Comparison of Five Models for Assessing Patient Dose From Radiological Examinations.

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Five different models of indirect entrance skin dose (ESD) measurement were examined and used to calculate the effective doses for chest postero-anterior (PA) and LAT, Abdomen anterior-posterior (AP), head and neck lateral (LAT). The effective doses (ED) were calculated from the ESD and National Radiological Protection (NRPB) published data. The mean effective dose obtained for different hospital and X-ray projections were: 0.01, 0.08, 0.11, 2.09, 1.56, 0.08 and 0.06 mSv for chest PA(LTH), chest PA (OSH) chest LAT (LTH), abdomen AP (LTH), abdomen AP (OSH), Head PA and LAT (both in LTH) radiographs. The ED calculated in chest PA projections were higher in both hospitals than the NRPB reference dose determined in UK by at least a factor of 2.6, while the ED obtained in head PA (paediatric) was higher than NRPB reference dose and the adult dose calculated by a factor of 12.6 and 9.6 respectively. The results showed that there were significant difference between the reference model (Davies model) and both of Faulkner and Tung models. There was no significant difference found between the reference model and the two other models (Edmond and Kepler). However, strong correlations were found among four of the five models investigated indicating that any of the four models could be used for determining patient entrance skin dose (ESD), the starting point for the calculation of effective doses. Finally, patients investigated in this study are at higher health risk than patients examined in the United Kingdoms (UK).

Keywords: Entrance; Skin; Dose; Effective; Technique; Factor; Thermoluminescent; Dosimeter; Model; Patient.

1. Introduction

Worldwide interest in patient dose measurement was stimulated by the 1990 publication of National Radiological Protection Board [1]. Also, the need for patient dose measurement has been emphasized in national protocol for patient dose measurement in diagnostic radiology published by National Radiological Protection Board (NRPB) in collaboration with Institute of Physical Sciences in Medicine (IPSM) and the College of Radiographer [2]. Based on the needs for knowledge of the doses absorbed by patients and the consequences of the absorbed doses, National Occupational Health and Safety Commission [3] indicated that dose assessment of employee and members of the public are required, and appropriate to ensure compliance with recommendation. Directives from regulatory bodies stipulates that radiation should be measured in every hospital and compared to the reference doses established by the competent authorities [4,5]. Although, diagnostic imaging using X-rays produces a net benefit, the potential for radiation-induced injury to the patients exist. As a result, understanding of absorbed doses and the factors that affect them therefore are very important [6]. Several major radiation doses delivered to the patient during diagnostic imaging have been reported, especially

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from advanced countries [7-10].

Both direct and indirect methods have been used to measure the entrance skin dose (radiation dose absorbed by the skin where the X-ray beam enters the patient) by different researchers. The entrance skin dose could be measured directly with thermoluminescent dosimeters (TLD) or computed from measurement made with ionization chamber [11-13]. Another method which can be used in the measurement of ESD is the use of X-ray output, technique factors and the backscatter factor. The calculation of ESD from output measurement and technique factors is a realistic alternative method to dosimeter measurements such as for example measurements with TLD [14].

In specific terms, ESD in diagnostic radiography is proportional to the tube curent (mA) the period of exposure, the square of peak kilovoltage and backscatter factor. Other factors include inverse square law (inverse of the square of the distance between the X-ray source and the patient) and filtration of the X-ray tube [4,14,16].

Although the entrance skin exposure has been a popular method of expressing patient radiation doses, however, this parameter does not take into account the X-ray beam quality or the size of the X-ray beam. Therefore, the patient exposure is generally a poor indicator of the risk associated with a given radiographic examinations [17]. Recently effective dose (ED) has been used to quantify the dose to patients undergoing radiographic examinations [18]. The major benefit of using the effective dose is that this parameter accounts for the absorbed doses and relative radiosensitivities of the irradiated organs in the patient and, therefore better quantifies the patient risk [7,19,20]. Calculation of effective dose requires the knowledge of mean absorbed dose to each irradiated organ in the body [2,22]. Also ED could be calculated from the energy imparted [23]. In the National Radiological Protection Board (NRPB) report R262, methods for calculating effective dose using dose-area product and entrance skin dose were presented. These methods are considered more accurate even for complete examinations when the applied potential and filtration are not known. In this method, the calculated entrance skin dose is converted into effective dose using the published data provided by NRPB in the report R262 for different radiographic projections, filtration and applied voltages.

This study examines five different models for calculating ESD [4,15,16,24]. Entrance skin dose (ESD) was calculated using different models proposed by different authors. The following are the models examined:

**1.1 Davies Model**
The model is represented by equation (1)

\[
ESD = O/P (\text{kV})^2 \text{mAs} \left(\frac{100}{FSD}\right)^2 \text{BSF}
\]

where \(O/P\) is the output of the tube of the X-ray machine in mGy (mAs)\(^{-1}\) at 80 kV at a distance of 1m normalised to 10 mAs; kV is the tube potential; mAs, the product of the tube current (in mA); and the exposure time (in s); FSD is the focus-to-skin distance (in cm) and BSF the backscatter factor.

The BSF accounts for the radiation scattered back to the surface of the patient; it depends partly on the energy, field size of the X-ray beam, kVp, FFD, body tissue etc. They are typically in the range of 1.30-1.40. In this study we used 1.30 for paediatric patients and 1.35 for adult patients as suggested in European guidelines [30,31]. The normalisation at 80 kV and 10 mAs was used as the potential across the X-ray tube and the anode current are highly stabilised at this point [27].

**1.2 Kepler Model**
This model left out the tube potential but accounted for the BSF. The entrance skin dose \(ESD_y\) is given as follows:

\[
ESD_y = Y_{100} \times \text{mAs} \left(\frac{FFD}{FSD}\right)^2 \text{BSF}
\]

where \(Y_{100}\) (mGy/mAs) is the X-ray tube yield.

This parameter is tube potential and filtration dependent and it is the same as the output described in equation (1) at a standard distance of 100 cm from the tube focus. The FFD is the focus-to-film distance (100 cm) used in the tube yield measurement.
1.3 Faulkner Model

Here Faulkner model is defined by the following equation:

\[
ESD = \text{output} \left( \frac{kV^2}{80^2} \right) \left( \frac{100^2}{FSD^2} \right) \frac{mAs}{BSF} \]

where all the parameters are as defined in equation (1)

1.4 Edmonds Model

Edmonds [4] demonstrated that the X-radiation dose to patients from diagnostic X-ray machines assume a simple functional dependence on radiographic exposure

\[
ESD = \frac{836 (kVp)^{-74}}{(FSD)^2} mAs \left( \frac{1}{T} + 0.114 \right)
\]

where T is the total filtration which include the inherent and the added in mm Al.

The model does not account for the output of the machine and BSF.

1.5 Tung Model

The entrance skin dose to air with backscatter could be obtained using Tung model. This is given by equation (5):

\[
ESD_{air} = FAE \times 0.00877 \times BSF
\]

where FAE is the free-in-air exposure (in mR) without backscatter. The factor 0.00877 converts the exposure, in mR into the absorbed dose to air in unit of mGy.

Moreover, to convert \( ESD_{air} \) to tissue \( ESD_{tissue} \), it is multiplied by 106± 1% [28]. The \( ESD_{air} \) was recommended by International Atomic Energy Agency (IAEA) as the dose descriptor for guidance levels in diagnostic radiography. This stems from its simplicity and indication of the maximum skin dose. This dosimetric parameter is used for periodic checking of patient doses [29].

The results obtained using these models were converted into effective dose (ED) and compared to see if there were significant differences between the reference (Davies model) [15] and four other models. Also the test of relationship was carried out to find out the level of correlation among all the models proposed by different authors and the effects on the effective dose.

2. Materials and Methods

The data used for this work were collected at two different hospitals; LAUTECH Teaching hospital (LTH), Osogbo and Ogun State Hospital (OSH), Ijebu Ode. Technique factors such as kilovoltage peak (kVp), product of X-ray tube current and time (mAs), focus-to-film distance (FFD) and focus-to-skin distance (FSD) with the patient characteristics such as weight, height, age and thickness of irradiated regions were obtained during the routine X-ray examinations with the assistance of radiographers on duty. The thickness of the patient was obtained using, thickness = FFD - FSD. A total of 197 patients’ radiographs and exposure factors were obtained in both LTH and OSH. This consist of 156 adults (140 in LTH and 16 in OSH) and 41 paediatric patients in LTH. The age groups of the patients considered were 0-16 years (paediatrics) and above 16 years (adults). Necessary permission was obtained from the appropriate quarters of the institutions investigated.

The two X-ray machines used were analogue installed more than twenty four years before. The output (in mGy/mAs) at 80 kVp at a distance of 1m normalised to 10 mAs [14] was measured using factory calibrated KV meter (US made Victoreen X-ray test device model 4000 M+) obtained from the Department of Physics University of Ibadan, Ibadan. The KV meter measures mean, effective and the maximum peak tube voltage, power phase exposure and exposure time.

The device determines the tube voltage with accuracy of ± 2% [32]. The internal ionization chamber that measures exposure has a volume of 36 cm³. The exposure time is measured to an accuracy of ± 2%.

The ESD for both hospitals and different projections were calculated using equation (1) [15] and converted into effective dose. Other four models (given by equations (2)-(5)) proposed by different authors [4,16,24,25] were also used for calculating
ESD and converted into effective dose (ED) using published conversion factor of NRPB in the report NRPB R262 [21]. The results obtained were subjected to test of significance difference (t-test) and test of relationship (correlation).

The mean value of effective dose obtained using Davies model was compared with the mean values obtained using Kepler model, Faulkner model, Edmonds model and Tung model. The model of Davies in equation (1) is considered as reference model against which other models were compared. This consideration stemmed from the fact that it has been used by several authors to obtain realistic results that compared well with the direct measurement using thermoluminescent dosimeter [14,15,26].

3. Results

Tables 1 and 2 present the mean values of effective dose (ED) obtained for different hospitals and projections using different models both for adults and paediatric patients. The results in Table 1 shows that the doses obtained in LTH and OSH are greater than the reference doses published by NRPB by at least a factor of 2 for chest PA in LTH and OSH (adult patients). Similar trend was found for Head LAT in LTH where doses higher than NRPB was obtained with Tung model. It is evident from table 2 that the mean value of the dose got with different models were higher than the reference doses by factors that range between 1.2 and 6.0. For the same projection and in OSH, the results of calculated ED

### Table 1: Mean value effective dose (mSv) calculated for adult patient with different models and NRPB conversion factors

<table>
<thead>
<tr>
<th>Projection (Hospital)</th>
<th>£Davies</th>
<th>£Kepler</th>
<th>£Faulkner</th>
<th>£Edmonds</th>
<th>£Tung</th>
<th>Mean</th>
<th>£NRPB (UK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest PA (LTH)</td>
<td>0.13</td>
<td>0.19</td>
<td>0.07</td>
<td>0.10</td>
<td>0.09</td>
<td>0.12</td>
<td>0.03</td>
</tr>
<tr>
<td>Chest PA (OSH)</td>
<td>0.07</td>
<td>0.06</td>
<td>2.91</td>
<td>0.09</td>
<td>0.07</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>Chest LAT (LTH)</td>
<td>0.14</td>
<td>0.17</td>
<td>0.08</td>
<td>0.10</td>
<td>0.06</td>
<td>0.11</td>
<td>-</td>
</tr>
<tr>
<td>Abdomen AP (LTH)</td>
<td>3.17</td>
<td>3.14</td>
<td>1.74</td>
<td>0.92</td>
<td>0.12</td>
<td>2.09</td>
<td>1.36</td>
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<tr>
<td>Abdomen AP (OSH)</td>
<td>1.03</td>
<td>2.31</td>
<td>2.91</td>
<td>0.09</td>
<td>0.09</td>
<td>1.56</td>
<td>1.36</td>
</tr>
<tr>
<td>Head PA (LTH)</td>
<td>0.10</td>
<td>0.11</td>
<td>0.06</td>
<td>0.07</td>
<td>0.01</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>Head LAT (LTH)</td>
<td>0.09</td>
<td>0.09</td>
<td>0.05</td>
<td>0.07</td>
<td>0.01</td>
<td>0.06</td>
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### Table 2: Mean value of effective dose (mSv) calculated for children with different models and NRPB conversion factor

<table>
<thead>
<tr>
<th>Projection (Hospital)</th>
<th>£Davies</th>
<th>£Kepler</th>
<th>£Faulkner</th>
<th>£Edmonds</th>
<th>£Tung</th>
<th>Mean</th>
<th>Coefficient of Variation (%) CV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest PA (LTH)</td>
<td>0.05</td>
<td>0.01</td>
<td>0.03</td>
<td>0.04</td>
<td>0.07</td>
<td>0.04±0.022</td>
<td>55</td>
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<tr>
<td>Chest LAT (LTH)</td>
<td>0.05</td>
<td>0.12</td>
<td>0.03</td>
<td>0.05</td>
<td>0.06</td>
<td>0.06±0.034</td>
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<tr>
<td>Head LAT (LTH)</td>
<td>0.52</td>
<td>0.78</td>
<td>0.31</td>
<td>0.42</td>
<td>0.05</td>
<td>0.42±0.26</td>
<td>62</td>
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<tr>
<td>Head PA (LTH)</td>
<td>0.88</td>
<td>1.18</td>
<td>0.52</td>
<td>0.70</td>
<td>0.56</td>
<td>0.77±0.27</td>
<td>35</td>
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<tr>
<td>Neck LAT (LTH)</td>
<td>0.06</td>
<td>0.05</td>
<td>0.02</td>
<td>0.02</td>
<td>0.06</td>
<td>0.04 ± 0.02</td>
<td>50</td>
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Table 3: Correlation among different models used

<table>
<thead>
<tr>
<th></th>
<th>Davies</th>
<th>Kepler</th>
<th>Faulkner</th>
<th>Edmonds</th>
<th>Tung</th>
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<td>Davies</td>
<td>1</td>
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<tr>
<td>Kepler</td>
<td>0.96309</td>
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<tr>
<td>Faulkner</td>
<td>1</td>
<td>0.96309</td>
<td>1</td>
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<tr>
<td>Edmond</td>
<td>0.999474</td>
<td>0.971283</td>
<td>0.999474</td>
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<td>1</td>
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<tr>
<td>Tung</td>
<td>0.348395</td>
<td>0.108634</td>
<td>0.348395</td>
<td>0.321057</td>
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Table 4: Test of significant difference between Davies and Kepler

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<td>0.095753</td>
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<tr>
<td>Variance</td>
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<td>0.002197</td>
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<td>Observations</td>
<td>27</td>
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<tr>
<td>Hypothesized Mean Difference</td>
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<td></td>
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<tr>
<td>df</td>
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<td>t Stat</td>
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<td>P(T&lt;=t) one-tail</td>
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<td>P(T&lt;=t) two-tail</td>
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<td>t Critical two-tail</td>
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Table 5: Test of significant difference between Davies and Edmonds

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<td>0.000466</td>
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<tr>
<td>Observations</td>
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<td>27</td>
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<tr>
<td>df</td>
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<tr>
<td>t Stat</td>
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<td>P(T&lt;=t) one-tail</td>
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<tr>
<td>t Critical one-tail</td>
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<tr>
<td>P(T&lt;=t) two-tail</td>
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<tr>
<td>t Critical two-tail</td>
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Table 6: Test of significance between Davies and Faulkner

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<td>df</td>
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<tr>
<td>t Stat</td>
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<td>t Critical one-tail</td>
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<td>P(T&lt;=t) two-tail</td>
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<td>t Critical two-tail</td>
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Table 7: Test of significance between Davies and Tung et al

<table>
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<td>Mean</td>
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<td>Variance</td>
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<td>Observations</td>
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<td>Hypothesized Mean Difference</td>
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<td>t Stat</td>
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<td>t Critical two-tail</td>
<td>2.04523</td>
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- **Table 3**: Correlation among different models used
- **Table 4**: Test of significant difference between Davies and Kepler
- **Table 5**: Test of significant difference between Davies and Edmonds
- **Table 6**: Test of significance between Davies and Faulkner
- **Table 7**: Test of significance between Davies and Tung et al
using Davies and Tung models were in agreement and comparable with Kepler and Edmonds models. Moreover, for chest LAT and in LTH, the results of ED obtained using Davies and Kepler models are comparable, while those of Faulkner, Edmonds and Tung also compared well. In abdomen AP (in LTH) the dose obtained using Davies and Kepler are in good agreement. Moreover, in abdomen AP (OSH), the results of Edmonds and Tung are the same. Meanwhile, the results of Davies and Kepler were similar for head LAT projection in LTH, while Faulkner and Edmond were in close agreement.

Results in Table 2 also indicate that the EDs obtained in paediatric patients fall in the range of 0.01-0.07, 0.03-1.2, 0.05-0.78, 0.52-1.18 and 0.02-0.06 mSv in chest PA, chest LAT, head LAT, head PA and Neck LAT respectively with standard deviation, that range between 0.02 and 0.27. The coefficient of variations (CVs) in table 2 indicate that the highest spread is found in head LAT and the least in the head PA. Also, comparing the result of mean values obtained for children in head PA and head LAT with the NRPB reference data show that each is higher than the NRPB reference dose (obtained from the third quartile).

Table 3 shows the correlation among the five models used. The first column is an indication that the dose calculated using: Davies, Kepler, Faulkner and Edmonds models correlated, while that of Tung model has relatively low correlation.

Tables 4-7 show the test for significant difference in the results between Davies and each of other models investigated in this study. In Table 4, the t-calculated is less than t-tabulated, in Table 5, t-calculated is greater than t-tabulated. Also, in Table 6 the t-calculated is less than t-tabulated while in Table 7, t-calculated is greater than t-tabulated.

Figs 1 and 2 indicate the plot of dose (mSv) against level of exposures. The two figures show that the results from Davies, Kepler, Faulkner and Edmonds models followed the same trend, while Tung generally maintained an average dose for all levels of exposures considered.
4. Discussion

The results in this work showed that the effective doses obtained in LTH and OSH were greater than the NRPB reference doses for both adult and children patients in chest PA and LAT indicating that, patients examined in LTH and OSH are at higher health risk than patients examined in NRPB (UK) report. Higher children doses recorded in head LAT and head PA is far from a good practice since the risk of carcinogenesis is greater in children than for adult, it is necessary for the personnel to optimize the justified X-ray examination. This could be achieved by keeping in focus the consequences of higher doses to the patients and, therefore, carefully match the patient age and size to the technique factors during radiographic examinations.

Moreover, Table 3 revealed strong correlations among Davies, Kepler, Faulkner and Edmonds (almost 1), while low correlation was found between Davies and Tung models. The strong correlation found among the models used indicate that the doses delivered to the patients, besides product of tube current and time (mAs), inverse square law and total filtration, is also dependent of the output of the X-ray machine, age of the machine. Higher value of mAs and low focus-to-skin distance (FSD) contribute to increase in radiation dose to the patient [28]. The aforementioned factors were taken into consideration by Kepler, Edmonds, and Tung models. Other important factors which contribute to doses are backscatter factor (dependent of field size and half value layer) and partially on energy.

Table 4 shows that there is no significant difference in ED calculated using Davies and Kepler models indicating that both could be used to calculate ESD. However, Table 5 shows that there is significant difference between the ED computed using Davies and Edmonds models. This trend could be attributed to the fact that Edmonds did not include backscatter factor and machine output in his model.

Result of Table 6 indicate that t-calculated is less than, t-tabulated; this implies that there is no significant difference in the dose calculated using Davies and Faulkner models.

In addition, Table 7 shows that there is a significant difference between the effective dose (ED) calculated using Davies and Tung models.

5. Conclusion

The entrance skin dose and effective dose have been measured using indirect methods (computation using technique factors and machine parameters)
employing different models proposed by various authors in the field and compared with Davies model. The ESD obtained were converted to effective dose using NRPB published conversion factors. The radiation dose to the patients is dependent of mAs, output of X-ray machines, filtration, focus- skin distance, field size and backscatter factor. Though the use of the indirect method of radiation measurement is a realistic alternative to the use of TLD, it is important to use the appropriate model that includes all the factors that contribute to the dose of the patient. This enhances the determination of true value of the dose delivered to the patient during radiographic examinations, and hence, the risks involved. Since most of the doses calculated in this study were greater than the NRPB reference dose showing that patients examined in this study are at higher health risk than patients in the UK study. Therefore, it is important for the personnel involved in the radiographic examinations to understand the factors that affect patient doses, and make necessary effort to select the appropriate exposure parameters such that the doses to the patient are kept as low as reasonably achievable (ALARA) while maintaining the image quality.

References


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