvis (right, R-squared 0.554) phantoms both without fat (blue) and with (red).

When dividing the whole dataset into anatomic regions, body habitus and ROI placements, this resulted in a total of eight subsets. These eight subsets can be further divided into tube voltage. All eight R-squared values are above 0.987, showing a strong correlation between EI and DAP this is visually represented in **Figure 3**.

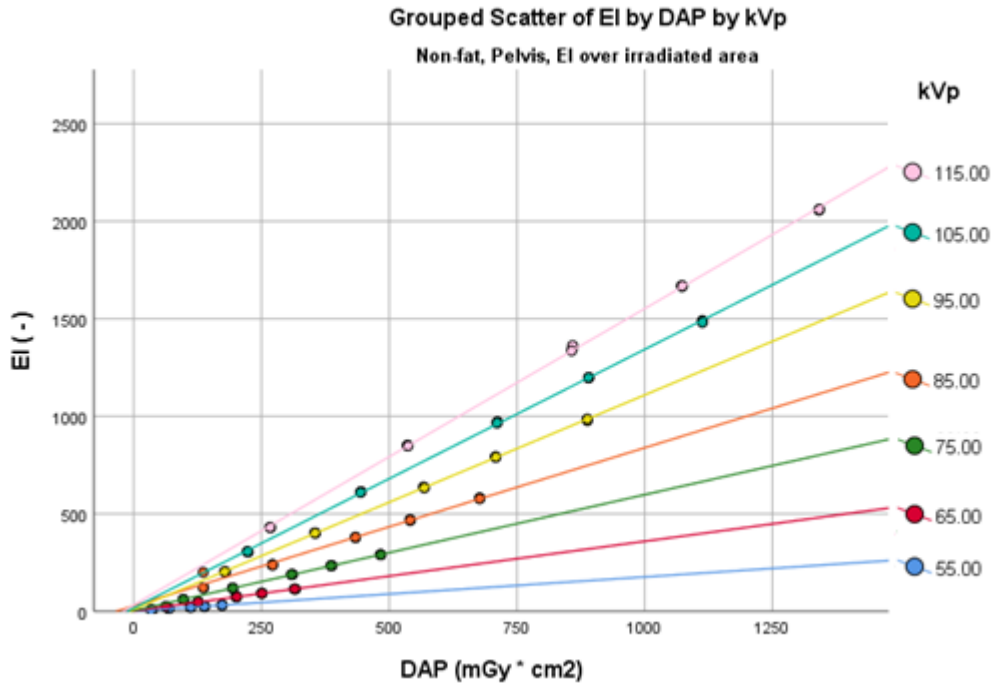

Figure 3: EI as a variable of the DAP categorised by the kVp on a Pelvis without Fat added measured by using a ROI placement over the whole irradiated area.

For all the eight subsets the regression coefficient per data subset are plotted against the tube voltage as shown in **Figures 4 & 5**.

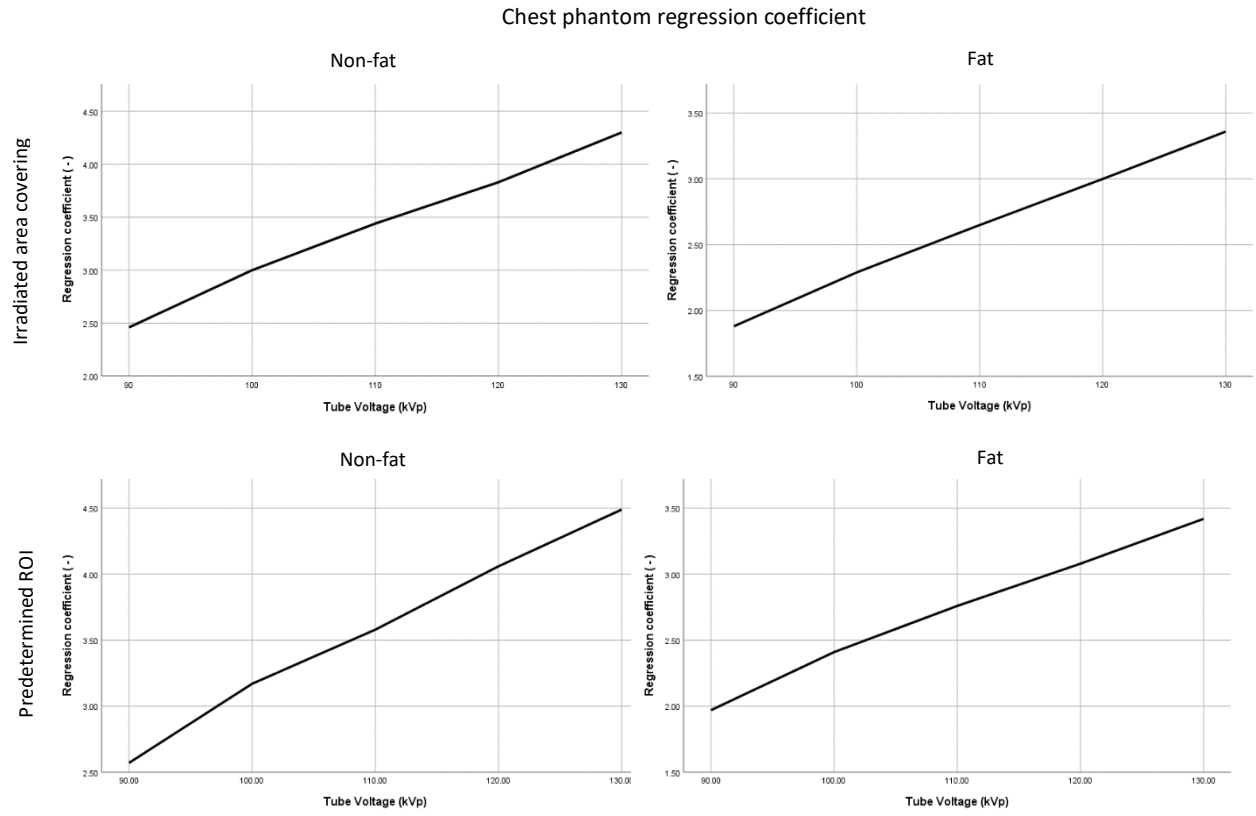

Figure 4: Regression coefficient as a function of tube voltage for all chest phantom subsets.

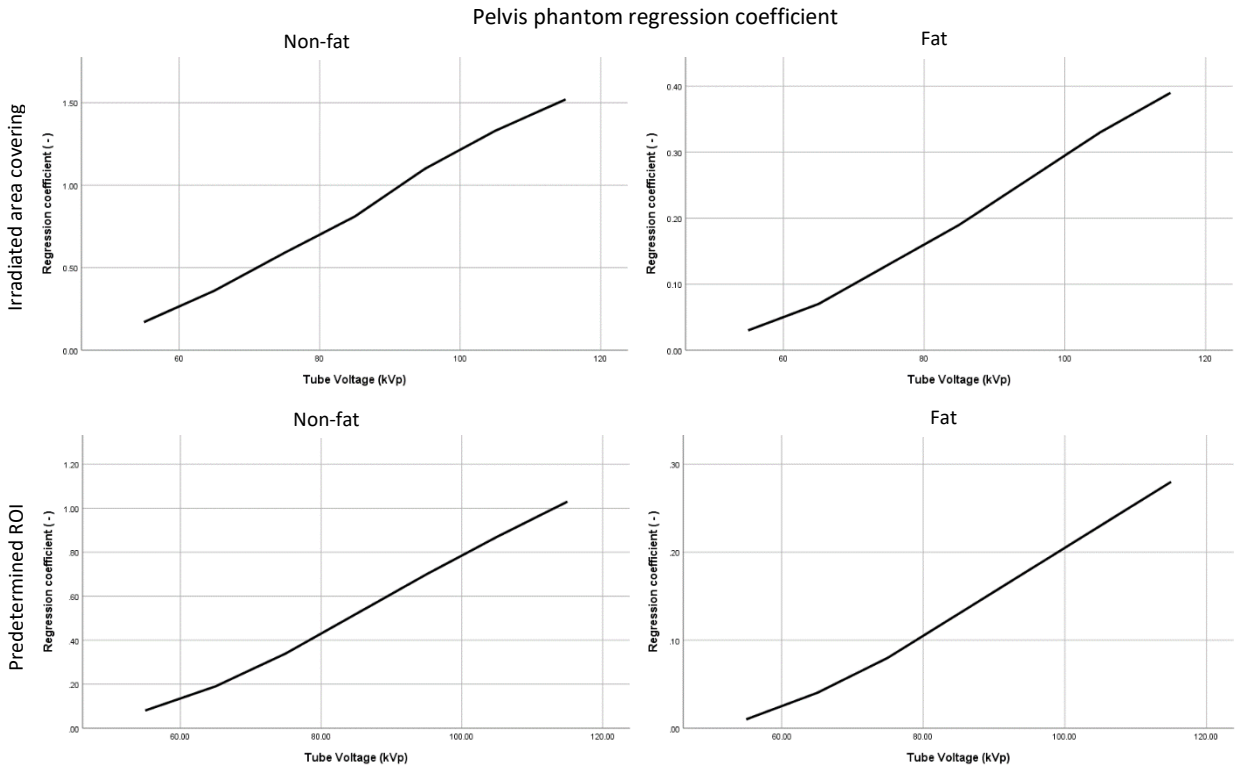

Figure 5: Regression coefficient as a function of tube voltage for all pelvis phantom subsets.

DISCUSSION

The research study was performed to validate the relationship between EI and DAP. The results show that it is possible to estimate the DAP, and with that the patient dose, based on a given EI value. However, the linear relationship between EI and DAP is dependent on multiple variables, of which body habitus is the most influential.

This is clearly expressed by the R-squared values within the various data subsets of anatomical region and body habitus. The R-squared of the entire data set, the correlation between EI and DAP is moderate (0.506). Once the data is separated, the effect of body habitus on the EI values is clearly demonstrated because the correlation without additional fat is very strong (0.866) as opposed to the weak correlation (0.411) when additional fat is added in two different thicknesses per anatomical region. This is significant because the patient dose can be estimated using EI but patient habitus must be taken into consideration. Depending on the known variables, DAP and EI can be estimated relatively simply, using the appropriate slope resultant from regression.

Previous studies substantiate these findings, as a strong relationship has been proven between EI and ESD (R-squared value of 0.67), suggesting that EI can be used for estimating absorbed patient dose (3). However, literature suggests that EI values still differ from manufacturer to manufacturer, this lack of a universal EI provides further concern in the implementation of EI as a dose indicator (7). Therefore, before using the EI as a dose indicator, experiments and further research should be performed on various other DR systems since only a Konica Minolta CS7 system was tested in this study. It should be noted that Konica Minolta CS7 implements the IEC62494-1 in order to calculate the EI, a linear approach which is common for other vendors as well.

This study has considered three different factors in order to further investigate the relationship between EI and DAP. Compared to other studies, which changed one factor when investigating this

relationship and used other anatomical areas of interest, for example the knee (8). Though a linear relationship was proved in the current study between the EI and DAP for both the pelvis and chest, the results are likely to be applicable for other anatomical regions too.

In addition to the three included variables in this research was focused on the DAP measurements compared to the ESD in other studies. The DAP was chosen as the preferred measurement because measuring the ESD would require the placement of a dosimeter over the anatomical area of interest. Such a modification to the study protocol would likely influence the EI value, as there would be an electronic component within the resultant image. Additionally, the use of the DAP is widely implemented in patient dose legislation regarding the diagnostic reference levels (DRL's) (9,10).

One important note should be placed on pathology. The anthropomorphic phantoms gave a representation of the human anatomy but lacked in representing different pathologies and anatomies and therefor the effect it may have on EI ^{2}. Previous studies have shown that the EI values may vary for different pathologies and because of this should be considered when aiming for optimal EI values (2).

Any practical implementation of EI as a dose indicator is not only limited by the effect of pathology but also by ROI placement. This study has shown the position of the ROI is of influence on the EI in this system, therefore ROI placement for EI measurements should be placed using clear definitions if the system used determines the EI within a given ROI. Please note that there are vendors which supply systems which determine the EI from the whole detector instead of within a given ROI. In addition to this any differences in anatomy, pathology or patient positioning could influence the measurements within a determined ROI. Finally the variation in collimation and SID in practice will influence both the values and relationship between the EI and DAP, this should be taken into account.

In view of the linear relation between EI and DAP there is likely to be an equal relationship between EI and exit dose within the exposure parameters used. Given this, a possible future implementation of EI as a dose indicator could involve the EI as an exit dose indicator. This, in combination with the ESD calculated from DAP could be used to estimate the absorbed patient dose from information available in the DICOM-header.

CONCLUSION

This study has shown the feasibility of using EI as a dose indicator, however before clinical implementation, it is important that the influence of other factors on the EI values are investigated more thoroughly. These factors include a wider range of body habitus, ROI positioning, differences between manufacturers' technology, variations in anatomy and the presence of pathology.

ACKNOWLEDGMENT
The authors would like to acknowledge Prof. Peter Hogg and Dr. Annemieke van der Heij-Meijer for facilitating the research and providing feedback. Additional acknowledge go towards the Optimax steering committee and supporting staff for organising Optimax 2019 at the University of Salford.

REFERENCES

1. Ma WK, Hogg P, Tootell A, Manning D, Thomas N, Kane T, et al. Anthropomorphic chest phantom imaging - The potential for dose creep incomputed radiography. Radiography. 2013;19(3):207–11.
2. Mothiram U, Brennan PC, Lewis SJ, Moran B, Robinson J. Digital radiography exposure indices: A review. J Med Radiat Sci. 2014;61(2):112–8.
3. Radiography C. Exposure Index and Entrance Surface Dose of ANSI Chest Phantom with I nternational J ournal of A llied M edical S ciences and C linical R esearch (IJAMSCR) Exposure Index and Entrance Surface Dose of ANSI Chest Phantom with. 2018;(January):2–9.
4. Ener C, Doses EP, Exposure M, Datamed D. DDM2 Project Report Part 1 : European Population Dose RADIOLOGY IN EUROPE - GENERAL DATA. Ddm2 [Internet]. 2010;Part1: Eur. Available from: http://www.eurosafeimaging.org/wp/wp-content/uploads/2015/05/Radiation-Protection-180.pdf
5. Alzyoud K, Hogg P, Snaith B, Flintham K, England A. Impact of body part thickness on AP pelvis radiographic image quality and effective dose. Radiography [Internet]. 2019;25(1):e11–7. Available from: https://doi.org/10.1016/j.radi.2018.09.001
6. Adult overweight and obesity - NHS Digital [Internet]. [cited 2019 Dec 27]. Available from: https://digital.nhs.uk/data-and-information/publications/statistical/statistics-on-obesity-physical-activity-and-diet/statistics-on-obesity-physical-activity-and-diet-england-2019/part-3-adult-obesity
7. Seibert JA, Morin RL. The standardized exposure index for digital radiography: An opportunity for optimization of radiation dose to the pediatric population. Pediatr Radiol. 2011;41(5):573–81.
8. Butler ML, Rainford L, Last J, Brennan PC. Optimization of exposure index values for the antero-posterior pelvis and antero-posterior knee examination. Med Imaging 2009 Image Perception, Obs Performance, Technol Assess. 2009;7263(September 2014):726302.
9. European Commission. Radiation Protection N ° 180 Medical Radiation Exposure of the. Dir Energy [Internet]. 2014;1–181. Available from: https://ec.europa.eu/energy/sites/ener/files/documents/RP180.pdf
10. National Diagnostic Reference Levels (NDRLs) from 19 August 2019 - GOV.UK [Internet]. [cited 2019 Dec 27]. Available from: https://www.gov.uk/government/publications/diagnostic-radiology-national-diagnostic-reference-levels-ndrls/ndrl