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Patient Dose in Dual X-ray Absorptiometry

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Abstract. Dual x-ray absorptiometry (DXA) provides a convenient, non-invasive method of assessing skeletal bone mineral which is widely used for clinical studies. This report describes a study to estimate the effective dose of radiation (ICRP-60 (1990)) to a typical female patient from scans performed on three DXA scanners: the Hologic QDR-1000, QDR-1000/W and QDR-2000. The scans modes studied were: total body; antero-posterior (AP) lumbar spine; lateral lumbar spine; proximal femur; distal forearm. An ionization chamber and tissue-equivalent phantom were used to determine entrance surface dose and percentage depth–dose curves for each scan mode. Anatomical data from ICRP-23 (Reference Man) and a body section atlas were used to estimate the absorbed dose to each organ in the scan fields. Effective dose was estimated using the ICRP-60 tissue weighting factors and the fraction of each organ in the scan field. Results are summarized below. Figures for the effective dose are given both excluding and (in brackets) including the ovaries to cover the cases of postmenopausal and premenopausal women respectively.

	QDR-1000/QDR-1000W		QDR-2000	
Scan type	Scan time (min)	Effective dose (μSv)	Scan time (min)	Effective dose (μSv)
Total body	17	3.6 (4.6)	6	2.7 (3.6)
AP spine	8	0.5 (0.5)	2	1.8 (1.8)
Lateral spine	20	0.6 (0.6)	3	1.2 (1.2)
Hip	6	0.1 (1.4)	2	0.6 (5.9)
Forearm	6	0.07 (0.07)		

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Introduction

Recent years have seen the rapid development of new radiological methods for the assessment of skeletal status [1]. Currently one of the most widely used techniques for the non-invasive measurement of bone integrity is dual X-ray absorptiometry (DXA) [2–4]. Any technique involving exposure of the patient to ionizing radiation requires an assessment of the risk of radiation injury. In the past patient dosimetry for diagnostic X-ray exposures often took the form of the measurement of entrance skin dose as this quantity can readily be measured [5]. Although a useful quantity for dose surveys and comparisons between machines, the measurement of skin dose dose not predict the probability of carcinogenesis in patients or genetic injury in their offspring. The appropriate quantity for the assessment of the risk of radiation injury is the effective dose [6]. As defined by the recent ICRP-60 report [7], effective dose is the sum of the absorbed dose to each irradiated organ weighted for the radiation type and radiosensitivity of that organ.

Although data for entrance skin dose for DXA densitometers are readily available from the manufacturers, only a few studies have examined the effective dose to patients from the commonly performed investigations such as the pencil beam scans of lumbar spine and proximal femur [6,8–10]. More information on patient dosimetry is required so that the risks from the widespread use of DXA scanning for screening studies [11,12] and for clinical trials [13] can be properly evaluated. The study described here was undertaken to

assess the effective dose from all DXA investigations, both pencil beam and fan beam, performed on dual X-ray bone densitometers supplied by Hologic Inc. (Waltham, MA).

Materials and Method

Patient dosimetry data were obtained for the following scan modes: total body; anteroposterior (AP) lumbar spine; lateral lumbar spine; proximal femur; distal forearm. Tissue weighting factors allowing for the radiosensitivity of each organ were taken from ICRP-60 [7]. The list of organs included and their weighting factors are summarized in Table 1.

Table 1. Tissue weighting factors from ICRP-60 (1990) [7]

Tissue type	Weighting factor
Ovaries	0.2
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surfaces	0.01
Remainder	0.05

The following 10 tissues are included in the remainder with weighting factor 0.005 each; adrenal, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus.

The DXA Bone Densitometers

Estimates of effective dose were made for three models of DXA bone densitometer: the Hologic QDR-1000, QDR-1000/W and QDR-2000. All three operate using the kilovolt-switching technique to give alternating generator potentials of 70 and 140 kVp with effective energies of 43 and 110 keV respectively [2]. The QDR-1000 and QDR-1000/W both have a pencil beam coupled to a single detector and scan the patient in a raster pattern. The QDR-2000 uses a fan beam coupled to an array of 32 detectors which move together in one direction over the patient [14]. If required, the QDR-2000 can perform pencil beam scans to emulate the QDR-1000 and QDR-1000/W. The scan modes available in pencil and fan beam configurations are listed in Tables 2 and 3 respectively, together with data on scan times. Fan beam scan times are significantly shorter than pencil beam scan times and vary depending on the image resolution chosen (Table 3).

Measurements of the Depth Dose Curves

To evaluate patient dosimetry depth–dose curves were measured for each scan mode on each densitometer using an MDH-1015 180 cm^3 ionization chamber (MDH Industries, Monrovia, CA) and a tissue-equivalent phantom. The material for the phantom was chosen to simulate the typical soft tissue composition over the trunk measured by DXA body composition scanning (34% fat and 66% lean tissue) [15]. Exposure dose measurements were taken at various depths in the phantom with at least three measurements at each depth.

The exposure readings were corrected for background and the mean dose plotted against depth in the phantom. The data were used to establish the entrance skin dose (ESD) and the percentage depth dose (PDD) curve for each scan mode. For the purpose of the dose calculations figures for ESD were converted from units of exposure (mR) to units of absorbed dose (μGy) using the conversion factor for ICRU muscles [5], which was calculated to by 9.17 μGy/mR. This has been calculated knowing the proportion of the low and high effective beam intensities detected at the detectors: 63% and 37% respectively (private communication with the manufacturer).

Organ Depths for a Reference Woman

Knowledge of the depth of each relevant organ was required in order to use the PDD curves in calculations of absorbed dose for a reference female patient. Where only parts of the total organ were included in the scanning field (for example bone marrow, bone surfaces and skin) the fraction of these organs irradiated was also required for the determination of effective dose.

The depth and irradiated fraction of all organs specified in the IRCP-60 report (Table 1) were estimated using data for a 53-kg reference woman taken from ICRP-23 (Reference Man) [16] and a cross-sectional atlas of human anatomy [17]. The latter gave images of transaxial body sections at intervals 25 mm apart. The body sections were digitized and analysed using commerical image processing software (Microsoft Optimas). This allowed the outline of the radiation beam to be superposed on each body section (Fig. 1). A region of interest was manually drawn around that part of the organ inside the radiation beam and the centroid and cross-sectional area for each organ calculated by the program. The distance of the centroid from the entrance surface gave the depth for each section and the mean depth over all the sections was used in calculating the absorbed dose to that organ. The irradiated fraction of the organ was determined from the area inside the beam relative to the whole organ area summed over all sections.

For large or widely distributed organs the use of mean depth underestimated organ dose because the PDD curves varied exponentially with depth. For these

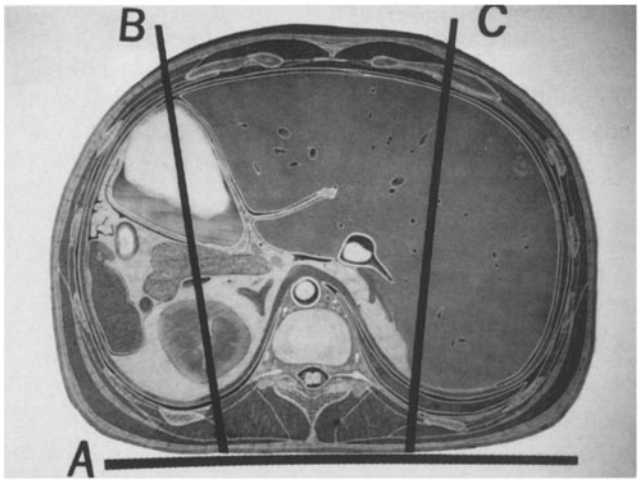

Fig. 1. An example of a digitized transaxial body section, from Eycleshymer and Schoemaker [17]. The X-ray beam emerges from under the bed, indicated by line *A*. The outline of the fan beam for the QDR-2000 AP lumbar spine scan mode is indicated by lines *B* and *C*. All organs, or parts of organs, lying between *B* and *C* are irradiated.

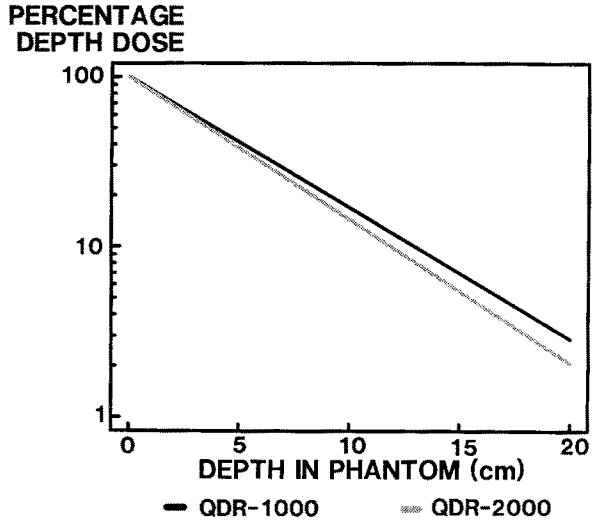

Fig. 2. The percentage depth–dose curves for the QDR-1000: (partial-body pencil beam modes: the partial-body pencil beam scans on the QDR-2000 give identical curves) and for the QDR-2000 (partial-body fan beam modes).

organs each body section was subdivided into 5 cm intervals of depth and the centroid and organ fraction determined for each interval. Certain organs required additional data for the calculation of the irradiated fraction. Data on the distribution of red bone marrow were taken from ICRP Reference Man [16]. The fraction of total bone surfaces in each scanning field was obtained by comparing bone mineral content (BMC) measurements derived from the part body scan modes with the total body DXA measurements of BMC in the same individuals, together with data on the distribution of cortical and trabecular bone [16].

Calculation of Effective Dose

The equivalent dose for each irradiated organ was obtained by applying the mean organ depth estimation to the appropriate PDD curve and multiplying by the ESD. Since the radiation quality factor for X-rays is 1 the resulting organ absorbed dose (units: μGy) was numerically equal to the equivalent dose (units: μSv) [7]. The effective dose for each organ was calculated by applying the appropriate tissue weighting factor (Table 1) to the equivalent dose of that organ. For the part-body scans the equivalent dose was also weighted by the fraction of the organ irradiated by the individual scan mode. Total effective dose for each scan mode was obtained by summing the effective dose to each organ. Total effective dose was calculated both including and excluding the ovaries to take account of premenopausal and postmenopausal women respectively.

Results

Results for QDR-1000 and QDR-1000/W pencil beam and QDR-2000 fan beam scans are given in Tables 2 and 3 respectively. Column 3 in each table gives results of the measurements of ESD, including backscatter, for each scan mode. PDD curves for the QDR-1000 and QDR-1000/W part-body scans were found to be identical (Fig. 2), with ESD varying in proportion to the speed of the scanning arm (Table 2). The QDR-2000 pencil beam PDD curves were identical to those for the QDR-1000 and QDR-1000/W with the ESD a factor of 1.6 higher due to the use of a lighter scanning table. The PDD curves for the QDR-2000 1-min, 2-min and 3-min fan beam spine and hip scans (Fig. 2) were identical with ESD measurements varying in proportion to scanning speed (Table 3).

Column 4 of Tables 2 and 3 gives results for effective dose. As would be expected from the ESD and PDD curve data the effective doses for scans performed on the QDR-1000 and QDR-1000/W were identical while those for the QDR-2000 pencil beam mode were higher

Table 2. Scanning times, entrance surface doses and effective doses for postmenopausal women (i.e. excluding the ovaries) for pencil beam mode scans performed on the QDR-1000 and QDR-1000/W

Scan type	Scan time (min)	Entrance surface dose (μGy)	Effective dose (μSv)
Total body	17	18	3.6 (4.6)
AP spine (L1–L4)	8	60	0.5 (0.5)
Lateral spine (L2–L4)	20	238	0.6 (0.6)
Proximal femur	6	60	0.1 (1.4)
Distal forearm	6	113	0.07 (0.07)

Figures for premenopausal women including the ovaries are shown in brackets. A pencil beam scan option on the QDR-2000 emulates the QDR-1000/1000W scan modes but gives entrance surface doses and effective doses higher by a factor of 1.6.
ESD (μGy) = ESD (μSv) as the radiation quality factor for X-rays is unity.

Table 3. Scanning times, entrance surface doses and effective doses for postmenopausal women (i.e. excluding the ovaries) for fan beam mode scans performed on the QDR-2000

Scan type	Scan time (min)	Entrance surface dose (μGy)	Effective dose (μSv)
Total body	6	11	2.7 (3.6)
AP spine (L1–L4)	0.1	57	0.4 (0.4)
	1	138	0.9 (0.9)
	2	271	1.8 (1.8)
	3	432	2.9 (2.9)
Lateral spine (L2–L4)	3	684	1.2 (1.2)
	6	1390	2.5 (2.5)
Proximal femur	1	138	0.3 (3.0)
	2	271	0.6 (5.9)

Figures for premenopausal women including the ovaries are shown in brackets. The effective dose for the combined AP/lateral spine study is the sum of AP spine and lateral spine doses shown here.
ESD (μGy) = ESD (μSv) as the radiation quality factor for X-rays is unity.

by a factor of 1.6. The figures for effective dose are given both excluding and (in brackets) including the ovaries to cover the cases of postmenopausal and premenopausal women respectively.

Discussion

An evaluation of the effective dose received by patients from DXA scanning is necessary for an objective assessment of the radiation risks involved in clinical studies. The results of the present report may be used to estimate the patient dose for some common procedures. A screening study [11,12] of a postmenopausal woman involving scans of the spine and hip performed on the QDR-1000 would deliver a total effective dose of 0.6 μSv (Table 2).The same study performed on the QDR-2000 using the 1-min fan beam mode would give an effective dose of 1.2 μSv (Table 3). These doses are 9% and 18% respectively of the average daily natural background in the United Kingdom of 7 μSv [18]. For a clinical trial [13] in which a subject underwent 2-minute AP spine and hip fan beam scans together with lateral and total body studies on the QDR-2000 the total effective dose would be 6.3 μSv. Such a protocol performed at the commencement of a trial and repeated at 12-monthly intervals for 3 years would entail a total radiation burden to the patient of 25 μSv. This dose is low compared with those entailed by common radiological procedures: for example 50 μSv for a chest radiograph, the UK national average of 2100 μSv for lumbar spine radiographs [19], and 3400–5500 μSv for CT of the head [20].

For women in the studies discussed above the radiation hazard of concern is carcinogenesis since the genetic risk to future offspring is no longer a factor. For this reason the effective dose results in Tables 2 and 3 are shown excluding the ovarian contribution. Values including ovarian dose are shown in brackets and are relevant to younger women for whom the genetic risk applies. The ovaries are definitely included in the scanning field only for whole body scans. They should not normally be included in AP or lateral lumbar spine scans provided the starting position for the scan is at the level of L5 or above. Exclusion of the ovaries in scans of the proximal femur is less certain and depends on the exact positioning of the edges of the scanning field. For this reason the data for premenopausal women in Tables 2 and 3 omit the ovarian contribution for spine scans but include it for the hip.

Prior to the definition of effective dose [7] the quantity recommended by the ICRP for the evaluation of radiation risk was the effective dose equivalent [21]. Effective dose and effective dose equivalent differ in that the former is calculated using more recent estimates of the tissue weighting factors (Table 1). The new ICRP-60 factors were used for the dose estimates presented in Tables 2 and 3. When the old ICRP-26 factors were substituted, figures for effective dose equivalent were found to be larger by a factor of 2.5 for the AP spine and, in a postmenopausal woman, a factor of 3 for the proximal femur. The larger dose using the old weighting factors was explained by the contribution of the remainder tissues (the five unnamed organs receiving the highest doses) in the ICRP-26 scheme. Remainder tissues such as muscle, intestines and kidneys received weighting factors of 0.06 in ICRP-26 whereas in ICRP-60 they are assigned values of 0.005 (Table 1).

Several previous studies have discussed patient dosimetry in DXA scanning. Pye et al. [8] calculated an effective dose equivalent of 6.4 μSv for a QDR-1000 spine scan. However, a major contribution to this figure came from the assumption that both ovaries were included in the scanning field. With the ovaries omitted, Pye et al. estimated a dose of 0.6 μSv. Kalender [6] compared effective dose equivalent of DXA and quantitative computed tomography (QCT) studies of the lumbar spine and estimated that pencil beam DXA studies gave doses of 1 μSv compared with 60 μSv for QCT. Rawlings et al. [9] used thermoluminescent dosemeters in an anthropomorphic phantom to study patient dosimetry on a QDR-1000/W and reported doses of 2.9 μSv for the spine and 0.9 μSv for the hip. Laskey et al. [10] reported an effective dose equivalent for a QDR-1000 lumbar spine scan of 1.1 μSv when the ovaries were excluded from the scanning field.

Allowing for the differences between effective dose and effective dose equivalent discussed above, these studies all agreed within a factor of 2 with the pencil beam lumbar spine results presented in Table 2. The present report extends the data available on patient dose in DXA studies by including estimates for total body, lateral spine, hip and distal forearm scans as well as the conventional AP lumbar spine. For the first time data are presented that allow an objective comparison of pencil beam and fan beam scanning modes. The results show that for all DXA procedures patient dose is less than the daily dose from natural background radiation [18].

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