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THE ESTABLISHMENT OF REFERENCE DOSES IN PAEDIATRIC RADIOLOGY AS A FUNCTION OF PATIENT SIZE

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Abstract — There is a wide range in paediatric patient size from a newborn baby to a 15-year-old adolescent. Reference doses for paediatric radiology can sensibly be established only for specific sizes of children. Five standard sizes of patient have been chosen at ages 0 (newborn), 1, 5, 10 and 15 years. Standard AP and lateral thicknesses for the head and trunk for the reference ages were derived from published measurements on children. Normalisation factors for entrance surface dose and dose–area product measurements were calculated which depend on the thickness of the real patient, the thickness of the nearest standard 'patient', and an effective linear attenuation coefficient (μ). These normalisation factors were applied to European data to derive some preliminary reference doses.

INTRODUCTION

A method is discussed for normalising doses measured on children to doses relating to patients of a standard size, and for establishing reference doses. This procedure will enable persons carrying out dose surveys to compare their results with reference doses set for standard-sized paediatric patients representing children of specific ages.

METHOD

Selection of standard sizes for paediatric patients

The number of standard-sized patients required depends on how rapidly patient size changes with age and the maximum normalisation factor that is thought desirable to relate a measured dose to the dose for the nearest standard sized patient. It is suggested that the normalisation factors should not be more than about a factor of two up or down. With half-value-thicknesses for diagnostic quality X rays in soft tissue of about 3 to 5 cm, differences in thickness of about 5 cm between adjacent standard-sized patients should suffice.

AP and lateral thicknesses for the trunk and the head were derived for each of the standard-sized patients from published measurements on children[1]. These thicknesses can be used to normalise entrance surface dose (ESD) values for specific radiographs taken with the corresponding projection. When dose measurements (usually of dose–area product (DAP)) are integrated over a complete examination comprising multiple radiographs and/or fluoroscopy, the projection of the X ray beam is likely to change and may include AP, PA, lateral and oblique projections. In this case separate AP and lateral standard trunk thicknesses are inappropriate and an 'average' trunk thickness would be more useful. A simple estimate of patient average trunk thickness can be made from height and weight data by assuming the patient is a circular cylinder of unit density. The equivalent cylindrical diameter (ECD)[2] is given by:

$$\mathrm{ECD} = 2(\mathrm{weight}/\pi\ \mathrm{height})^{0.5} \quad (1)$$

where ECD and height are in cm and weight is in grams.

Factors for normalising measured ESDs to those for patients of standard size

Assuming exponential attenuation of diagnostic X ray beams through the patient and a fall in dose with distance from the X ray tube focus which follows the inverse square law, the relationship between the ESD and the exit surface dose is given by:

$$\mathrm{Exit\ dose} = \mathrm{ESD}\ e^{-mx}\ [\ \mathrm{FSD}/(\mathrm{FSD} + x)\ ]^2 \quad (2)$$

where m is the linear attenuation coefficient for the part of the patient's body being X rayed, x is the thickness of that part of the body and FSD is the focus to skin distance.

For a constant exit dose, the patient entrance surface dose (ESD_x) will vary with patient thickness, x, according to:

$$\mathrm{ESD}_x = k\ e^{mx}\ [(\mathrm{FSD}_x + x)/\mathrm{FSD}_x]^2 \quad (3)$$

Measured values of ESD for a patient of thickness d can, to a first approximation, be normalised to the ESD for a patient of standard thickness, s, which would result in the same exit dose by multiplying by the normalisation factor, F_{ESD} where:

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$$F_{ESD} = \frac{ESD_s}{ESD_d} = \frac{e^{ms}\,[(FSD_s + s)/FSD_s]^2}{e^{md}\,[(FSD_d + d)/FSD_d]^2} \quad (4)$$

For values of m in the region of 0.2 cm^{-1} the inverse square law term in the above equation contributes about 10% to the value of F_{ESD}. Instead of dealing with the inverse square law as a small extra term, it is more convenient to allow the inverse square law effect to be incorporated into the linear attenuation coefficient. Thus, Equation 2 becomes:

$$\text{Exit dose} = ESD\, e^{-\mu x} \quad (5)$$

where μ is an effective linear attenuation coefficient which includes the inverse square law effect, and for a constant exit dose:

$$F_{ESD} = ESD_s/ESD_d = e^{\mu(s-d)} \quad (6)$$

This effective linear attenuation coefficient must not be used in Eequation 2, of course, or there would be a double-counting of the inverse square law effect.

Factors for normalising measured DAPs to those for patients of standard size

The factor, F_{DAP}, for normalising DAPs for complete examinations involving multiple projections, measured on a patient of known thickness to the nearest standard thickness, can be derived in a similar way to that for ESD measurements. In this case, the normalisation for dose is identical to that in Equation 6, and there should be an additional term to account for the fact that the area component of DAP will increase with patient size roughly as s^2/d^2 (assuming the dimensions of the patient in a plane perpendicular to the axis of the X ray beam are proportional to the thickness of the patient along the axis of the beam)

$$F_{DAP} = e^{\mu(s-d)}\,(s^2/d^2) \quad (7)$$

Derivation of effective linear attenuation coefficients, μ

Appropriate values of μ for the exposure conditions prevailing in paediatric radiology were obtained from measurements of entrance and exit doses on a tissue-equivalent phantom (WT1 material) representing paediatric patients of 5, 10, 15, and 20 cm thickness with a number of typical diagnostic X ray spectra and field sizes. Exit doses were measured in front of and behind an antiscatter grid (grid ratio 12:1, 36 lines per cm) since the ratio of primary to scattered radiation in the exiting beam is also a function of patient thickness. As the grid removes most of the scattered radiation, the attenuation coefficient derived from the through-grid exit dose was higher than that measured without a grid. Values of μ were obtained from the slopes of graphs of ln ESD per unit exit dose against phantom thickness.

Similar entrance and exit dose measurements were also made with a lung-equivalent material phantom to simulate chest radiography. The lung sections of an Alderson Rando phantom were used which have a density of 300 $kg.m^{-3}$ representing semi-inflated lung, since chest radiographs are taken at inspiration. Only one field size was possible and measurements with a grid were not made, since grids are rarely used in paediatric chest examinations. Values of μ were obtained from the slopes of graphs of ln ESD per unit exit dose against phantom thickness.

These phantom measurements of effective linear attenuation coefficient were verified and extended to a wider range of exposure conditions by Monte Carlo simulation. Remarkably close agreement was achieved (to within 2% without a grid, and 6% with a grid) between the Monte Carlo calculated μ values and those measured in the soft-tissue-equivalent phantom. For the lung-equivalent phantom the agreement was not so close, but the discrepancy can be quantitatively explained by small soft-tissue components in the lung sections of the Alderson phantom which were not simulated in the Monte Carlo calculations.

RESULTS

Standard sizes of patients

Mean values of AP and lateral (LAT) thicknesses of the head and three sections through the trunk (chest, abdomen and pelvis) had been measured on samples of children of six ages by Bohmann[1]. For the trunk thicknesses, values for the 7-year-old were within 1.5 cm of those for the 5-year-old, so five standard trunk sizes corresponding to 0, 1-, 5-, 10- and 15-year-old children were sufficient to cover the whole paediatric age range. There was then a significant difference in size (2–5 cm in thickness) between all adjacent reference ages, but normalisation factors for any intermediate size were unlikely to exceed a factor of two. This selection of reference patient ages has the additional advantage of matching those for which mathematical phantoms are available for use in Monte Carlo calculations of organ doses from paediatric X ray examinations[3].

For the head, there was only a relatively small change in size with age after 5 years and only three standard sizes corresponding to 0, 1- and 10-year-old patients were necessary.

Chest, abdomen and pelvis thicknesses were sufficiently close to warrant taking rounded values of the mean thickness for all three sections to derive standard AP and LAT trunk thicknesses for the five reference ages. Similarly, rounded values of the measured skull thickness were used as standard AP and LAT head thicknesses for the three reference ages. These standard thicknesses are shown in Table 1.

Average ECDs for the children measured by Bohmann were calculated from the average heights and weights of the children in each age group. Rounded

values of the ECDs for the five reference ages suitable for normalising multiprojection examinations are shown in the last column of Table 1.

Effective linear attenuation coefficients

Without a grid, values of μ for soft tissue (WT1) range from 0.20 to 0.25 cm^{-1} for the range of X ray qualities and beam areas likely to be met in paediatric radiology and with a grid from about 0.25 to 0.30 cm^{-1}. They are more dependent on kV than field size over the ranges studied. The measured values of μ for lung are considerably lower than the values for soft tissue and range from 0.11 to 0.13 cm^{-1}.

Estimated values for F_{ESD} and F_{DAP}

Using the equations for F_{ESD} and F_{DAP} (Equations 6 and 7) and the values for μ and the thicknesses of standard patients as discussed above, values of the normalisation factors were calculated for a range of patient thicknesses in 0.5 cm increments from those appropriate for a baby to those for a 15-year-old. These normalisation factors are given in Reference 4. For F_{ESD} for AP trunk, lateral trunk, AP head and lateral head, respectively and for F_{DAP} for multiple projections of the trunk, it was found that the normalisation factors were no larger than a factor of two up or down for all the ESD measurements, and for all of the DAP measurements apart from occasional exceptions for babies or very large 15-year-olds.

ESD reference doses

The wide-ranging survey data collected for the European paediatric radiology trial[5] were analysed to develop reference doses for individual radiographs. To eliminate unacceptable practices, the data were restricted to those from hospitals which were using the technique factors recommended in the European Guidelines[5] as regards grid usage, kV and film–screen speed. Data for patients of any size were included and the doses normalised to those for the nearest standard-sized patient using the F_{ESD} normalisation factors discussed above. The thickness of the radiographed section through the patient was derived from patient height and weight data using a method developed by the authors[4]. The distribution of the size-normalised doses from the European trial has been used to derive reference doses for standard-sized paediatric patients based on the

Table 1. Standard thicknesses for the trunk and head.

Age (y)	Standard thickness by beam projection (cm)				
	Trunk AP	Trunk LAT	Head AP	Head LAT	Multiprojection of the trunk
0	8.5	10	12	9	9
1	12	15	16	12	13
5	14	19	18.5	14.5	15
10	16	23	18.5	14.5	18
15	18	27	18.5	14.5	21

Table 2. Paediatric radiology reference dose values for common radiographs.

Age	Paediatric reference doses (μGy)					Adult
	Neonate	1 year	5 year	10 year	15 year	
Standard thickness	*8.5 cm*	*12 cm*	*14 cm*	*16 cm*	*18 cm*	
Chest AP/PA	50	50	70	120	–	300
Abdomen AP/PA	–	400	500	800	1200	10,000
Pelvis AP	–	500	600	700	2000	10,000
Standard thickness	*12 cm*	*16 cm*	*18.5 cm*	*18.5 cm*	*18.5 cm*	
Skull AP/PA	–	800	1100	1100	1100	5000
Standard thickness	*9 cm*	*12 cm*	*14.5 cm*	*14.5 cm*	*14.5 cm*	
Skull LAT	–	500	800	800	800	3000

rounded third quartile values, as shown in Table 2. Adult reference doses[6] are also shown for comparison.

By normalising for patient size and rejecting unacceptable practices, the paediatric reference doses now show a reasonable trend with patient age, which was not evident in the original data[5]. The values, even for a 15-year-old child, are substantially lower than those shown for an adult, which reflects the expected additional care taken when children are radiographed and the improvements made in patient protection since the adult reference doses were derived over ten years ago.

DAP reference doses

DAP data were collected for micturating cystourethrogram (MCU) examinations at a sample of 12 European hospitals as part of this EC research contract. Between 10 and 30 paediatric patients were included from each hospital with ages ranging between neonate and 15 years. However, the majority of patients were under 5 years as is usual for MCU examinations. Information on weight, height and trunk thickness was collected for each patient. The DAP for each patient was normalised to that for the nearest standard trunk thickness(es) for multiprojection examinations as shown in Table 1 using the normalisation factor F_{DAP}. Values of μ appropriate for the field size and grid use were used in the derivation of F_{DAP} for each patient and, in the absence of tube voltage data for each examination (it is difficult to obtain a representative value when the tube voltage is varying throughout the examination), 80 kV was assumed. The rounded third quartiles of the distributions of the mean normalised DAP values were suitable for use as provisional reference doses. These are given in Table 3.

Table 3. MCU reference doses.

Age (y)	DAP ($Gy.cm^2$)
0	0.6
1	0.9
5	1.2
10	2.4

CONCLUSION

It has been shown to be feasible to establish reference doses for a set of standard-sized children and a method has been developed for normalising doses measured on any child to the analogous dose to a standard-sized child.

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