ORIGINAL ARTICLE

A SINGLE-CENTRE EXPERIENCE OF RADIATION DOSE MITIGATION IN COMPUTED RADIOGRAPHY USING DOSE CHARTS

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ABSTRACT

BACKGROUND: Digital radiographic technology comprising computed radiography (CR) and direct digital radiography (DDR) have significantly reduced repeats due to inappropriate exposure factors in film-screen radiography (FSR). The opportunity cost, however, is the introduction of dose creep which jeopardizes radiation protection. Minimizing or elimination of dose creep is, therefore, imperative but this is difficult to achieve for the radiographer/technologist. A radiographic exposure chart can forestall dose creep as it minimizes unnecessary arbitrariness in the selection of exposure intensity. This work was an attempt to use exposure index (EI) and deviation index (DI), two digital imaging software concepts accessible at the workstation, to derive an exposure chart for addressing dose creep in computed radiography. **RESULTS:** Three hundred sthenic and hyposthenic adult patients and 150 paediatric patients were enlisted in this study, and with focus on seven specific anatomical regions. With standard exposure index of 250 - 350, deviation index was reduced from a range of -11.1 to +8.1 to a lower range of -2.6 to +1.4 without loss in image quality. There was however, an 8 to 28 % upward adjustment in tube current (mA) to reduce quantum noise. A new exposure chart was derived at the end of the study that has great potential to address digital dose creep in hyposthenic and sthenic Negroid subjects. **CONCLUSION:** Dose creep in digital radiographic technology can be mitigated with an empirically-derived exposure chart.
Keywords: Dose, Radiography, Charts, Exposure, dose creep, ALARA, Digital Radiography

Introduction

Radiographic imaging involves a tradeoff between dose and image quality. This tradeoff entails that images of high diagnostic quality should be generated using dose that are as low as reasonably achievable (ALARA).[1] However, wide variation in dose, as well as high rates of repeats between radiographers within and across facilities locally and globally,[2,3,4] suggest that arriving at a perfect compromise is often difficult.[5]

Radiation dose is influenced by multiple patient and machine parameters. Patient s wide range of body habitus, especially in paediatrics, pose a challenge to radiographers when selecting these exposure parameters.[6,7,8] Challenges from x-ray machine arise from the difficulty in skillfully combining tube potential (kVp), tube current (mA), time for the flow of current (mAs), and focus-detector-distance (FDD).[4] Tube

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potential and current determine beam intensity, and its reduction is the most significant way of reducing patient dose. A 50% reduction in tube current reduces dose by half because current-time settings (mAs) are proportional to the photon fluence and beam energy.[4,9,10] Although this tip is well known to radiographers, it is tough to implement due to the risk of image noise and consequently, a repeat exposure.[4]

In film-screen radiography (FSR), inappropriate selection of intensity often compromises image quality due to narrow exposure latitude of silver halide films which is a snare for repeats. Digital radiographic technology, introduced in the mid-1980s and comprising computed radiography and direct digital radiography,[11] has however, helped to reduce repeats in FSR from 10 - 15 % down to 3 - 5 % due to wider exposure latitude (WEL), higher detective quantum efficiency (DQE) and post-processing features.[2,3] However, the gain in wider exposure latitude is somewhat compromised through a new challenge of dose creep.[7,11,12]

Dose creep goes undetected because digital systems mask inappropriate selection of intensity. Whereas, underexposure introduces noise (quantum mottle) into digital images and can be detected, overexposure often goes undetected because image resolution remains optimum.[7,11,12] The masking of overexposure in a digital radiographic system is what is now termed dose creep, [7,12] a gradual increase in x-ray exposures over time that results in increased radiation dose to the patient. This occurs where judgment to determine the correct radiographic exposure factors is needed when taking into account a large range of patient sizes.[6,8] Unless radiographers share common views on image quality and acceptance criteria, dose creep may persist.[3]

To address the challenges of dose creep, manufacturers of digital radiography systems, the International Electrotechnical Commission (IEC) and the American Association of Physicists in Medicine (AAPM) developed the concept of exposure index (EI) and deviation index (DI) as standards to indirectly track radiation exposure in a digital detector.[7,13] The EI stipulates acceptable noise levels in images,[12] while DI gives feedback on whether dose applied to a detector is lower or higher than the standard exposure index originally configured. Negative and positive DI indicate reduced and increased exposures, respectively.[13] The ideal value of EI is configured into the workstation by vendors or radiographers. Once there is an ideal EI, there should be no deviation in exposure (zero DI), but this is impracticable due to varying anthropotechnical parameters of patients and machines.[7] Despite the novel and helpful concepts of EI and DI, repeats still persist in digital systems, especially in computed radiography which is the more common modality.[3,14,15,16]

Exposure and deviation indices are retrospective quality control tools that only predict, but do not stop dose creep and repeats. An exposure chart is, however, used prospectively, and allows for accurate determination of dose to a wide range of patients.[17] These charts are recommended internationally and can reduce arbitrariness in exposure factors for similar body habitus and equipment as well as reduce the range of deviation index.[6]

Computed radiography was installed in the facility in focus in 2014, but it was in 2016 that a centre-specific exposure chart was derived. Although the exposure chart eliminated positive DI (overexposure), the range of negative DI was observed to be wide, rather than being narrow or zero. The implication is that although dose creep was mitigated, the ideal dose was not being applied. The present work is an attempt to improve on the previous exposure chart,[18] by identifying exact tube potentials (kVp) capable of narrowing or reducing negative DI to zero.

The facility is a regional teaching hospital in southeast Nigeria established in the early 1990s to cater for a population of about three million persons. It had a staff strength of about 2,500 persons. The radiology department had $\leq$ 120 staff with radiographers (n $\leq$ 52) and radiologists (n $\leq$ 35) cons-tituting over 70 %. Modalities available as at the time of the study were five ultrasound scanners, a 0.2 Tesla magnetic resonance imaging (MRI) scanner, two mammography machines, a static and mobile fluoroscopy units, a 4-slice computed tomography scanner, and two static and three mobile x-ray units. Equipment was purchased from General Electrics (GE) and was installed by VAMED, their partners, in 2012. Computed radiography supplanted automatic processing of images in 2014. Annual throughput of patients for all modalities was $\geq$ 55,000 with 18,482 (33.6 %) being maximum contribution from computed radiography in 2017 - 2018.

Subjects, Materials & Methods

Ethical approval was obtained from the institutional, Departmental Research Ethics Sub-Committee on 8th February 2016 (RAD/EZ/ETH/002). Also, all patients included in the study gave informed, written consent. Caregivers gave consent on behalf of patients aged ≤17 years. Radiographers who posed for pictures also gave consent for their images to be published. This multi-stage work was undertaken from January to May 2019. A GE silhouette VR, high fre-quency, 3-phase, static x-ray machine with a maximum tube potential of 140 kVp, tube current of 600 mA, and total filtration of 2.7 mm AL was involved.

The x-ray machine was manufactured in 2003 and installed in 2012. Within that time frame, it underwent several preventive and restorative maintenance, as well as re-calibrations. The machine had incorporated under-couch and erect potter-bucky detector trays. Other equipment and accessories were a computed radiography digitizer (model CR 12-x) made by Agfa Healthcare (Belgium) in December 2013. A 25 x 30 cm (10 x 12 inch) and 35 x 43 cm (14 x 17 inch) standard photostimulable phosphor imaging plates (model CR MD4.0T General) also by Agfa Healthcare (Germany). The CR system was linked to the x-ray machine in October 2014.

Exposure factors for x-ray which were derived at the centre in 2016 and had been in use there were retrieved and documented in a data collection sheet. Next, a radiologist with ≥ 15 years cognate experience identified at the workstation, three most diagnostically useful original/native images from those generated between 2016 to 2018. Seven anatomical regions with high throughput were considered, making a total of twenty-one images. The range of EI on those images were noted. Exposure index is numerical and with no negative or positive upper limits. It automatically appears on an image once it is digitally processed at the workstation. The value is neutral of any meaning until the radiographer analyses it in line with other imaging parameters. If narrow range of exposure parameters on x-ray machines are used for fairly similar body habitus, EI should be similar or nearly so. If the resulting image is not rejected by a reporting radiologist due to quantum noise, then the EI index is considered appropriate to meet imaging expectations. In this work, the range of EI for similar anatomical regions in three most diagnostically useful images, as determined by a radiologist, was noted. The range of deviation indices was also noted. Deviation of x-ray images generated between January to May 2019 from pre-determined average EI will be the focus of the work. Although positive DI will always produce diagnostically useful images due to increased dose which reduces noise, some negative DI will compromise image quality by introducing quantum mottles/noise. The focus of the study was on negative deviation index that will not compromise image quality. The previous exposure chart was derived solely from that. Current exposure chart shall be derived from narrower range of negative and positive DI that tended towards zero.

The next stage was a prospective computed radiography examination of 300 adult and 150 paediatric, ambulant, seemingly healthy patients aged ≥12 years, between January and May 2019 in our facility. Body mass index (kg/m^2) was calculated from weight (kg) and height (cm) which were read off to the nearest 0.5 kg and 0.1 cm (1 mm), respectively. There was a multi-stage categorization of patients. The first sorting was into adults and paediatrics. The next was a re-categorization of adult into body habitus in an ascending manner of size; asthenic, hyposthenic, sthenic and hypersthenic. Hyposthenic and sthenic patients were enlisted in this work because they tended towards average sizes. Paediatric cases were operationalized considered as asthenic in terms of size (Fig. 1).

Patients were examined with fixed focus-detector-distance (FDD), tube current (mA) and tube current-time product (mAs) while using variable tube potential (kVp) for each subsequent patient. As kVp increased, deviation index tended from negative towards zero (average exposure index). The procedure was halted when the target sample size was reached. Radiographers who generated images and radiologists who wrote reports were aware of the research but were blinded to its objectives. Data were analyzed with statistical packages for social sciences, version 20.0 (SPSS Incorporated, Chicago, Illinois, USA).

Results

Machine technical parameters and that of some accessories are summarized in (Tab. 1). (Tab. 2) summarizes detector sizes available for investigation and those used. Due to erroneous coding of detectors for many decades as a result of inattention to details during conversion from imperial to metric system, the corrections are now given. As shown in (Tab.3), the annual average throughput of patients for x-ray was between 14,602 to 18,482 out of total throughput of ≥ 55,000. There was a marginal increment as the years went by. Seven anatomical regions were included in the work (Tab. 4). Paediatric patients were aged 12 years and above while adults were between 18 to 70 years. Adult patients were marginally obese (Tab. 5). (Tab. 6) gives old and new exposure parameters. The old exposure chart (EC) had negative deviation index in all examinations except paediatrics. The inference is that a lower than optimum dose was deployed, except for paediatrics where both lower and higher dose were used. There was noticeable reduction in DI with increasing tube potential (Tab. 6). Body habitus was clearly defined with extremes of hypersthenic and asthenic excluded (Fig. 1). Torso shielding during head and neck radiography complements exposure chart by attenuating scattered radiation (Fig. 2). Visual guidance to determine dose creep is misleading. A deviation index is a more reliable guide (Fig. 3 - 6).

Parameters	Available choices	Commonly used by radiographers
FDD (cm)	90, 100, 150, 180	100/150/180
kVp	40 - 150	50 - 90
mA	10 - 600	100 - 250
Time (s)	0.001 – 6.3	0.02 - 0.2
mAs	0.5 - 630	5 - 25
Exposure index	Infinite	220 - 565
Deviation index	Infinite	-12.5 to +2.1

Table 1: Exposure factors and accessories involved in radiographic examination.

Parameters	Imperial dimensions (inch)	Metric dimensions (cm)	Erroneously coded in literature as (cm)	Remarks
Small (not used for this study)	8 x 10	20 x 25	18 x 24	18 x 24 cm is small detector size for use in mammography
Small (not used for this study)	10 x 12	25 x 30	24 x 30	24 x 30 cm Is large detector size for use in mammography
Medium (not used for the study)	14 x 14	35 x 35		
Medium (not used for the study)	6 x 17	15 x 43		
Medium (not used for the study)	12 x 17	30 x 43		
Large (mostly used in the study	14 x 17	35 x 43		

Table 2: Detector (PSP) sizes commonly used in x-ray imaging and in the study

Parameters	Adults		Paediatrics		Total
Period	Male	Female	Male	Female	
2012 - 2014	5,548	7,008	876	1,170	14,602
2015 - 2016	6,440	7,761	990	1,323	16,514
2017 - 2018	7,695	7,741	1,374	1,672	18, 482
Total	**19,683**	**22,510**	**3,240**	**4,165**	**49,598**

Table 3: Average annual throughput of patients for computed radiography

Group	Adults		Paediatrics		Total
	Male	Female	Male	Female	
Skull	27	23	12	13	75
Spine (L/S)	25	25	13	12	75
Chest	22	28	11	14	75
Abdomen	25	25	12	13	75
Pelvis	26	24	12	13	75
Femur	25	25	11	14	75
Total	**150**	**150**	**71**	**79**	**450**

Table 4: Frequency of patients enlisted and examined in this study

Parameters	Adults (n = 350)		Paediatrics (n = 175)	
	Range	Mean ± SD	Range	Mean ± SD
Age (years)	18 - 70	56 ± 18.4	12 - 17	13 ± 1.2
Height (cm)	151 - 175	163 ± 6.2	145 – 167	154 ± 6.0
Weight (kg)	55 - 89	74.4 ± 6.4	38 - 63	48.6 ± 12.6
Body Mass Index (kg/m^2)	24.2 - 37.4	32.32 ± 4.05	16.2 – 27.2	21.30 ± 5.02

Table 5: Demographic characteristics of subjects examined

Parameters	2017 – 2018 CR exposure factors (old) (Ref:18)					2019 CR exposure factors (new)					
	FDD	kVp	mA	mAs	DI	FDD	kVp	mA	mAs	EI	DI
Spine (L/S)	90 - 100	94	250	20	-5.2/-0.2	100	100	250	20	350	-1.2/0
Abdomen					-8.5/0	100	92	250	20	350	-2.6/0
Skull	90 - 100	70	180	8.5	-6.2/-1.5	100	85	250	8.5	350	-0.8/+0.2
Chest (adult)	150 - 180	73	230	10	-2.6/-0.5	180	82	250	10	350	-1.4/0
Pelvis	90 - 100	75	220	12.8	-9.5/-0.8	100	82	250	12.8	350	-1.6/0.2
Femur	90 - 100	75	200		-5.2/-0.8	100	80	250	10	300	-0.8/0
Chest (paediatrics)	150	65	220	6.5	-11.1/+8.1	150	65	220	5	250	-2.2/+1.4*

*Deviation index was narrowed yet dose creep was not completely eliminated

Table 6: Previous (2016) and presently-derived expsosure charts

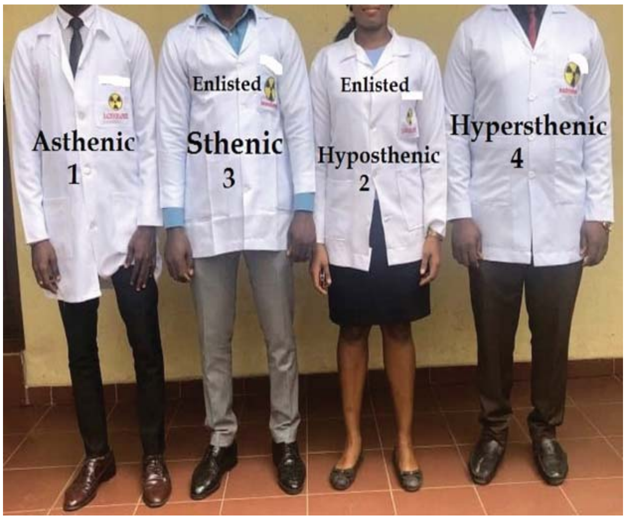

Figure 1: Different body habitus as used in the investigation

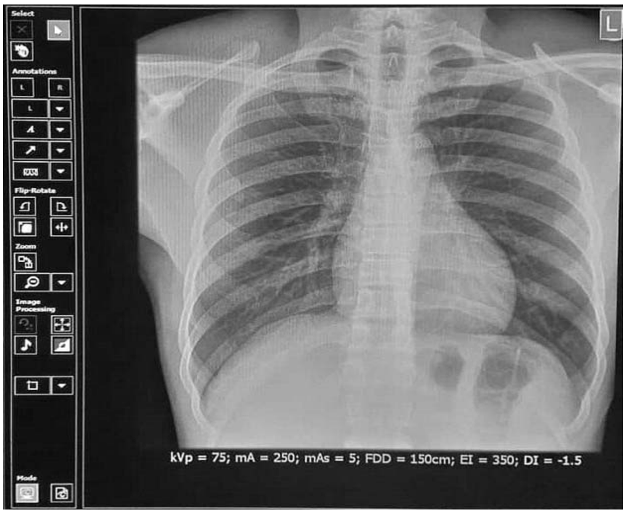

Figure 3: Computed radiography image with negative deviation index have reduced optical density compared to those with positive deviation index

Figure 2: Torso shielding during head and neck radiography complements exposure chart by attenuating scattered radiation

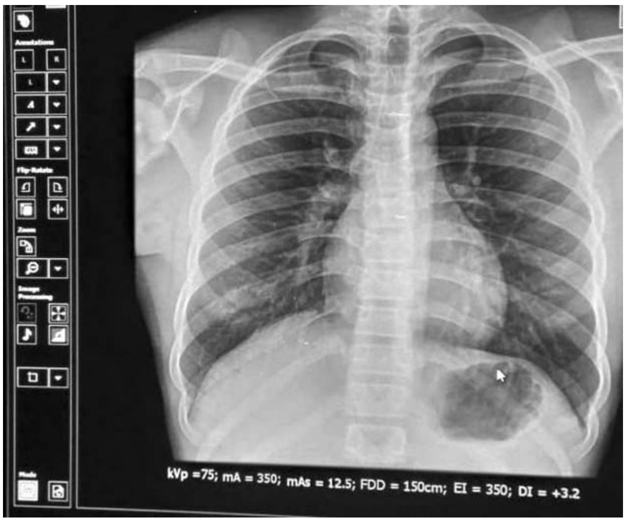

Figure 4: Computed radiography image with positive deviation index have increased optical density compared to those with negative deviation index

Figure 5: Abdominal image with narrow deviation index is barely different from that with wider deviation index

Figure 6: Abdominal image with wider deviation index is barely different from that with narrow deviation index

Discussion

Digital radiographic technology comprising computed radiography (CR) and direct digital radiography (DDR) have significantly reduced repeat due to inappropriate exposure factors in film-screen radiography (FSR). The opportunity cost however, is the introduction of dose creep, which jeopardizes radiation protection. Minimizing or elimination of dose creep is, therefore, imperative. This is however, cumbersome visually and virtually. A radiographic exposure chart can forestall this problem as it minimizes unnecessary arbitrariness in selection of exposure intensity.[6,8,12,15,17,18] This work was an attempt to improve on a previous exposure chart which eliminated dose creep but was unable to narrow the range of negative deviation index, an indication of low dose as desired but the risk of skin dose was not zero. The current work relied on exposure and deviation indices to remedy identified flaws.

To address the issue, specific range of exposure (220 - 565) and deviation (-12.5 to +2.1) indices accompanying computed radiography images in a foremost Nigerian teaching hospital were noted. Available detector sizes (10 x 12 /25 x 30 cm; and 14 x 17 /35 x 43 cm) were also noted. The researchers were aware that computed radiography (CR) detectors (PSP) degrade after multiple expo-sures,[19] so efforts were made to see that PSP plates in use at the centre were still in optimum condition, even after being subjected to tens of thousands of exposure. Three hundred sthenic and hyposthenic adult patients and 150 paediatric patients were enlisted in this study (Fig. 1).

The present and previous exposure charts had similar time (seconds) for which tube current (mA) flowed, and fairly similar tube current (mA) and focus-detector-distance (FDD). The new chart however, had an 8 to 28% upward adjustment in tube current to compensate for reduced factors and hence to increase resolution while reducing image noise. The emphasis was to adjust tube potential (kVp) in order to reduce the wide range of deviation index (-11.1 to +8.1). Adjustments in kVp indeed produced desirable outcomes as deviation index decreased from -9.5/-0.8 to -1.6/+0.2 (pelvis), -8.5/0 to -2.6/0 (abdomen), -6.2/+1.5 to -0.8/+0.2 (skull), -5.2/-0.2 to -1.2/+0 (lumbosacral spine), -5.2/-0.8 to -0.8/0 (femur), -2.6/-0.5 to -1.4/0 (adult chest), and -11.1/+8.1 to -2.2/+1.4* (paediatric chest).

The absence of quantum mottle in the images (Fig. 3-6) indicate that intensity selection was dose effective.[20,21] The positive deviations, however, indicate higher than normal dose. Since dose creep receives less attention from radiographers,21 efforts made in reducing DI of paediatrics from +8.1 to +1.4 is a significant improvement. The difficulty encountered in the process reiterates the observation that paediatric patients pose more challenge than adults due to the wider range of sizes, from neonates to young adolescents.[7] Although our age range was 12 to 17 years which was narrow, it was wide enough to create complexities. Further, a careful upward adjustments in kVp while keeping tube mA, mAs and FDD constant, may produce zero deviations eventually. Although it has been suggested that a 50 % reduction in tube

current was possible,[4] this should not be done without a corresponding increment in tube potential, else absorbed dose in tissue may increase.[22]
An exactly zero negative deviation index was not achieved in our work despite gross reduction in range of DI towards zero. For paediatrics, the wider range in age (12 -17 years) which is an indication of a wide body habitus might have been responsible for the difficulty in achieving zero DI. For adults, slight variation between hyposthenic and sthenic body types may have been responsible. This is not however, much of a problem since large deviations in DI do not necessary represent large variations in dose. A +1 and - 1 represents about 20% positive and negative difference from recommended exposure.[23]
The main concerns about patient dose relate to the stochastic effects which encompasses carcinogenesis and hereditary changes.[24] As a result, efforts must be made to trap dose that have the tendency to be deposited as skin dose in adjacent anatomical regions. Apparel shielding of torso during head examinations could mitigate this risk. Evidence abound to show that, with or without negative deviation index, significant amount of scatters reach the chest during radiographic examination of head.[25,26,27] Scattered radiation deteriorates image quality which may necessitate repeats and a concomitant increased radiation dose to patients.[26,27] It has been postulated that over 90 % of scattered radiation could be attenuated by lead aprons.[28,29] A more complete picture for radiation protection of patients is therefore given through a combination of radiographer s exposure chart and apparel shielding as postulated in this work (Fig. 2).
Limitation: Paediatrics patients younger than 12 years were not enlisted due to a fewer throughput and com-plexity in handling them in a busy centre. Furthermore, the exposure chart was derived using Negroid population and AGFA photostimulable phosphor plates. There may be variations in exposure and deviation indices if modalities, accessories and population are changed. Nonetheless, differences in image resolution between different models of computed radiography PSP plates are hardly discernible, visually. As a result, our work can be extrapolated to other models of computed radiography detectors and human populations without fear of significant variations.

Conclusion

In view of the superior advantages of digital radiographic technology over traditional film-screen system,[30,31] its acquisition and use in Africa, especially in Nigeria, is on the rise. The drawback is however, a tendency towards dose creep which has serious implication for radiation protection. An exposure chart has great prospect in mitigating dose creep. Such an exposure chart was derived in this work for Negroid subjects aged ≥12 years. Although it tackled dose creep fairly well in adult patients it was unable to replicate the feat perfectly well with paediatric cases. In adult patients, the old exposure chart produced an EI and DI of 220 to 565 and -11.5 to +8.1, respectively. The EI was maintained in the new chart but the DI decreased significantly (-2.6 to +0.0). The old chart also produced in paediatrics a deviation index of -11.1/+8.1 which was reduced by the new chart (-2.2 to +1.4).
Centres with digital technology may find our exposure chart a starting point for the selection of exposure factors. Furthermore, torso should be shielded with photon-attenuating materials during head and neck radiographic examinations, and not just gonads alone, in order to reduce scattered radiation.

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