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Assessment of the radiation dose associated with X-ray examinations using the DoseCal and CALDose_X software packages

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► ***Original article***

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ABSTRACT

Background: The aim of this study was to estimate the entrance skin dose (ESD) in adult patients undergoing skull and pelvis X-ray examinations in Najran, Saudi Arabia using the DoseCal (Radiological Protection Center of Saint Georges' Hospital, London, England) and CALDose_X (Department of Nuclear Energy, Federal University of Pernambuco, Recife, Brazil) software packages. Additional aims included conducting comparisons between these two software packages and against international reference dose levels and estimating the radiogenic risk during X-ray examinations. ***Materials and Methods***: A dataset of 410 patients seen at Najran University Hospital was examined to assess the radiation dose using the DoseCal and CALDose_X software packages. ***Results***: The values of the entrance dose, organ doses and effective dose obtained by the DoseCal and CALDose_X software were reported in this study. The ESD values estimated from the X-ray units ranged from 0.32 to 2.65 mGy for skull anteroposterior/posteroanterior (AP/PA), 0.62 to 2.13 mGy for skull lateral (LAT), and 1.23 to 3.15 mGy for pelvis AP projection. According to the DoseCal and CALDose_X, the dose absorbed by the pelvis and skull varied by a factor ranging between 1.2 and 2.4. ***Conclusion***: All entrance doses calculated for the skull and pelvis were found to be within the corresponding dose reference levels recommended by the international agency, board and commission highlighted in this study.

INTRODUCTION

X-ray technology has been used for more than a century for diagnosis, treatment and human research. Diagnostic X-ray examinations are by far the most significant source of medical exposure reported among the world's population [1].

The diagnostic reference level (DRL) is considered a useful tool to monitor the practice of and optimise the radiation dose delivered to the patient during diagnostic X-ray examinations. Radiation dose can be evaluated in patients undergoing X-ray examinations from the entrance skin dose (ESD), either directly using thermoluminescent dosimeters (TLDs) or indirectly by measuring the output values of the X-ray tube [2]. The dose area product (DAP) is also a measurable dose quantity recommended for monitoring individuals undergoing radiographic examinations; however, both the ESD and DAP are not direct risk-related quantities. The standard International Commission on Radiological Protection (ICRP) method for estimating cancer risk requires the calculation of the effective dose (E) from the absorbed dose delivered to individual organs. The effective dose can be estimated from the ESD or DAP and published conversion factors and software tools are currently available to assist with this process [3].

DoseCal (Radiological Protection Center of Saint Georges' Hospital, London, England) and CALDose_X (Department of Nuclear Energy, Federal University of Pernambuco, Recife, Brazil) are software tools published by Kyriou *et al.* [4] and Kramer *et al.* [5], respectively, and are used to calculate the organ-absorbed dose, entrance dose and E. DoseCal employs MIRD5 (adult and pediatric) phantoms with conversion factors determined by Jones and Wall [6] and by Hart *et al.* [7] to calculate the E and does not work in an environment using an operating system newer than Windows 98 (Microsoft Corporation, Redmond, WA, USA). DoseCal gives the user an option to select the patient's weight and age. By comparison, we found that CALDose_X uses MAX06 and FAX06 phantoms, which were developed to include ICRP 103 tissues and organs such as the oral mucosa, prostate and salivary glands. The developer of CALDose_X used EGSnrc MC code to calculate the absorbed dose over 29 organs and tissues of the MAX06 and FAX06 phantoms [8]. In addition, the CALDose_X software shows the absorbed dose to the organs and tissues together with the statistical errors

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that arise according to the type of examination. Furthermore, CALDose_X provides the cancer risk for patients based on factors reported by the National Research Council (NRC) [9] and presents the organ- and tissue-absorbed doses normalised to the incident air kerma (INAK), entrance surface air kerma (ESAK) and kerma area product (KAP) quantities. Meanwhile, DoseCal presents the absorbed doses normalised to ESD values.

Recently, Alsayyari *et al.* conducted surveys in Saudi Arabia to study the radiation doses experienced by patients undergoing chest, skull and abdomen X-ray examinations in Qassim state [10]. Further, several studies have evaluated the variation in the risk of cancer between different radiology techniques like angiography [11] or oral and panoramic radiography [12]. As a continuation of this effort and as complementary to a previous survey that investigated the radiation doses for chest and lumbar spine imaging [13] in Najran state, the authors of this study measured ESD and ESAK values for the skull and pelvis in patients undergoing X-ray examinations using the DoseCal (version 2.31) and CALDose_X (version 5.0) software packages. Additional aims of this investigation included the completion of comparisons between the two software packages and against international reference dose levels and the estimation of the radiogenic risk inherent during these examinations. The data collected in the present work may be used as a baseline with which future dose measurements might be compared. Moreover, this dose survey can be useful for national and professional authorities.

MATERIALS AND METHODS

This study was carried out at Najran University Hospital (NUH) in Najran, Saudi Arabia in 2018 to assess radiation doses administered to patients undergoing skull and pelvis X-ray examinations. This hospital was chosen for involvement in this study because it's one of the largest hospitals in Najran province in terms of workload and serves a diverse group of patients ranging from local residents to university staff. Three different X-ray units were included in this study, all of which were analogue systems – namely, Neo Diagnomax (Medicor, Sidney, Australia), Radiotex (Shimadzu, Kyoto, Japan) and DRX-3724 (Toshiba, Tokyo, Japan) – and were equipped with filtration capacities equivalent to 3.0, 2.5 and 2.5 mm Al, respectively. The three standard radiographic projections considered in this study (which included skull and pelvis examinations) with the contribution percentages of the annual collective dose from radiography presented in table 1.

In May 2018, the present study was ethically cleared by the Scientific Research Ethics Committee at Najran University (registration no. 03-02-5-18EC). Study data were collected over a period of five months between August 2018 and December 2018. Anthropometric characteristics of each patient, such as age and weight, were obtained before the X-ray examination, whereas exposure parameters such as peak tube voltage (kVp), exposure current (mAs) and focus to surface distance (FSD) were recorded at the time of the examination.

Table 1. Standard radiographic examinations and projections.

Examination	Projection	Contribution to the annual collective dose from radiography (%)
Skull	AP, LAT	4
Pelvis	AP	15

In the present work, the ESD was estimated by using the DoseCal software [4] based on equation (1) [14].

$$\text{ESD} = OP\left(\frac{kVp}{80}\right)^2 \times mAs \times \left(\frac{100}{FSD}\right)^2 \times BSF \quad (1)$$

where BSF is the backscatter factor calculated automatically by the DoseCal software and OP is the X-ray tube output (in mGy/mAs) measured at 80 kV and a distance of 100 cm from the tube focus along the beam axis using a calibrated Unfors Xi dosemeter (Unfors Inc., Billdal, Sweden) with an accuracy of better than 5%.

The DoseCal software [4] was also used to calculate the E using formula (2).

$$E = ESD \times Cf(D) \quad (2)$$

where Cf (D) is the conversion factor used to change ESD to ED based on the National Radiological Protection Board (NRPB) tables [15] adopted by DoseCal.

Separately, the CALDose_X software [5] was used to calculate ESAK based on formula (3).

$$ESAK = INAK \times BSF \quad (3)$$

where BSF provided by CALDose_X is based on data from Monte Carlo calculations.

The E value was estimated by the CALDose_X software using equation 4, based on the mathematical model proposed by ICRP 103 [16].

$$E=1/2[F + M]=1/2\Sigma^{W_T}[H_T(Female)+H_T(Male)] \quad (4)$$

where F is the weighted female dose and M is the weighted male dose, W_T is the tissue weighting factor and H_T is the average of the equivalent dose in a tissue or organ.

Then, CALDose_X was used to estimate the cancer risk based on Equation 5, proposed by Brenner and Huda [17].

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$$ER = \sum_T r_T H_T \quad (5)$$

where ER is the whole body effective risk and r_T is the cancer risks coefficients as reported by the NRC [9].

Descriptive statistics were calculated using either Microsoft Office Excel 2014 (Microsoft Inc, Redmond, WA, USA) and/or SPSS version 12 (IBM Corporation, Armonk, NY, USA). A two-sample t-test was used to analyse the study results.

RESULTS

A total number of 410 radiographs were included in this study. The patient demographic data and exposure factors for the skull and pelvis examinations performed are shown in table 2. Study participant ages and weights ranged between 18 to 81 years and 51 to 95 kg, respectively, while the male -to-female ratio for patients younger than 80 years of age was 1.4:1, approaching 1:1 with increasing age. It can be seen from table 2 that all X-ray units used low tube voltage protocols, ranging between 60 and 75 kVp, with median values of 65 kVp and 66 kVp for skull anteroposterior/posteroanterior (AP/PA) and lateral (LAT) examinations, respectively.

Table 2. Statistical data of the radiographic parameters (kVp and mAs values) and patient anthropometric data for selected X-ray examinations.

	Skull AP/PA		Skull LAT		Pelvis AP	
	Male	Female	Male	Female	Male	Female
Sample size	61	44	54	41	99	111
Patient age (y)	29 (18–53)	30 (19–55)	30 (18–47)	29 (20–41)	33 (25–81)	34 (23–74)
Patient weight (kg)	58 (51–75)	59 (51–95)	68 (51–92)	67 (51–87)	71 (60–82)	72 (54–87)
kVp	68 (61–75)	69 (62–75)	64 (60–70)	63 (60–69)	69 (72–77)	69 (71–77)
mAs	24 (9–39)	25 (10–42)	19 (7–29)	18 (7–28)	30 (32–36)	29 (31–36)
FSD (cm)	100 (90–115)	100 (90–115)	100 (94–119)	100 (94–119)	110 (105–125)	110 (105–125)

Table 3 presents the statistical data for ESD and ESAK values calculated for the skull AP/PA, skull LAT and pelvis AP projections. It can be seen that the maximum mean value of ESD or ESAK was identified in the pelvis AP projection.

Figures 1 and 2 show a comparison of the average values of the absorbed doses for organs and tissues between DoseCal and CALDose_X for the pelvis (AP) and skull (AP and LAT) examinations. According to the higher number of photons (five million photons per examination) used by the CALDose_X developer in the Monte Carlo code dose calculations, the statistical error was reduced and most of the absorbed dose present in figures 1 and 2(a) had a mean statistical error of just 1.5% for the skull and pelvis examinations [5]. Except for the variation observable in the absorbed dose values for red bone marrow (RBM), it can be seen that all such values for organs or tissues varied between the two software packages, with a factor range of 1.2 to 2.4.

The average values of E for the skull (AP and LAT) and pelvis (AP) examinations were 0.01, 0.1 and 0.51 mSv using DoseCal, whereas values of 0.1, 0.02 and 0.36 mSv were obtained using CALDose_X. Regarding the relationship between DoseCal and CALDose_X, the t-test, performed for organs located inside and outside the field of the radiation, showed that the correlation between the software programs was statistically insignificant ($p = 0.05$), with p-values ranging between 0.24 and 0.518. Regrading the radiogenic risk for patients undergoing skull and pelvis examinations, table 4 shows the values obtained using CALDose_X. The mean cancer risk probability per procedure was largest in correlation with pelvis exposure.

Table 3. ESD and ESAK for skull AP/PA, skull LAT and pelvis AP examinations.

	ESD*			ESAK**		
	Skull		Pelvis	Skull		Pelvis
	AP/PA	LAT	LAT	AP/PA	LAT	LAT
Min	0.32	0.62	1.23	0.48	0.82	1.57
Max	2.65	2.13	3.15	3.98	2.77	3.36
Median	1.52	1.15	1.92	2.41	1.58	2.61
Mean	1.39	1.12	1.95	2.35	1.59	2.55
Standard deviation (SD)	0.82	0.54	0.76	0.32	0.42	0.52
Sample size	105	95	210	105	95	210

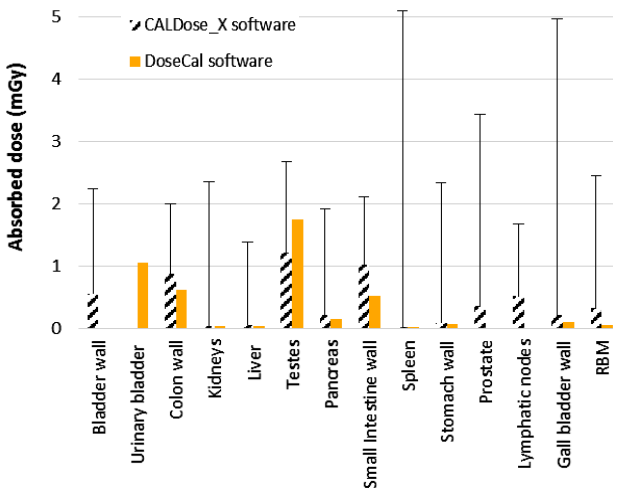


Figure 1. The doses absorbed by organs and tissues according to DoseCal and CALDose_X, respectively, during pelvis AP examinations. The bars represent the absorbed dose error (%) when using the CALDose_X software.

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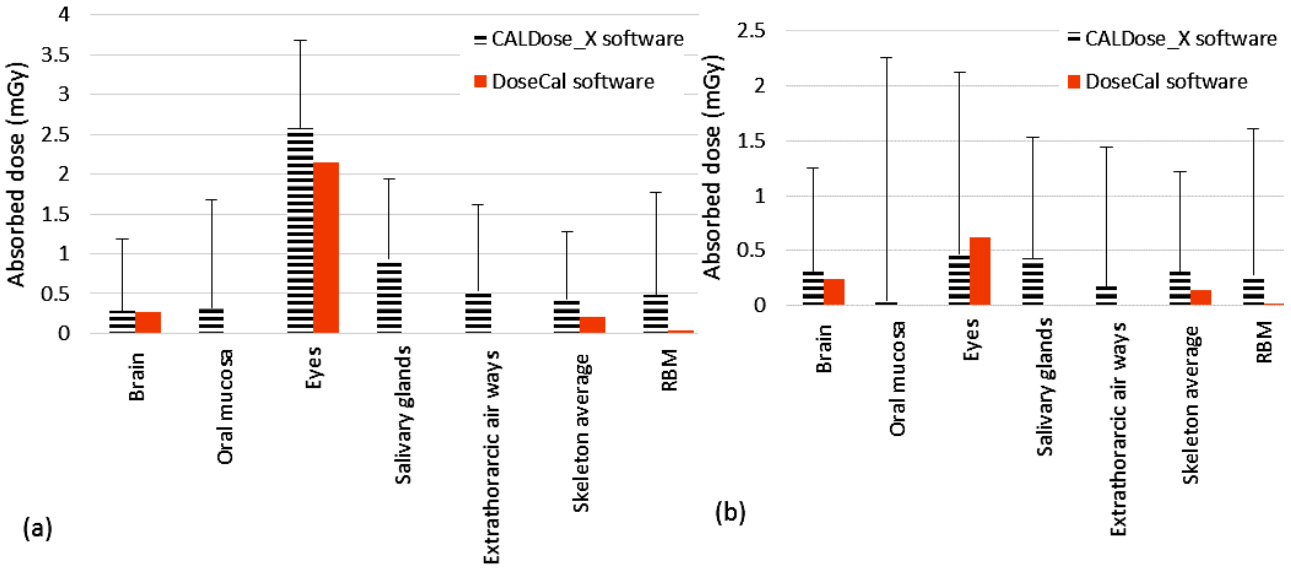


Table 4. The radiogenic risk for patients undergoing skull and pelvis examinations.

	Skull AP/PA (cases per 10^5)	Skull LAT (cases per 10^5)	Pelvis AP (cases per 10^5)
Risk of cancer incidence	0.444	0.241	1.979
Risk of cancer mortality	0.326	0.181	0.896

DISCUSSION

As previously mentioned in the Results section of this report, all skull and pelvis examinations were completed in this study using low tube voltage values (table 2). The kVp and mAs parameters of the pelvis examinations were in good agreement with the European Community (EC) guidelines [18]. For the comparison of dose performance, we only considered the ESD and the mean values of such for the skull and pelvis examinations included in this study were considerably below the NRPB [19], IAEA [20] and EC [18] reference levels for all projections (figure 3). These results are not surprising since the weight of our study population ranged from 51 to 95 kg with a median of 72 kg, which is comparable to the weight of a standard-sized person recommended by ICRP-60 [21].

If we assume as Muhogora *et al.* did [22] that the quantity of ESD equals the ESAK in diagnostic radiology, we found that their average values vary, with a factor range of 1.3 to 1.7 (table 3). This result could be attributed to several factors, such as different BSF, patient weight and total filtration values entered in the respective software programs. For the sake of clarification, the BSF presented in the two software packages show negligible variation (± 5%), which can affect the entrance doses. On the other hand, CALDose_X used a reference body mass value (73 kg) and does not permit the user to enter in a new patient weight, which may drive a difference in the entrance dose values between the two software packages. It's worth mentioning that DoseCal covers the range of 2.0 to 5.0 mm Al for the total filtration, while CALDose_X computes the entrance dose using only a value of 2.5 mm Al. In this study, we were forced to use a specific thickness filtration value in CALDose_X despite adopting different filtration protocols as in the case of DoseCal. As it's known, increasing the filtration thickness results in removal of lower-energy photons from the beam, which would contribute to changing the patient entrance dose [23].

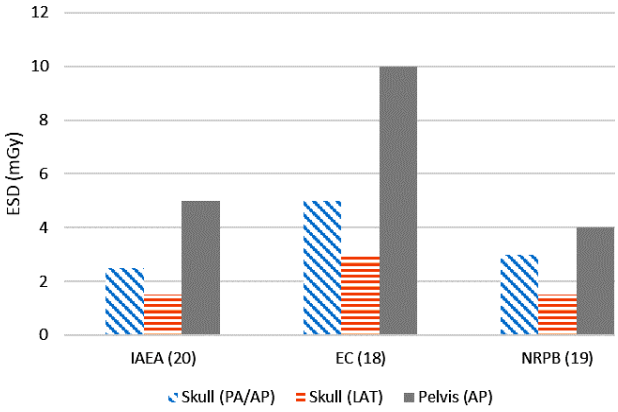


Figure 3. International reference dose values for skull and pelvis examinations.

In figure 4(a–c), a comparison is established between the average ESD, ESAK and exposure factor values obtained in this study and the ESD values reported in previous studies from India [24], Korea [25], Iran [26], the United Kingdom (UK) [27], Malaysia [28], Switzerland [29], Bangladesh [30], Bulgaria [31], Italy [32], Sudan [33], Nigeria [34], Lithuania [35] and Russia [36]. It can be observed that the mean ESD values of the skull LAT exami-

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nation in this study were higher than those reported in the UK [27] but less than those in several other countries [24, 28-31, 34-36]. In this study, we chose to compare our mean ESD values with the internationally reported dose metrics, but the recent recommendations favour median values. Accordingly, a comparison is also arranged between the median ESD values obtained in this study and those reported in Iran [26], the UK [27], Malaysia [28], Sudan [33] and Russia [36] in figure 5.

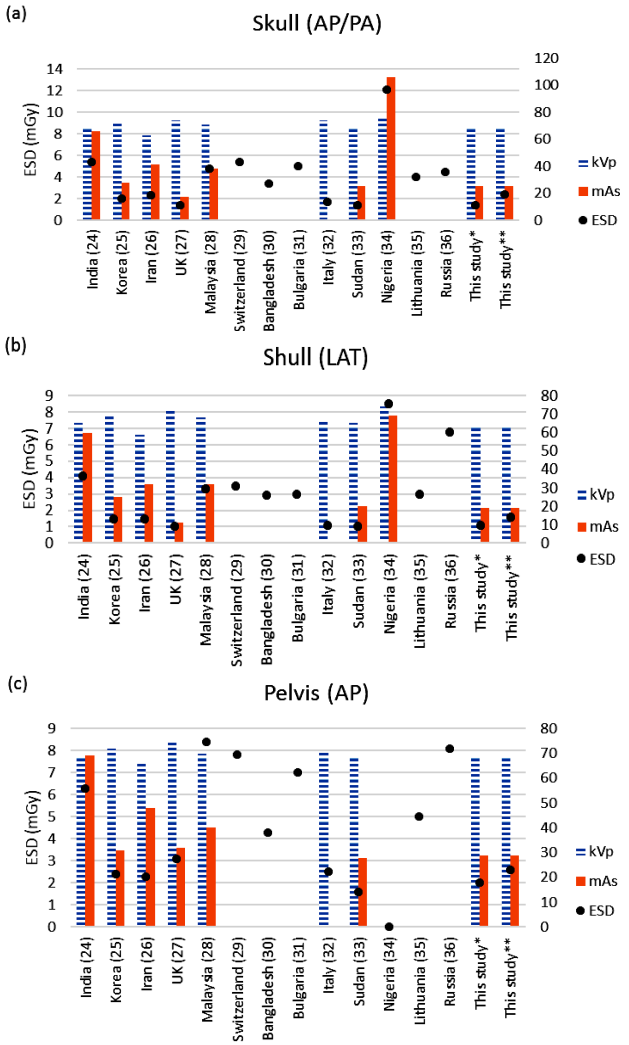


Figure 4. The average ESD and ESAK values (in mGy) and exposure parameters recorded at our hospital as compared with data presented in the literature for **(a)** skull (AP/PA), **(b)** skull (LAT) and **(c)** pelvis (AP) examinations. *ESD using DoseCal; **ESAK using CALDose_X.

For the sake of clarification, the mean ESD values found in the present study were lower than those in other investigations in India [24], Korea [25], Iran [26], Malaysia [28], Switzerland [29], Bangladesh [30], Bulgaria [31], Nigeria [34], Lithuania [35] and Russia [36]. One possible explanation for this is that the reference dose levels of some of these countries are based on data collected several years ago and using older, less efficient technology. Additional factors might also be considered, such as variations in exposure parameters, sample size and patient weight. For example, the exposure parameters (kVp and mAs values) of the skull (LAT) examinations in this study were lower than the values reported in Nigeria by factors of 1.6 and 3.6, respectively (figure 4 (b)). In comparison, we found that the average ESD value was decreased by a factor of 7.7, which could be attributed to a variation in exposure parameters. Moreover, the FSD can also affect the dose; Brennan and Nash [37] reported that there is an inverse relationship between the FSD and radiation dose and using the optimum FSD value is considered essential to optimise the dose for patients.

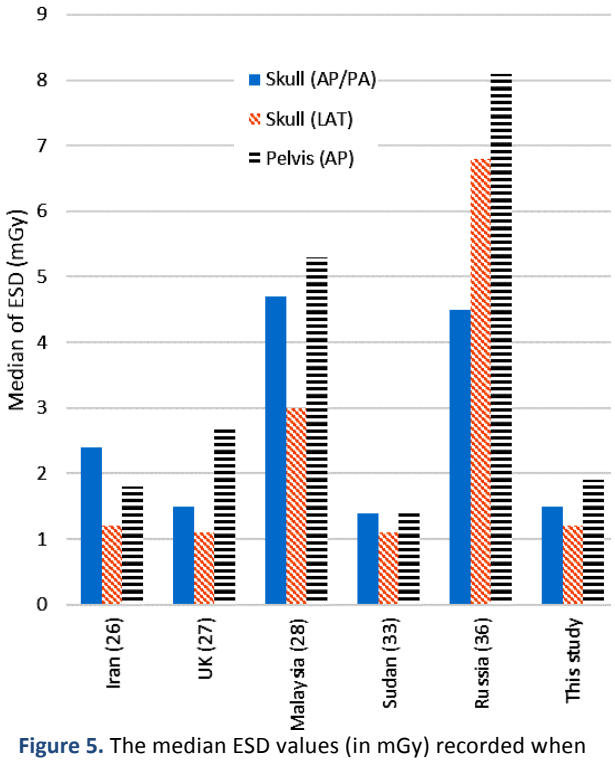


Figure 5. The median ESD values (in mGy) recorded when using DoseCal at our hospital in comparison with the data presented in the literature for (a) skull (AP/PA), (b) skull (LAT) and (c) pelvis (AP).

In some cases, it can be observed that the ESD values in this study were lower than those reported in the other international facilities by 20% to 30%. For example, the ESD value in the skull (LAT) examinations shown in figure 4(b) was lower than Korean results by 26.7% [25]. According to the local radiologist's opinions, most of the images included in this study were acceptable and easy to diagnose; however, the reduction of the ESD in this study can be associated with a degradation in image quality. An assessment of the image quality and diagnostic outcomes was absent in this study and this could be considered as one of the limitations of this research.

In this study, the median and mean ESD values for the skull (AP/PA), skull (LAT) and pelvis (AP) examinations varied by a factor of 1.1. Moreover, the

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median and mean ESD values for skull (AP/PA and LAT) examinations varied by a factor of up to 1.25 relative to the data reported in Iran [26], the UK [27], Malaysia [28], Sudan [33] and Russia [36], whereas a significant variation was observed for the pelvis (AP) as compared with results from Malaysia [28]. It can be observed that the minimum variation between the mean and median ESD values reported in this study did not affect the findings of the mean ESD values that were previously mentioned (figure 4). However, comparisons with previous studies that used mean values can achieve different outcomes as compared with comparisons with studies favouring median values. Consequently, the attention of all dose surveyors is necessary to use the median dose metric values to eliminate outlier effects.

The difference in organ or tissue dosing results seen between DoseCal and CALDose_X may be attributed to phantom formation. The organs or tissues considered in these software packages do not correspond to one another, in that the MAX06 and FAX06 phantoms were updated according to the organs/tissues specified by ICRP 103 [16]. Differences in organ and tissue absorbed doses varied up to a factor of 2.4, which may be attributed to the variable depths of some organs used in voxel phantoms. However, this is not the case for the dose absorbed by RBM, where the variation between the two software packages increased to a factor of 14.7 during the skull (AP) examination. This could be attributed to the different methods used by both software programs to calculate the absorbed dose in the RBM: specifically, DoseCal presents the dose for the active RBM, whereas CALDose_X presents the dose for maximum RBM based on the transport of the secondary electrons in micro–computed tomography images as reported by Kramer *et al.* [38].

The effective dose can be used to compare the radiation doses of different diagnostic examinations and to evaluate the associated radiobiological risks. The mean values of E for complete examinations and/or for single projections in adult patients obtained in this study were compared with data from Syria [39], Italy [32], the NRPB [40], Iran [41] and the UK and New Zealand as reported in the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [42] (table 5). It can be seen that the E values using the two software packages for skull examination varied because the assessments involved in this study consisted of more than single projections. The E values for the pelvis (AP) varied by a factor of 1.4, while the other E values calculated by both software packages were found in good agreement with the data from Syria [39], Italy [32], the NRPB [40] and the UK and New Zealand [42]. In general, the E value and cancer risk are dependent upon the type of examination: for example, during a skull examination, the brain and eye are at higher risk as compared with the others examinations [43].

Table 5. The average of E values (in mSv) as compared with data presented in the literature.

Projection	Syria [39]	Italy [32]	Iran [41]	NRPB [40]	UK [27]	New Zealand [42]	This study*	This study**
AP Pelvis	0.86***	0.58	0.337	0.67	0.66	0.63	0.51	0.36
AP skull	0.052	0.02	0.01	****	0.03	0.03	0.01	0.02
LAT skull	0.052	0.01	0.02	****	0.01	0.02	0.01	0.01

*Using DoseCal software. **Using CALDose_X software. ***Pelvis and hips. ****Data not available.

CONCLUSION

The findings of this study clearly show that both ESD and E values for skull and pelvis X-ray examinations are in good agreement with the values reported by different countries and international agency, board and commission reported in this study. The results of this study can be useful to the Saudi Arabia Nuclear and Radiological Control Authority (SNRCA) as a baseline of DRLs and, in the future, dose measurements may be compared and the collective dose from medical exposure experienced by the population can be evaluated.

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Ethical Consideration: *This study was approved by the Scientific Research Ethics Committee at Najran University (registration no. 03-02-5-18EC). Informed consent was obtained from all individual participants included in this study.*

Conflicts of interest: *None declared.*

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Authors contribution: (M.K.S.) conceptualization, data creation, formal analysis, funding acquisition, investigation, methodology, project administration; (Y.A) supervision; validation; visualization; roles/ writing - original draft; writing - review and editing.

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