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Estimates of Patient Radiation Doses in Digital Radiography Using DICOM Information at a Large Teaching Hospital in Oman

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Abstract

In this study, we sought to estimate the patient radiation doses in the digital radiography X-ray examinations conducted in a large hospital. The patient exposure factors and kerma-area product (P_{KA}) were retrospectively recorded via the Digital Imaging and Communications in Medicine (DICOM) header for 547 patients. The entrance surface air kerma (ESAK) was estimated from the measurements of the X-ray tube output and recorded exposure factors, as well as from the console that displayed P_{KA} as an alternative method. Effective doses were estimated from ESAK and P_{KA} values using the appropriate conversion coefficient. In the chest PA, chest LAT, cervical spine AP, cervical spine LAT, abdomen AP, pelvis AP, lumbar spine AP, and lumbar spine LAT, the median ESAK (mGy) was found to be 0.13, 0.27, 0.35, 0.52, 0.70, 1.06, 2.33, and 4.18 mGy, respectively. Median P_{KA} values were 0.10, 0.26, 0.14, 0.17, 0.77, 0.68, 0.81, and 1.11 Gy cm^2, respectively. The estimated effective dose from ESAK and P_{KA} values yielded comparable results. The comparison revealed that the ESAK and P_{KA} values fell far below the reported in the literature. The results showed that the information of the DICOM deader is valuable for dosimetry and optimization.

Keywords Digital radiography · Patient doses · Entrance surface air kerma · Kerma-area product · Diagnostic reference levels

Introduction

Medical diagnostic X-ray examinations are indispensable tools in the modern healthcare; however, they also represent by far the largest manmade source of radiation exposure to population [1]. The benefits of the digital systems include faster acquisition and image processing compared with old screen-film systems, plus a wide dynamic range, computer-aided adjustment of contrast and brightness, and electronic cropping. Despite the aforementioned benefits, overexposures and underexposures in X-ray film-screen radiography produce films that are too dark and too light, respectively, that can no longer be detected in digital radiography (DR). This has the risk of overexposure of the patient or risking the quality of the diagnostic image in case of underexposure, and this may risk image retake [2, 3]. Dose measurements and optimizations are therefore important in digital imaging.

International radiation protection organizations require that the typical patient's radiations in radiological procedures are measured at approved intervals and compared with the diagnostic reference levels (DRLs) [4, 5]. When the average doses regularly exceed or below the established DRLs, an investigation is required. Inappropriate imaging protocols or equipment malfunction might be the cause, which requires prompt corrective action. High patient doses are of concerns from radiation protection viewpoint whereas very low doses could result in significantly increased image noise that could risk the quality of diagnostic image.

In comparing the patient radiation doses with the DRLs, the measurements should be made using a simple and easily measurable dose quantity. In radiography, entrance surface air kerma (ESAK) and kerma-area product (P_{KA}) are used. ESAK is defined as the air kerma measured on the X-ray beam axis at the point where the X-ray beam enters the patient or a phantom, including the contribution of backscatter radiation [6, 7]. P_{KA} is defined as "the integral of the air kerma over the area of the X-ray beam in a plane perpendicular to the beam

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axis" and does not include backscatter [6]. It is a measure of the total radiation energy entering the patient. For the measurements of P_{KA}, P_{KA} meters are available that are integrated into the radiographic unit or installed as add-on devices. On the other hand, there are two approaches for evaluating ESAK: the use of thermoluminescent dosimeters (TLD) applied to the patient's skin at the center of the radiation field or the assessment based on the exposure factors and measurement of X-ray tube output by an ionizing chamber [8].

Following the introduction of digital radiography, several dose optimization studies were carried out using Digital Imaging and Communications in Medicine (DICOM) header information [9, 10]. Indeed, the international radiation protection organizations and advisory bodies have encouraged using dose information provided by the DICOM header and hospital information system (HIS) in patient dose management digital imaging [11].

In Oman, not much work has been carried out in diagnostic radiology. It is observed that in spite of large number of medical X-ray installations within the country, studies aimed at assessing the patient dose in diagnostic radiology were rare [12]. Typical doses encountered during these examinations are not exactly known.

The present research project was initiated with the aim of evaluating the radiation doses to patients undergoing some common diagnostic X-ray examinations of the chest PA, chest LAT, cervical spine AP and cervical spine LAT, abdomen AP, pelvis AP, lumbar spine AP, and lumbar spine LAT in a teaching hospital in Oman. The gradual increase in the use of the digital radiography in the region has raised concerns over the dose consequence of DR; therefore, it has become necessary to study the radiation exposure and explore potentials for optimizations. It was anticipated that this study will help in the optimization of radiation protection of the patient.

Materials and Methods

Radiation doses were estimated for 547 examinations performed on patients in five X-ray rooms at the Sultan Qaboos University Hospital. It is the largest academic hospital in the country with over 30 different imaging installations including 12 fixed and mobile radiographic units; 4 fluoroscopy units, 4 dental radiography units, mammography, CT, MRI, and SPECT-CT units in addition to several ultrasound imaging devices.

DICOM Information

The P_{KA} values per procedure were extracted from DICOM header information and were used for the retrospective dose analysis. The P_{KA} meters were calibrated during the annual routine quality assurance showing results that not deviate from the actual value by more than ± 35% as recommended [13]. In addition, the patient exposure factors (tube voltage, tube current-exposure time product (mAs), and focus-to-detector distance (FDD)) were also extracted from the DICOM header information and later used for calculating the ESAK. Adult patients (≥ 18 years old) who underwent DR X-ray examinations were included without any selection criteria regarding weight.

Estimates of ESAK

The output of each X-ray unit was determined using calibrated Xi Unfors digital dosimeter (Unfors Raysafe Inc., Billdal, Sweden). The ESAK was estimated from the tube output and exposure factors that were collected during the routine examinations; these values were also estimated according to the methods described in relevant international protocols [6, 7].

$$ESAK = Y\,(kV, d)\cdot Q\cdot\left(\frac{d}{d_{\mathrm{FSD}}}\right)^2\cdot \mathrm{BSF}, \tag{1}$$

where $Y\,(kV, d)$ is the normalized tube output (mGy/mAs) measured 1 m from the point of focus, depending on the tube voltage. Q is the routinely used tube current–time product (mAs) and d_{FSD} the focus-to-skin distance calculated from the FDD using

$$d_{\mathrm{FSD}} = \mathrm{FDD} - t_p - x \tag{2}$$

where t_p is the patient thickness. A standard t_p value of 23 cm was used for chest PA, abdomen AP, pelvic AP, and lumbar spine AP [14]. The standard t_p value is 30 cm for all LAT projections. The BSF is the backscatter factor [15]. x is the distance from the detector to the front of the detector holder taken to be 5.0 cm approximately.

Results

Table 1 presents the equipment information, radiographic X-ray tube output, and the half-value layer (HVL). All radiographic units studied were made by Philips type Dig.Diagnost. HVL values were above the minimum requirement of 2.5 mm Al, and X-ray tube output measured at 70 kV ranged from 14.6 to 40.2 μGy m^2 mAs^{-1} [7]. Despite that all X-ray devices are of the same maker and model, output variations could be due to the difference in inherent filtration and uses.

Table 2 presents the patient information and exposure parameters for the selected X-ray examinations with mean (±σ) values and ranges. The median kV used ranged from 125 kV (chest PA) to 66 kV (cervical spine AP). The median mAs ranged from 1.71 mAs (chest

Table 1 Equipment information, radiographic X-ray tube output, and the half-value layer (HVL)

Code	Maker/model	Modality	Installation year	Output (μGy m^2 mAs^{-1})	HVL at 70 kV mm Aleq
U01	Philips/Dig.Diagnost	Fixed/DR	2004	36.1	2.7
U02	Philips/Dig.Diagnost	Fixed/DR	2005	37.3	2.8
U03	Philips/Dig.Diagnost	Fixed/DR	2005	16.7	2.8
U04	Philips/Dig.Diagnost	Fixed/DR	2005	40.2	2.9
U05	Philips/Dig.Diagnost	Fixed/DR	2005	14.6	2.9

PA) to 21.0 mAs (lumbar spine AP). All the examinations were performed using FFD of 100 cm, except chest (PA and LAT) where FFD of 180 cm was used. Median BSF used ranged 1.38 to 1.59.

Table 3 shows the statistical summary ESAK (mGy) distribution for standard digital radiographic examinations in SQUH, Oman. Achievable ESAK (median) ranged from 0.0.13 mGy (chest PA) to 4.18 mGy (lumbar spine LAT). Achievable P_{KA} (median) ranged from 0.10 Gy cm^2 (chest PA) to 1.11 Gy cm^2 (lumbar spine LAT). Data regarding the adult patients (≥ 18 years) were included in the study.

Table 4 shows the comparison between the median ESAK (mGy) obtained in this study and the UK and EC reference doses, as well as the results of the previous studies carried out in Iran, Brazil, and India [4, 16–19]. The current study revealed lower ESAK values compared with doses presented by similar studies and the corresponding internationally established DRLs. Seventy-five percent percentile of the ESAK distributions is presented as local diagnostic reference levels (LDRLs) (Table 4).

Table 5 exhibits the comparison between the median P_{KA} (Gy cm^2) obtained in this study with UK and EC reference doses and the results of previous studies performed in Nigeria, Nickoloff [20, 21]. Seventy-five percent percentile of the P_{KA} distributions is presented as LDRLs (Table 5).

Estimates of the effective dose per radiological procedure were obtained using ESAK and P_{KA} to effective dose conversion coefficient given in the UK Health Protection Agency Report [16].

$$E_{ESAK} = k^{ESAK} \cdot ESAK \quad (3)$$

$$E_{P_{KA}} = k^{P_{KA}} \cdot P_{KA} \quad (4)$$

where k^{ESAK} is the ESAK to effective dose conversion coefficient with values 0.131, 0.09, 0.035, 0.023, 0.132, 0.099, 0.116, and 0.027 mSv mGy^{-1} for chest PA, chest LAT, cervical spine AP and cervical spine LAT, abdomen AP, pelvis AP, lumbar spine AP, and lumbar spine LAT, respectively [22].

For the conversion of P_{KA} to effective dose according to Eq. 4, the $k^{P_{KA}}$ values are 0.158, 0.125, 0.187, 0.118, 0.180, 0.139, 0.244, and 0.092 mSv mGy^{-1} cm^{-2} for chest PA, chest LAT, cervical spine AP and cervical spine LAT, abdomen AP, pelvis AP, lumbar spine AP, and lumbar spine LAT, respectively. k^{ESAK} and $k^{P_{KA}}$ conversion coefficients used to calculate effective doses are based on ICRP 103 [22].

Table 6 manifests the comparison of the median effective doses (μSv) obtained in this study with those previously published in the literature. The comparison of E_{ESAK} (effective doses calculated using ESAK) and the $E_{P_{KA}}$ (effective doses calculated using P_{KA}) and UK2010 are depicted in Fig. 1. The results showed comparable effective doses in the radiological procedure studies except in abdomen AP and lumbar spine LAT examinations, where the E values calculated by two methods differed by almost 100%.

Table 2 The median and range of patients' age and exposure parameters for the standard X-ray examinations

Projection	Age (years)		kV*		mAs**		BSF	FFD (cm)
	Median	Range	Median	Range	Median	Range		
Chest AP	49	18–106	125	81–150	1.71	0.50–21.90	1.49	180
Chest LAT	47	18–87	150	117–150	5.96	1.65–25.50	1.53	180
CS AP	46	26–74	66	66–66	7.95	3.91–15.90	1.38	100
CS LAT	31	23–74	66	66–77	15.9	4.65–40.50	1.38	100
Abd. AP	57	22–81	81	77–102	10.13	1.93–38.90	1.41	100
Pelvis AP	49	19–106	77	77–77	10.60	2.91–71.12	1.41	100
LS AP	50	18–88	77	77–77	21.0	3.38–160	1.41	100
LS LAT	50	18–88	90	73–102	20.0	4.00–85.00	1.44	100

*For all examinations, kV value is predetermined according to the examination program

**For a given kV value, mAs values are determined by the AEC for all examinations

Table 3 Statistical summary of ESAK (mGy) and P_{KA} (Gy cm^2) distributions for standard digital radiographic examinations in SQUH, Oman

Examination	Mean ± σ	Percentile of the dose distributions (%)				
		10	25	50	75	95
ESAK (mGy)						
Chest AP	0.14 ± 0.09	0.04	0.07	0.13	0.19	0.32
Chest LAT	0.49 ± 0.61	0.05	0.11	0.27	0.59	1.82
Cervical spine AP	0.36 ± 0.27	0.12	0.14	0.35	0.45	0.90
Cervical spine LAT	0.72 ± 0.67	0.11	0.33	0.52	0.91	1.85
Abdomen AP	1.18 ± 1.11	0.31	0.45	0.70	1.58	3.54
Pelvis AP	1.92 ± 2.07	0.42	0.53	1.06	2.27	6.69
Lumbar spine AP	3.41 ± 3.33	0.94	1.59	2.33	3.83	8.66
Lumbar spine LAT	4.69 ± 3.17	1.44	2.39	4.18	6.08	10.20
P_{KA} (Gy cm^2)						
Chest AP	0.14 ± 0.13	0.05	0.06	0.10	0.18	0.41
Chest LAT	0.34 ± 0.31	0.08	0.17	0.26	0.43	0.98
Cervical spine AP	0.14 ± 0.06	0.06	0.10	0.14	0.17	0.22
Cervical spine LAT	0.20 ± 0.13	0.07	0.10	0.17	0.29	0.42
Abdomen AP	0.95 ± 0.64	0.03	0.44	0.77	1.25	2.26
Pelvis AP	1.15 ± 1.09	0.19	0.44	0.68	1.72	3.34
Lumbar spine AP	1.16 ± 1.06	0.31	0.53	0.81	1.44	3.04
Lumbar spine LAT	1.21 ± 0.73	0.40	0.65	1.11	1.62	2.30

Discussions

Distributions of the ESAK Values

The concerned ESAK values for chest PA (0.13 mGy) comparable with the UK and EU DRL are 0.15 mGy, whereas the ESAK values in others are lower than the half of the DRLs. The ESAK values are also below doses, as reported by Rasuli in Iran and Osibote in Brazil, respectively [18, 19]. The comparison of patient dose values between different countries assumes similarities in patient population. Compared with other studies used to establish UK and EC DRLs, the sample size in this study is very limited. This is expected to result in relatively large uncertainties.

Despite the low ESAK values, the patient dose variations are high. The dose variability in the X-ray examination could indicate the need for standardized radiographic techniques for the optimization of the patient protection. In the light of results obtained, several dose optimization measurements were considered.

The radiographic examinations in Philips/Dig.Diagnost are performed with redefined programs that use specific examination kV, whereas mAs is completely determined using AEC. kV setting is not the same for radiographic devices under study, which is reflected but small differences in the used kV (Table 2).

Therefore, certain degree of variations or technique factors and hence radiation dose are inevitable. To statistically have a significant number of samples, the data for all adult patients aged ≥ 18 years were included in the study. The doses were evaluated in terms of median

Table 4 Comparison between the median ESAK (mGy) for digital radiography obtained in this work with UK reference doses and results of similar studies in the literature

Study	Chest PA	Chest LAT	CS AP	CS LAT	Abdomen AP	Pelvis AP	LS AP	LS LAT
UK 2010, ref. [16]	0.15	0.5	**	**	4	4	5.7	10
EC 180, ref. [4]	0.30	1.5	7	20	10	10	10	30
Iran, ref. [17]	**	**	1.3	1.65	**	**	3.09	7.5
Brazil, ref. [18]	0.19	0.48	0.64	0.6	1.75	**	2.37	4.75
India, ref. [19]	0.35		2.75	2.9	2.43	3.27	3.21	4.98
Median, this study	0.13	0.27	0.35	0.52	0.70	1.06	2.33	4.18
LDRLs, this study	0.20	0.60	0.45	0.91	1.60	2.30	3.80	6.10

**Data are not available

Table 5 Comparison between the median P_{KA} (Gy cm^2) for digital radiography obtained in this work with UK reference doses and results of similar studies in the literature

Study	Chest PA	Chest LAT	CS AP	CS LAT	Abdomen AP	Pelvis AP	LS AP	LS LAT
UK 2010, ref. [16]	0.1	–	0.15	0.15	2.5	2.2	1.5	2.5
EC 180, ref. [4]	0.16	0.6	1.3	1.7	3.0	3.0	2.3	4.2
Nigeria, ref. [20]	3.06	**	**	**	17.16	3.28	2.72	**
US, ref. [21]	0.1–0.3	0.3–0.9	**	**	3.2–4.5	**	**	1.6–2.2
Median, this study	0.1	0.26	0.14	0.17	0.77	0.68	0.81	1.11
LDRLs, this study	0.18	0.43	0.17	0.29	1.25	1.72	1.44	1.62

**Data are not available

as preferential because the mean can be greatly affected by the high- and low-dose extremities of the dose distribution.

In radiography, the radiation dose is proportional to the tube current, exposure time, and square of focus to skin distance (FSD) [24]. The use of the higher peak kilovoltages increases the beam penetration, and this allows the use of a lower tube current. In the present study, the chest (AP and LAT) examinations were performed using high kV (110–120) and low mAs (1.0–4.0) techniques (Table 1). The increasing sensitivity of DR flat-panel detectors is the reason for the use of low mAs values. For example, a dose reduction of 50% for the chest radiography using a flat-panel detector without the loss of diagnostic information was demonstrated by Herrmann et al. [25]. Another study by Sjöholm et al. [26] reported that the patient doses could be reduced by a factor of four by using flat panel detectors with no significant difference in image quality.

Radiation protection of the patient in the hospital would be greatly assisted if the present doses are used to suggest local DRLs. DRLs are important dose optimization tools, set as the third quartile of the median room doses that are used as the LDRLs [5]. When these DRLs exceed in practice, the hospital medical physicist or the radiation safety adviser should act appropriately to bring doses below what is considered acceptable. Actions are also necessary when doses are very low compared to DRLs as this may risk the quality of diagnostic information.

However, it is possible that in a large hospital with many X-ray installations, as in the case of this study, radiological examinations are carried out using doses lower than the corresponding DRLs. In these cases, new dose levels can be established in a similar way as the DRLs and thereafter adopted to be used only locally, as local diagnostic reference levels (LDRLs), to improve the already good practice [27]. The LDRLs suggested in this study are presented alongside the achievable median doses (Tables 3 and 4).

Distribution of the P_{KA} Values

As shown in Table 4, the P_{KA} values obtained in this study for the chest (PA and LAT) and cervical spine (PA and LAT) are similar to the UK and EC DRLs, as well as the doses reported by Jibiri and Olowookere in Nigeria [20]. The doses in abdomen, pelvic, and lumbar spine examinations are far lower than their corresponding DRLs and the doses reported in similar studies. According to ref. [28], the DRLs should be used as remedial action levels. When the P_{KA} values are as high as double the corresponding DRL value, the respective radiographic examination should be suspended.

The P_{KA} values not only depend on the amount of ESAK but also on the radiation quality and field size. However, P_{KA} is better estimate of the total energy imparted to the patient, and therefore, the total radiation detriment can be better estimated using the P_{KA}, assuming the proper collimating radiation field size.

Effective Doses

Further, the effective doses were determined from the measured ESAK and console displayed P_{KA} values according to dose conversion coefficients, which were calculated using tissue-weighting factor given in the ICRP103 [16]. The

Table 6 Comparison of the median effective doses (μSv) obtained in this study with those previously published in the literature

Study	Chest PA	Chest LAT	CS AP	CS LAT	Abd. AP	Pelvis AP	LS AP	LS LAT
UK, 2010, ref. [16]	14	38	24	14	430	280	390	210
Vilar-Palop et al. ref. [23]	50	50	50	50	500	370	800	800
This study, E_{ESAK}	17.0	24.3	12.3	12.0	92.4	104.9	270.3	112.9
This study, E_{PKA}	15.8	37.5	18.7	23.6	144	97.3	179.2	101.2

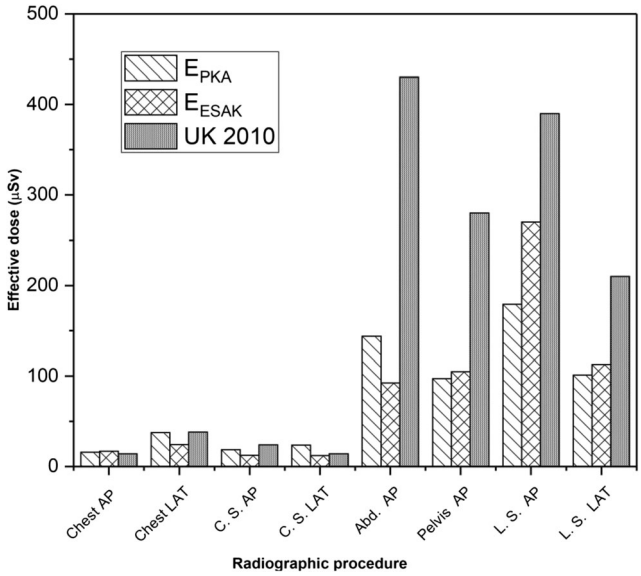

Fig. 1 Comparison of effective doses, the E_{ESAK} obtained from the ESAK values, the E_{PKA} obtained from the P_{KA} values, and the effective doses reported in UK 2010

effective dose ratios are as follows: E_{ESAK} to $E_{P_{KA}}$ was 1.1 (chest PA), 0.6 (chest LAT), 0.7 (CS AP), 0.5 (CS LAT), 0.6 (abdomen), 1.1 (pelvis AP), 1.5 (LS AP), and 1.1 (lumbar spine LAT).

The results manifested comparable effective doses except for the CS LAT and LS AP, where the significant differences were observed (Fig. 1). Assuming a standard thickness for all patients could be the main reason for these differences. Thus, it is expected that the two approaches would result in much closer values when using actual patient sizes. It should be noted that the calculated effective dose values do not refer to an individual patient but to a population of standard sized patients.

Compared with the literature (Table 3), current effective dose values were lower than their reported corresponding figures [16, 23]. The results showed that the information of the DICOM header can be used with acceptable accuracy. The effective dose (E) is the accepted quantity to be used for the assessment of carcinogenic and heritable risk to the irradiated person and permits doses from DR to be compared with those from other imaging modalities as well as those of the natural background radiation. The quantity effective dose is used for cancer risk estimates. For example, according to the International Commission on Radiological Protection, the risk of fatal cancer for the general population is approximately 5% Sv^{-1} [16].

The results of this study could provide an important guidance for the purpose of estimating patient doses in DR as prerequisite to dose optimizations. This study provided a starting point for institutional dose optimization using readily available dose information courtesy of DR systems. Further efforts are certainly needed to fully utilize DR feature for dose optimization through exposure index (EI) information analysis [29].

Conclusion

In this study, the radiographic exposure factors and P_{KA} values were retrospectively extracted from the information provided by the DICOM header. The ESAK values were determined from the patient exposure factors and the X-ray tube output measurements. The obtained ESAK and P_{KA} values were lower than their corresponding DRLs, and the doses were reported in similar studies. The small number of radiographic devices that is all digital might have contributed to the results. Seventy-five percent percentile of the dose distributions was used to suggest LDRLs for future dose optimizations. Both the ESAK and P_{KA} values were used to estimate the patient effective doses. The results showed comparable effective doses in almost all the studies for radiological procedures except in abdomen AP and lumbar spine LAT examinations, where the E values calculated by the two methods differed by almost 100%. The study demonstrated the usefulness of DICOM header information for monitoring patient radiation doses in digital radiography for the sake of dose optimizations. The results contribute to national and international efforts for dose management in digital imaging.

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Compliance with Ethical Standards

Conflict of Interest The author declares that he has no conflict of interest.

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