A Comparison of the Suitability of Patient Dosimetry Methods for Establishing Diagnostic Dose Reference Levels and Optimisation Strategies.

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Abstract. For 50 adult patients referred for chest radiography, air kerma at the diaphragm $K_D$, dose area product and entrance skin dose were measured. The air kerma at the diaphragm and the dose area product were determined using Diamentor M4KDK(PTW) which allows measuring air kerma and dose area product simultaneously. For the measurement of entrance skin dose TLDs are used. A 50\% variation in dose, incident dose as well as entrance skin dose, was registered for the same patient thickness. The recommendation of ICRP to perform the measurements for DRLs at “representative patients” and that of the CEC to use “standard-sized patients” seem to make little sense in the case of chest radiography. It could be demonstrated, that the dose area product is the least appropriate dose quantity for patient measurements and to define dose reference levels. For some radiological examinations like chest, pelvis and lumbar spine the dose area product is even sex dependent. Incident dose and entrance surface dose are of equal quality for patient dose measurements in diagnostic radiography.

KEYWORDS: diagnostic radiology, patient dosimetry dose reference levels, dose area product, incident dose, air kerma, entrance skin dose.

1. Introduction

Measurement of dose is a foundation for the application of scientific methods to the field of diagnostic radiology and patient dose assessment is perhaps the most important aspect. Over the past 25 years, a great deal of effort has been expended by International, Governmental and Professional bodies in order to highlight this activity.

In 1996 ICRP[1] and in 2007 ICRP[15] recommended the use of diagnostic reference levels for patients. These levels, which are a form of investigation level, apply to an easily measured quantity, usually the absorbed dose in air (air kerma). In consequent pursuance of this principle the Council of the European Union adopted this principle in 1997, in the EC Directive 97/43/EURATOM[2]. In Article 4 of this Directive entitled Optimisation, it was stated that the optimization process should include the practical aspects quality assurance, including quality control, and the assessment and evaluation of patient doses. Thus patient dose measurements are seen as integral components of the optimisation process. Also in Article 4, the European Commission required that Member States should promote the establishment and the use of diagnostic reference levels for radio diagnostic examinations. Special guidance, to competent authorities as well as professional groups, on principles for the establishment of Diagnostic Reference Levels (DRLs), is given in Radiation Protection 109[3] as well as paediatric patients[4]. Hence DRLs, also, are seen to be part of the optimisation process. In principle three dose quantities are suitable for patient dosimetry in diagnostic radiology:

- The incident dose (ID) is the absorbed dose in air at the patients surface (without backscatter).
- The entrance surface dose (ESD) is the dose measured at the surface of the patient (including backscatter).
- The dose area product (DAP) is equivalent to the product of air kerma and field size, and
- usually measured at the beam collimating device.

Given the importance of patient dose assessments to the quantification of performance in diagnostic radiology, the aim of the present study was to explore those factors that can influence the effectiveness of DRLs in the optimisation process. The study involved the assessment of the results obtained by different dosimetric techniques for the radiographic PA chest examination, a very common examination. The purpose of the assessment was to determine those factors that may affect their utilisation and inter-comparison, both from the point of view of dosimetric method as well as the patients/phantoms employed.

2. Materials and Methods

For 50 adult patients referred for radiographic PA chest examinations, air kerma at the diaphragm $K_D$, dose area product (DAP) and entrance skin dose (ESD) were measured. Patient’s height and age as well as focus-to-patient-distance and the focus-to-stand-distance were registered. $K_D$ and DAP were measured using a Diamentor M4KDK (PTW) that has already been described elsewhere[7] and which is able to measure DAP and air kerma simultaneously. For the measurement of the ESD, 2 TLDs, type TLD100H (Bicron/Harshaw), sealed in PMMA sachets were pasted at the entrance point of the central beam. The evaluation of the TLDs was performed using a TLD-management system[8]. The precision of the TLD measurements was better than 2%.

The $K_D$ and DAP calibration was determined using a DIADOS dosimeter (PTW). In order to eliminate the influence of backscattered radiation from the chest stand, 30 cm foam was placed between the wooden stand and the DIADOS dosimeter during the calibration procedure. Thus calibration of the air kerma measurement was achieved. Because of the field size dependence of the DAP calibration, the DAP calibration was performed at the mean field size of the PA chest examinations. The kVp dependences of DAP and $K_D$ were ruled out by calibrating at 125 kVp – the tube voltage employed in the examinations. All radiographs were performed on a Siemens (Vertix, Polymat) X-ray unit with a focus-to-film-distance of 1.8 m, and 125 kVp X-ray tube voltage with total filtration of 2.5 mm Al equivalent and under automatic exposure control. A Fuji film screen system, with a nominal speed class of 200 was used, which was not in accordance with the European Guidelines3. Film processing was controlled each day before the first and after the last measurement and found to be constant.

In order to test the accuracy of the measurement process, measurements with a PMMA phantom were used. The exposure parameters were the same as for patient measurements. The phantom consisted of slabs of PMMA. Thus the thickness of the phantom could be varied. The focus-to-film-distance was constant and was the same as that employed in the patient measurements. The entrance surface dose was measured with two TLDs in the central beam. DAP and $K_D$ were measured as described above. The focus-to-surface-distance $d_{FS}$ is the sum of the focus-collimator-distance $d_{C}$ plus the collimator-surface-distance $d_P$. Using these relations $ID_1$ may be calculated according to equation 1.

\[
ID_1 = K_D \cdot \left(\frac{d_C}{d_{FS}}\right)^2
\]  
(1)

ESD can be related to $ID_1$ by the back scatter factor $B$.

\[
B = \frac{ESD}{ID_1}
\]  
(2)

Using the known beam size $A_s$ at the surface, the incident dose to air can also be calculated from the DAP by means of equation 3.

\[
ID_2 = \frac{DAP}{A_s}
\]  
(3)
Ideally the two quantities $ID_1$ and $ID_2$ should be identical but they do differ in the way they are measured. $ID_1$ is measured from a specific region of the DAP meter with a 1 square cm area and this measurement is corrected to the surface entrance dose by means of the appropriate distances. On the other hand $ID_2$ involves an area correction of the DAP reading.

3. Results

3.1 Incident dose and entrance skin dose

Figure 1: Entrance skin dose and incident dose $ID_1$ as a function of the thickness of PMMA

![Figure 1](image1.png)

Figure 2: Back scatter factor as a function of the PMMA thickness.

![Figure 2](image2.png)

3.1.1 Measurements with the PMMA phantom

Fig. 1 shows the relation between the measured ESD values and the corresponding $ID_1$ values as a function of the PMMA thickness. The measured ESD and $ID_1$ values fit almost exactly (Pearson square correlation coefficient 0.9998 and 0.9988 respectively) an exponential according to the standard law of attenuation. The quotient of the two curves represents the backscatter factor, according to equation 2. A calculation of $ID_2$ from DAP values resulted in identical results to that from $K_D$ in equation 1, which is to be expected because of the well defined geometrical conditions. The backscatter factor calculated from the quotient of the two curves is shown as a function of the PMMA thickness in Fig. 2. For a PMMA thickness larger than 10 cm $B$, reaches a maximum at roughly $B = 1.5$. 
3.1.2 Patient measurements

In Fig. 3 the measured ESD and ID₁ are plotted against patient thickness. The patient thickness was calculated from the difference between the collimator-to-stand-distance and the collimator-to-skin-distance. The data can again be fitted to an exponential but with a much lower correlation coefficient.

**Figure 4:** Differences of the measured ESD (○) and ID₁ (♦) values from the corresponding exponential fits.

This situation can be further demonstrated by calculating the differences between the measured ESD and ID₁ values and the corresponding exponential fits i.e. normalising the data to an “average” transmission curve. The differences, in percentages, are plotted in Fig. 4 against the patient thicknesses. A variation of ±50% can be observed for the same patient thickness. No significant difference in the deviations of the measured values from the fits can be observed between ID₁ and ESD and this effect will also be expected when measuring DAP. Because the same variations could be observed for ID₁ as well as ESD, the variations cannot be attributed to backscatter. The main reason for these variations must obviously be assigned to the differences in the effective attenuation due to the effective attenuation coefficient of the tissues and body fluids, even for the same thickness.

3.2 Incident dose and dose area product

3.2.1 Phantom measurements
In Fig. 5 the ID₂ calculated according to equation 3 is shown as a function of the measured ID₁. According to equation 3 for a fixed field size the DAP is directly proportional to the ID₂.

**Figure 5:** The ID₂ calculated from DAP against measured ID₁.

![Graph showing linear relationship between ID₂ (from DAP) and ID₁ (measured) with equation y = 0.9982x - 0.0011 and R² = 1.]

The measurements with the PMMA phantom, which were performed at a nearly constant field size, show this relation clearly. The points of measurement follow smoothly a straight line through the origin with a very high correlation factor.

3.2.2 Patient measurements

The actual field size used was determined from the radiographic images. This field size was corrected for distance in order to assess the actual field size at the patient’s surface plane by using the focus film distance and the focus-to-patient-distance. In Fig. 6, ID₂ was calculated from the DAP and is plotted against the measured ID₁. The line of regression is steeper than the diagonal line and starts at about 0.01. This means that the real field sizes are larger than the ones assumed from the patient’s film.

**Figure 6:** The ID₂ calculated from measured DAP against the measured ID₁ for patients.

![Graph showing linear relationship between ID₂ (calculated from DAP) and ID₁ (measured) with equation y = 1.2467x - 0.0154 and R² = 0.9638.]

The reason for this was that an unexposed rim at the cranial part of the radiographic images was mostly absent from the field size assessment. In addition the values are scattered by up to ±30% around the line of regression. This fluctuation can only be due to the uncertainty in field size, either...
because an unexposed rim was missing or because of the difficulty in finding the field size from the radiographic image.

**Figure 7:** DAP as a function of ID$_1$ for men and women respectively.

![Graph showing DAP as a function of ID$_1$ for men and women](image)

In Fig. 7 DAP values are plotted against ID$_1$ values for men and women respectively. As can be seen there is a significant difference between the DAP values of men and women. This difference must obviously result from the anatomical differences between men and women. In Table 1 the mean values and their standard deviations of ID, ESD and DAP respectively for men and women are summarized. Finally the value of the student’s t-test is shown. As can be seen from the values of the student’s t-test, the dose values for men and women belong to different distributions. The ratio of the values for men and women is equal for ID and ESD. This fact has to be attributed to a difference in the mean attenuation for men and women respectively. For the DAP we find in Table 1 a significantly higher value of 1.49. This additional variation of about 25% is due to the difference in field sizes used for men and women respectively. In our clinic this fact resulted in different format sizes used for men and women. For women usually a film size of 35x35 whilst for men one of 35x43 is used. Again we can observe a fluctuation in DAP around the regression lines, which is larger for men. The range of this fluctuation is about +/−25% and is only due to the different field sizes employed (i.e. variation at constant ID$_1$). These fluctuations will even be more pronounced (percentage-wise) the better the collimation of the region of interest.

### Table 1: A comparison of the mean values for men and women of ID$_1$, ESD and DAP respectively.

<table>
<thead>
<tr>
<th></th>
<th>Men (n=27)</th>
<th>Women (n=19)</th>
<th>Dose quantity</th>
<th>Student’s t</th>
<th>Men/women</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.170 ± 0.071</td>
<td>0.138 ± 0.053</td>
<td>Mean ID$_1$ ± SD</td>
<td>1.66</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>0.250 ± 0.113</td>
<td>0.204 ± 0.079</td>
<td>Mean ESD ± SD</td>
<td>1.52</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>201.5 ± 87.3</td>
<td>135.6 ± 54.9</td>
<td>Mean DAP ± SD</td>
<td>2.91</td>
<td>1.49</td>
</tr>
</tbody>
</table>

4. Discussion
Patient dose measurements for PA chest examinations have been performed for both male and female patients. This involved measurements of incident dose to air (ID), entrance surface dose (ESD) and dose-area product (DAP) all performed on the same patient. Incident entrance surface dose in air measurements were measured by means of a facility provided on the chamber of the DAP meter (ID₁) with a correction for the patient to focus distance. This was also measured by correcting the DAP value for the beam size at the patients entrance surface (ID₂). The inter-comparability of the different dose measurements can only be attributed to anatomical differences between patients since technique factors were the same for each measurement on each patient.

Figure 1 shows that all three dose quantities follow an exponential relationship with thickness under ideal phantom absorber conditions. The ESD and ID₁ values only differ by the backscatter factor. However, for patient measurements a completely different situation exists. Figure 3 indicates that the dependence of both dose quantities, ESD and ID₁, show a wider variation and the logarithmic fit to an exponential is less pronounced. A least squares fit to the data points shown in Figure 3 represents the average transmission curve for both ESD and ID₁ of a form log(dose)= kx + c, where x is the patient thickness, k the effective logarithmic transmission and c a constant.

The effective logarithmic transmission coefficients noted for the PA chest examinations were 0.0925 cm⁻¹ for ESD and 0.0882 cm⁻¹ for ID₁. Correction of the data for this average logarithmic transmission variation showed, in Figure 4, that variations of up to 50% existed in the dose for the same patient thickness. Also, results presented in Table 1 indicate that the ratio of mean ESD and ID₁ values for male and female patients were statistically different (ratio 1.23). These results pose the question as to what constitutes “representative patients” according to ICRP[1] or “standard-sized patients” according to CEC. This uncertainty or variation must be due to differences in the effective attenuation of both male and female patients.

Patient ESD values for adult PA chest examinations derived from a survey in Italy, showed significant differences in mean dose values measured for male and female patients[9]. Mean total examination doses were 0.68 mGy for men and 0.4 mGy for women. The average number of films employed was not quoted. Nonetheless, this difference (ratio 1.7) was larger than that observed in the present study (ratio 1.23). Differences between ESD for male and female patients have also been noted in a UK national study of patient doses undertaken in 1986[10]. The mean ESD for male PA chest examinations was 0.26 mGy and for females 0.2 mGy. The ratio of 1.3 agrees closely with the value found in the present study. In the UK study the average weights for the male patients was 71 kg and for the female patients 59 kg. A very large fraction of the female group who would be deemed to be of normal weight for female patients, would not meet the criteria for patient dose audit selection[5]. This is in agreement with the average weights for male (68 kg) and female patients (58 kg) noted in an investigation of fluoroscopic exposures[11]. These results also pose the question as to what is a satisfactory weight range when selecting adult patient dose audit criteria for both male and female patients[5].

Based upon the UK national study of patient doses, guideline DRL values were established in Europe for a number of common radiographic examinations of adult patients[3]. These were based upon third quartile values of a reasonably large sample of measurements. Compliance with these values is then assessed, by comparing the mean ESD of a suitable sample of patients. For the PA chest examination a third quartile value of 0.26 mGy was established for a sample of adult male and female patients. Whereas for the male patient group the mean ESD was also 0.26 mGy, for the female group the mean value was 0.2 mGy. Both of these values also corresponded to the third quartile values for each group. Thus, in effect, female patients may receive on average up to 30% more exposure, compared to their own population dose requirements, and still be deemed to be within existing DRL guidelines.

Figure 6 of the present study also demonstrates that for DAP measurements, there is an increased variation in patient area-dose arising from variations in field size, since variations in ID₁ and ID₂ can only arise from field dependent factors. This variation amounts to roughly 30%. Also by plotting DAP
value against the DAP calculated dose ID₂, shown in Figure 7, a purely area dependent component of the DAP reading which is due to patient variations has been noted. This variation is roughly 25% and is due to variations in the field size employed from patient to patient due to their lateral dimensions. This variation may be even larger, percentage-wise, if collimation to the region of interest is more strict to smaller field sizes.

In the present work the DAP meter was calibrated at the mean field size used for adult chest examinations. If a general calibration is employed an additional uncertainty of ± 7% results over the range of field sizes 300 to 1500 cm² expected for this type of examination. This is due to a field size dependent calibration factor[7]. However, Figure 7 also shows that an additional systematic uncertainty results from the fundamental difference in field sizes employed for male and female patients. The results are summarised in Table 1. The male to female DAP ratio is 1.49 and the observed DAP per unit dose is 1198 mGy cm² per m Gy for male patients and 744 mGy cm² per mGy for female patients (these values effectively represent the mean field sizes employed).

A further comparison of DAP values for patients who undergo PA chest examinations may be undertaken from the results of the comprehensive national dose surveys undertaken in the UK[10], in 1986. In the 1986 survey mean DAP readings for both adult female and male patients who underwent a PA chest examination were presented. For female patients (sample size 232) the mean DAP reading was 0.32 Gy cm² (37 R cm²) whilst for adult males it was 0.6 Gy cm² (69 R cm²), a ratio of male to female values of 1.87. For both groups of patients their mean and third quartile DAP values were identical. The third quartile DAP value for both male and female groups combined was 0.42 Gy cm² (48 R cm²). Thus again the mean DAP value for the female population may exceed its own population norm by roughly 25% and still be deemed acceptable. However, the average field size for female patients is (according to Figure 8) roughly 30% lower than the total male/female population average (970 mGy cm² per mGy). Thus the ESD component of a DAP reading could be over 50% higher than expected and still be considered acceptable from the point of view of the DRl expressed as an all adult DAP value. Alternatively, for an acceptable ESD the field size could equally be much larger than necessary whilst still maintaining a satisfactory DAP value. Without knowing both the ESD and DAP values, or alternatively the DAP and field size, for an examination we have no way of knowing whether an examination has been optimised for both ESD and field size.

Results of the present study indicate that the existing framework for DRLs in diagnostic radiology can permit significantly higher doses to female patients than is required according to best practice whilst still assumes that practices are acceptable. This is most noticeable when DRLs are expressed solely in terms of DAP values. It is possible to optimise DRLs, and hence radiological practice, by implementing separate DRLs for male and female patients in terms of both ESD and DAP. The ESD value would optimise practices for dose and the DAP for area. Both values would be required for each examination in order to independently optimise both factors. Alternatively the field size could be optimised if the field size itself was measured independently of the dose. This approach assumes that male and female patients constitute separate populations in terms of medical radiation protection and more fully recognises the concepts of ALARA and optimisation.

The fact that male and female patients may be considered to be separate population groups from the point of view of radiation protection is highlighted by the differences in those examinations that contribute to the Genetically Significant Dose (GSD) of each population[12]. Not only are the examinations that contribute most to the GSD, different for each group, but also their percentage contributions differ markedly.

Treating male and female patients as separate groups would represent a significant improvement in the overall radiation safety management of patients. In Europe over 300,000 man Sv of radiation are employed annually in diagnostic radiology[13]. If it is assumed that this is split equally between male and female patients, then separate DRLs for female patients, including improved monitoring of field size, could improve the management of roughly 37,500 – 75,000 man Sv of population exposure.
If it is possible to employ a lower ESD and field size for female patients compared to male, then it is not unreasonable to expect this to be applied in routine practice as a first stage optimisation process. Based upon data presented for other types of examination for both male and female patients, it appears that the same principle would apply generally[9,10,11]. The ability to discriminate, with sufficient accuracy, DRLs for subgroups of patients that undergo the same examination has already been addressed in the case of paediatric patients of different age groups[6,14].

5. Summary and Conclusions

Patient dose measurements undertaken on male and female patients who underwent PA chest x-ray examinations demonstrated a statistically significant difference in the mean dose [ESD, ID and DAP] received by each group. A detailed analysis of previously published work indicates that this finding is in agreement with results from other studies for, not only, the PA chest but also other types of radiographic examinations[9,10,11]. The existing criteria for selecting patients for inclusion in a dose audit, according to an average weight of 70 kg, would also appear to be biased towards male patients. Optimisation requirements indicate that separate DRLs for male and female patients is a realistic consideration and would constitute a first stage optimisation process that assumes constant diagnostic outcome from particular examinations for both groups.

Measurements of DAP undertaken on the same group of male and female patients indicates that, as well as differences in the mean ESDs for each group, there was also a difference in the mean DAP values that originates from statistically significant differences in the average field size employed for each group. Such differences have also been observed in other studies. Thus, there exists the possibility for optimisation of the radiographic process by not only selecting different DRLs for the dose component of the DAP value but also the area or field size component. Alternatively, direct measurement of the x-ray field size as well as the ESD would provide an independent assessment of these two components for use in optimisation strategies. The DAP value alone is not sufficient, since it combines these two individual components into a single measure of performance. Indeed it tends to mask the individual performances of each component.

In the case of fluoroscopic examinations also, there is every indication that, for a constant screening time, both the ESD and field size may also be different for male and female patients. If this is the case then DRLs expressed solely in terms of a total examination DAP value would not be sufficient for more detailed optimisation strategies. Total incident surface dose and average field size for a specific screening time would be more informative. It would be interesting to know whether similar differences in doses for male and female patients also exists for CT, at least for constant image quality.

The present situation regarding the deployment of unified DRLs for both male and female patients appears to be less than optimum.

6. References


