An assessment of the radiation dose to patients and staff from a Lunar Expert-XL fan beam densitometer

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Abstract. Dual-energy x-ray absorptiometry (DXA) is a widely used technique for measuring bone mineral density for the identification and management of osteoporotic subjects. The original DXA pencil beam systems expose patients to an effective dose of ionizing radiation of around 2 μSv and require no additional protective shielding for staff. The new fan beam densitometers incorporate solid state detectors and have a higher photon flux, enabling faster acquisition times and giving improved resolution. However, this may be at the expense of higher radiation dose. This study was conducted to assess the radiation dose to patients and staff from the standard scan modes using a Lunar Expert-XL fan beam densitometer. This is, we believe, the first dose assessment of the Expert-XL. The results indicate that the scatter dose at 1 m from the scan table, assuming four AP spine and femoral neck examinations per hour, is about 4 μSv h^{-1}. This is well below the limit of 7.5 μSv h^{-1} set by the UK's Ionising Radiation Regulations for defining a Controlled Area but above the lesser limit of 2.5 μSv h^{-1} for a Supervised Area. Typical effective doses to patients are 59 μSv for an AP lumbar spine scan, up to 56 μSv for AP femoral neck, 71 μSv for lateral spine morphometry and 75 μSv for whole body. Although exceeding those of pencil beam DXA machines, these doses are less than for standard radiographic procedures, particularly of the lumbar spine. Where reduced scan time, improved image resolution or morphometric analysis of the spine are required, the patient doses from the Lunar Expert-XL are not prohibitive.

Keywords: DXA, dosimetry, fan beam, BMD

1. Introduction

Dual-energy x-ray absorptiometry (DXA) is an accurate, precise and widely used technique for measuring bone density to identify and monitor osteoporotic subjects and to assess the effectiveness of treatment. The original DXA systems use a pencil beam x-ray and a sodium iodide scintillation detector moving, in unison, in a rectilinear fashion over the region of interest. With the advent of new fan beam densitometers, incorporating solid state detectors, faster acquisition times and improved resolution is made possible, although possibly at the expense of higher radiation dose. The Ionising Radiation Regulations (IRR 1985) and Approved Codes of Practice (ACOP 1985) aim to maintain radiation doses 'as low as reasonably achievable' (the ALARA principle). In order to comply with these regulations an assessment of the risk to staff and patients is required.

The quantity used to assess radiation hazard is the effective dose, which is the sum of the absorbed doses to each irradiated organ, weighted for the radiation type and radiosensitivity of the organ. The intention of this weighting process is to produce a value that is proportional to the risk of inducing cancer or hereditary disease. This study was conducted to assess the effective dose from a Lunar Expert-XL fan beam densitometer (Lunar Corp., Madison, WI, USA).

Such an assessment has been performed by others (Njeh *et al* 1996). However, this work was performed on a prototype machine (the Lunar Expert) using a now obsolete scan mode. Also, no mention is made in the paper about the contribution of scattered radiation to organs outside the primary beam.

2. Method

2.1. Lunar Expert-XL

The Lunar Expert-XL uses a fan beam of x-rays and an array of solid state scintillation detectors. The x-ray tube operates at a maximum continuous voltage of 134 kV and maximum tube current of 5 mA with 2 mm aluminium filtration. Original DXA systems use either a k-edge filter or kV switching to produce two discrete x-ray energies, of around 40 and 70 keV, chosen to optimize the differential attenuation between bone and soft tissue. The Expert-XL achieves this by dual-energy discrimination at the detector with one row of elements recording the low-energy and one the higher-energy x-rays. The x-ray tube and detector are mounted on a C-arm which may be rotated to enable lateral imaging. The distance from focal spot to image receptor is 112 cm. The system is capable of performing bone densitometry measurement of the lumbar spine, femoral neck, whole body, forearm, hand and morphometric assessment of the thoracic and lumbar vertebrae.

2.2. Rando anthropomorphic phantom

A Rando anthropomorphic phantom (Alderson Research Laboratory, Stamford, CT, USA) was used to determine doses at different depths within the body. The Rando phantom consists of a human skeleton embedded in a soft tissue equivalent material (density 0.985 g cm^{-3}, effective atomic number 7.30). Air-expanded material (density 0.3 g cm^{-3}) is incorporated to represent the lungs. The proportions of the phantom were determined from a survey of United States Air Force personnel, and the overall stature scaled to match the civilian population (height 1.73 m, weight 73.5 kg). It may be considered to represent a standard man as defined by the International Commission on Radiological Protection (ICRP 1975). The phantom is of standard male form, although breast attachments are available and were utilized for this study. The phantom is separated into 35 slices, which have an array of holes into which dosimeters or tissue equivalent pegs may be placed.

2.3. Measurement of half-value layer

The phantom is designed for use with photons generated at applied potentials greater than 70 kV, and doses may be significantly overestimated if used with lower energies (IPSM 53 (Wall *et al* 1988)). The phantom may therefore be inappropriate for use with the pencil beam DXA systems. Also, Shrimpton *et al* (1981) recommend that the phantom only be used with radiation with a half-value layer (HVL) of greater than 2 mm aluminium. To validate its use for the assessment of doses from the Lunar Expert-XL, the HVL of the x-ray beam was measured. A 6 cm^3 thimble ionization chamber (MDH 10X5-6) was placed in the beam path and a lead collimator placed above to minimize contributions from scatter. Measurements were performed using a 5 mA service mode. This allowed exposures to be made with both the x-ray tube and detector stationary. The exposure was repeated with increasing layers of 99.8% pure aluminium filters until the electrometer reading was half that for the unfiltered beam.

2.4. Measurement of dose to staff

Scatter dose rates were measured, at 1 m horizontal distance from the central axis of the scan table, using an Autoness Szintomat 6134A dose rate meter. The uncertainty in dose rate measurement for this instrument does not exceed 20% at the x-ray energies used. A tank of water (width 23 cm, length 35 cm, depth 20 cm) was placed on the table to simulate the scattering that would occur with a patient *in situ*. A scan mode using the maximum tube current of 5 mA was selected.

2.5. Measurement of patient dose

Patient dose was determined using lithium fluoride thermoluminescent dosimeters (TLDs) embedded in the Rando phantom, for whole body, AP spine, lateral spine and femur scans. For each scan mode, TLDs were placed at positions and depths within the phantom corresponding to those of major organs in the primary beam and also in adjacent areas just outside the primary beam to give an estimate of the contribution to the effective dose made by radiation scattered outside the primary field. The numbers of TLDs used to assess each organ/tissue dose for each scan type are listed in table 1. In order to obtain a satisfactory cumulative dose to the TLDs, 30 scans were performed using each scan mode. However, doses recorded on some TLDs outside the primary beam were still found to be below the dose error of 6 μSv stated by the Medical Physics Service, Lincoln, UK who were responsible for the calibration and reading of the TLDs. These doses were still included in the calculations but contribute little to the effective dose per scan. The above service also specifies a 3% standard deviation error due to TLD to TLD variation and about 2% error in the calibration procedure. The cumulative effective of the above on the final effective doses is estimated at 6%.

Table 1. Number of TLDs used for each scan mode.

	Number of TLDs used for each organ/tissue			
Organ/tissue	Whole body	AP spine	Lat. spine	R. femur
Stomach	3	2	2	—
Colon	2	2	1	2
Lung	6	1	7	—
Bone marrow	5	2	5	1
Bladder	2	2	—	4
Oesophagus	5	2	4	—
Breast	3	—	—	—
Liver	7	7	8	—
Ovary	2	1	—	3
Thyroid	1	—	—	—
Bone surface	5	2	5	1
Skin	10	4	10	4
Remainder	14	5	10	6
Total	65	30	52	21

2.6. Calculation of effective dose

The locations of major organs in the Rando phantom were determined using the drawing of reference man from NRPB-R250 (Jones and Shrimpton 1991). The weighting factors for each organ were taken from ICRP 60 (ICRP 1990, 1991). The effective dose is given by

$$E = \sum_T W_T H_T$$

where H_T is the equivalent dose in the organ or tissue T and W_T is the weighting factor for tissue T.

The calculation of effective dose requires a knowledge of: the proportion of each organ within the primary and scatter fields; the extent of scatter; and the average dose to the organs from primary and scatter fields. The above are dependent on the scan area. For the purposes of this assessment the manufacturers recommended scan widths and lengths for each scan mode were used.

By overlaying a rescaled scan field size on the NRPB drawing, the proportion of each organ or tissue within the primary field was determined.

The proportions of skin, red bone marrow and bone within each slice of the phantom were calculated using factors previously determined by Huda and Sandison (1984). The percentages of red bone marrow and bone in the primary beam were calculated by identifying the slices of the Rando phantom exposed to the primary beam. For the femur scan, the percentage calculated was divided by two as only one hip is scanned.

A similar method to that for bone surfaces and red bone marrow was used to calculate the 'remainder' organs in the scan field. This method, however, assumes a uniform distribution of remainder organs in the body. The average dose to these organs is calculated and a weighting factor of 0.05 applied to calculate the contribution to the effective dose. Any remainder organs receiving a dose of greater than the highest dose to any other organ should be considered separately and a weighting factor of 0.025 applied to that organ and 0.025 to the average of the rest of the remainder organs (ICRP 1990, 1991). Therefore, for AP spine, the doses to the intestines, kidneys, spleen and pancreas were calculated to determine whether separate assessment was required as, in this scan mode, these organs are all within the primary beam.

3. Results

3.1. Half-value layer

The manufacturer specifies that the Lunar Expert-XL has 0.5 mm inherent filtration, an additional 2 mm aluminium added filtration and a half-value layer of greater than 2.5 mm aluminium. Our results indicate that the half-value layer is 5.1($\pm$0.1) mm aluminium.

3.2. Dose to staff

The dose rate at 1 m from the central axis of the table, at scan table height, using the maximum tube current of 5 mA, was 50 μSv h^{-1}. A peak dose rate at 1 m of 120 μSv h^{-1} was measured at about tube height. The dose rate at the operator's chair, 2.25 m from the scan table axis, was 17 μSv h^{-1}.

The UK's Ionising Radiation Regulations (1985) require that, 'a Controlled Area be designated, in most circumstances, where the time averaged dose rate (averaged over an 8 h day) is greater than 7.5 μSv h^{-1}'. Such a dose rate for 8 h a day, five days a week for 50 working weeks a year would result in a dose of 15 mSv, which is the legal dose limit for unclassified radiation workers. Although the maximum legal limit for unclassified workers is 15 mSv, there is no threshold for risk. Risk is proportional to radiation dose therefore doses must be as low as reasonably achievable (ALARA) or as low as reasonably practicable (ALARP, IRR 1985). From our results, the numbers of scans required that would give time averaged dose rates of 7.5 μSv h^{-1}, at 1 m from the table axis, were calculated for various scan modes (table 2). The anticipated workload is considerably less than the limits indicated in table 2, and therefore it was decided that the Controlled Area could safely be limited to within 1 m of the couch. Assuming four fast mode AP spine and femoral neck examinations per hour (eight scans), the scatter dose at 1 m would be 4 μSv h^{-1}. This exceeds the IRR limit for a Supervised Area but is well within that for a Controlled Area. As an additional precaution, and to conform to the ALARA principle a lead-acrylic screen of 0.5 mm lead equivalence, and height 1.54 m was placed between the operator's chair and the scan table. This screen will attenuate in excess of 95% of the scattered radiation incident upon it.

Table 2. Scatter doses at 1 m from centre of scanning table.

Scan mode	Tube current (mA)	Exposure time (s)	Dose rate at 1 m (μSv h^{-1})	Dose at 1 m (μSv/scan)	Scan limits for 7.5 μSv h^{-1} dose rate (scans/day)
Whole body	1.5	231.3	36	2.31	26
AP spine (fast)	5	16	120	0.53	112
Lat. spine morph.	5	38	120	1.27	47
R. femur (fast)	5	14.4	120	0.48	125

3.3. Effective dose to patients

An isodose line of 50 μSv after 30 scans was used to define the extent of the scattered radiation field to be considered for each scan mode. The percentage of tissues and organs within the primary and scatter fields for each scan mode are shown in table 3. For the whole body scan mode, the organ doses have combined primary and scatter components. Tables 4 to 7 show the calculated organ doses, and how they contribute to the final effective dose per scan. Effective doses per scan are summarized in table 8. The total uncertainty for these dose values is estimated at 6%. The effective doses for other scan modes were derived using the calculated effective dose per mA s (table 9).

4. Discussion

The time averaged maximum scatter dose rate at 1 m from the central axis of the scan table is 4 μSv h^{-1} assuming four patients per hour undergoing 5 mA fast AP spine and femur scans. This exceeds the scatter dose of 1.06 μSv h^{-1} stated by Mazess (1996), but his figures are based on the shorter scan times of 6 s of the recently introduced turbo mode. After correcting for difference in scan times, there remains a significant difference in scatter doses, but it is not clear at which height the latter doses were recorded. The results of this study are similar to those stated by Patel *et al* (1996) of 5 μSv h^{-1} . The difference may

Table 3. Percentage of tissue or organ within primary and scatter field for each scan mode.

	Whole body		AP spine		Lateral spine		Right femur	
Organ	Primary	Scatter	Primary	Scatter	Primary	Scatter	Primary	Scatter
Bladder	100%	0	0	10%	0	10%	26%	74%
Bone surfaces	100%	0	14%	0	23%	0	8%	0
Breast	100%	0	0	0	0	100%	0	0
Colon	100%	0	7%	50%	18%	32%	0	0
Gonads	100%	0	0	100%	0	100%	50%* (0)**	50%* (100%)**
Liver	100%	0	58%	42%	55%	42%	0	0
Lung	100%	0	0	22%	50%	50%	0	0
Oesophagus	100%	0	0	19%	15%	50%	0	0
Pancreas***	—	—	50%	—	—	—	—	—
Red bone marrow	100%	0	24%	0	38%	0	14%	0
Remainder	100%	0	18%	0	30%	0	18%	0
Skin	100%	0	4%	14%	11%	19%	3%	13%
Stomach	100%	0	75%	25%	50%	25%	0	0
Thyroid	100%	0	0	0	0	10%	0	0

Calculations performed assuming one ovary within primary field * and excluded from primary field **.

*** Dose to pancreas in AP spine mode found to be higher than that to other organs, therefore, as stipulated in ICRP 60 (ICRP 1990, 1991), a separate assessment was performed in order to calculate effective dose. This assumed that 50% of organ in primary beam and 0% in scatter region.

Table 4. Organ/tissue doses using AP spine fast scan mode on Lunar Expert-XL.

	Mean dose (μSv/scan)				
Organ	Primary	Scatter	Total dose (H_T)	Weighting factor (W_T)	$H_T \times W_T$
Bladder		2	2	0.05	0.1
Bone surfaces	23		23	0.01	0.2
Colon	7	48	55	0.12	6.6
Gonads		16	16	0.2	3.2
Liver	132	7	139	0.05	7.0
Lung		5	5	0.12	0.6
Oesophagus		2	2	0.05	0.1
Pancreas	325		325	0.025	8.1
Red bone marrow	40		40	0.12	4.8
Remainder	36		36	0.025	0.9
Skin	18	2	20	0.01	0.2
Stomach	208	16	224	0.12	26.9
				Effective dose 59 μSv	

be due to the measurements being performed with patients *in situ* for the latter compared with the use of a tank of water as the scattering medium in this study.

With an expected workload of four patients per hour, steps should be taken to reduce the dose to the operator by increasing the operator's distance from the scan table and

Table 5. Organ/tissue doses using right femur fast scan mode on Lunar Expert-XL.

(i) Ovaries in primary field

Organ	Mean dose (μSv/scan) Primary	Scatter	Total dose (H_T)	Weighting factor (W_T)	$H_T \times W_T$
Bladder	18	16	34	0.05	1.7
Bone surfaces	11		11	0.01	0.1
Gonads	247	8	255	0.2	51.0
Red bone marrow	19		19	0.12	2.3
Remainder	11		11	0.05	0.6
Skin	9	1	10	0.01	0.1
				Effective dose 56 μSv	

(ii) Ovaries outside primary field

Organ	Mean dose (μSv/scan) Primary	Scatter	Total dose (H_T)	Weighting factor (W_T)	$H_T \times W_T$
Bladder	18	16	34	0.05	1.7
Bone surfaces	11		11	0.01	0.1
Gonads	0	177	177	0.2	35.4
Red bone marrow	19		19	0.12	2.3
Remainder	11		11	0.05	0.6
Skin	9	1	10	0.01	0.1
				Effective dose 40 μSv	

Table 6. Organ/tissue doses using lateral spine morphometry scan mode on Lunar Expert-XL.

Organ	Mean dose (μSv/scan) Primary	Scatter	Total dose (H_T)	Weighting factor (W_T)	$H_T \times W_T$
Bladder		1	1	0.05	0.1
Bone surfaces	39		39	0.01	0.4
Breast		32	32	0.05	1.6
Colon	12	5	17	0.12	2.0
Gonads		16	16	0.2	3.2
Liver	192	33	225	0.05	11.3
Lung	161	48	209	0.12	25.1
Oesophagus	41	11	52	0.05	2.6
Red bone marrow	65		65	0.12	7.8
Remainder	66		66	0.05	3.3
Skin	44	1	45	0.01	0.5
Stomach	72	32	104	0.12	12.5
Thyroid		1	1	0.05	0.1
				Effective dose 71 μSv	

consideration given to installation of a protective screen. In our centre, operators are positioned behind a protective screen at about 2 m from the scan table. Monthly monitoring of operator doses over a period of 1 year using personal film badge dosimeters, demonstrate doses below the limits of detection, i.e. less than 50 μSv per month (0.6 mSv per year). This is well below the current UK legal limits and also below the latest recommended limits

Table 7. Organ/tissue doses using whole body scan mode on Lunar Expert-XL.

Organ	Mean dose (μSv/scan) Primary	Scatter	Total dose (H_T)	Weighting factor (W_T)	$H_T \times W_T$
Bladder	114	0	114	0.05	5.7
Bone surfaces	39	0	39	0.01	0.4
Breast	133	0	133	0.05	6.7
Colon	73	0	73	0.12	8.8
Gonads	77	0	77	0.2	15.4
Liver	54	0	54	0.05	2.7
Lung	55	0	55	0.12	6.6
Oesophagus	77	0	77	0.05	3.9
Red bone marrow	39	0	39	0.12	4.7
Remainder	72	0	72	0.05	3.6
Skin	115	0	115	0.01	1.2
Stomach	58	0	58	0.12	7.0
Thyroid	166	0	166	0.05	8.3
				Effective dose 75 μSv	

Table 8. Effective doses to patient from standard procedures on Lunar Expert-XL.

Scan mode	Tube current (mA)	Scan time (s)	Field width (cm)	Scan length (cm)	Effective dose per scan (μSv)	Effective dose per mA s (μSv mA^{-1} s^{-1})
AP spine (fast)	5	16	17.3	20	59	0.74
AP right femur (fast)	5	14.4	14.7	18	56* 40**	0.78* 0.56**
Lateral spine morphometry	5	38	14.4	38	71	0.37
Whole body (medium)	1.5	131.3	4 sweeps covering whole body		75	0.38

Calculations performed assuming one ovary within primary field * and excluded from primary field **.

for both radiation workers and the general public which are expected to be implemented in January 2000 (ICRP 60 1990, 1991).

Results from this study suggest that scatter doses are higher than those of 2.4 μSv reported by others (Patel *et al* 1996) for the Hologic QDR 4500. However, the different system specification, geometry (e.g. below-table x-ray tube) and choice of scan technique make a direct comparison complex.

The HVL of the Lunar Expert-XL was found to be 5.1 mm aluminium at a set voltage of 134 kV. This quality of radiation is within recommended guidelines for use with the Alderson Rando anthropomorphic phantom. The total effective dose for an AP and lateral morphometric study of the spine was found to be 130 μSv compared with a typical effective dose of 1230 μSv for a lumbar spine radiological examination involving AP and lateral views (table 10). Although the radiation dose to patients from the Expert-XL exceeds that of the standard pencil beam DXAs more than 100 fold (Spencer *et al* 1994, Njeh *et al* 1996), scan time is reduced and the improved resolution provides additional information. Also, the

Table 9. Effective doses for other scan modes derived from the 'effective dose per mA s'.

Scan mode	Tube current (mA)	Scan time (s)	Field width (cm)	Scan length (cm)	Calculated effective dose (μSv)
AP spine (fast)	2	16	17.3	20	24
AP spine (turbo)	5	8	17.3	20	30
AP spine (turbo)	2	8	17.3	20	12
Femur (fast)	2	14.4	14.7	18	22* (16**)
Femur (turbo)	5	7.2	14.7	18	28* (20**)
Femur (turbo)	2	7.2	14.7	18	11* (8**)
Total body (fast)	1.5	65.6	4 sweeps		38

Calculations performed assuming one ovary within primary field * and excluded from primary field **.

Table 10. Some typical effective doses from common radiographs, calculated using typical entrance surface doses measured for adult patients at a random sample of 20 English hospitals[a] and NRPB Monte Carlo data[b].

Examination	Typical effective dose per film (mSv)
Lumbar spine—AP	0.88
Lumbar spine—lateral	0.35
Lumbar spine—lumbo-sacral junction	0.45
Chest—PA	0.28
Chest—lateral	0.69
Pelvis—AP	0.94

[a] NRPB 1992 *National Protocol for Patient Dose Measurements in Diagnostic Radiology.*
[b] NRPB-SR262 *Normalised Monte Carlo Doses for Medical X-ray Examinations Calculated using Monte Carlo Techniques* (NRPB-SR262).

vertebral morphometry capability may reduce the need for much higher dose radiographic procedures in order to determine degree and extent of vertebral deformities.

The greatest contribution to effective dose from femur and whole body scans is the dose received by the ovaries. However, the genetic risk considered here is not relevant for the majority of the population undergoing bone densitometry assessment since they are generally post-menopausal women. Also, careful positioning by the operator may exclude the ovaries from the primary beam during a femoral neck scan, reducing the effective dose by 16 μSv (29%).

5. Conclusion

We have performed what we believe is the first dose assessment of the Lunar Expert-XL. The results indicate that, where a throughput of four or or more patients per hour is anticipated, a protective screen for the operator may be required.

The effective dose to patients, although exceeding that of pencil beam DXA machines, is much less than standard radiographic procedures, particularly of the lumbar spine. The pencil beam DXA machines are to be recommended where a standard assessment of bone mineral density is required. However, the Expert-XL has the advantage where reduced scan times, improved image resolution or morphometric analysis of the spine are required and may reduce the need for higher-dose radiographic procedures.

References

ACOP (Approved Code of Practice) 1985 *The Protection of Persons Against Ionizing Radiation Arising From any Work Activity* (London: HMSO)

Huda W and Sandison G A 1984 Estimate of mean doses in diagnostic radiology from Rando phantom measurements *Health Phys.* **47** 463–7

ICRP 1975 Reference man: anatomical, physiological and metabolic characteristics *ICRP Publication* 23 (Oxford: Pergamon)

——1991 1990 Recommendations of the International Commission on Radiological Protection *ICRP Publication* 60 (Oxford: Pergamon) pp 1–3

IRR 1985 *The Ionising Radiation Regulations 1985* (London: HMSO)

Jones D G and Shrimpton P C 1991 Survey of CT practice in the UK, Part 3: Normalized organ doses calculated using Monte Carlo techniques (NRPB-R250) (London: HMSO)

Lanzl L H 1973 *The Rando Phantom and Its Medical Applications* (Stamford, CT: Alderson Research Laboratories)

Mazess R B 1996 Occupational dose to the radiographer in dual x-ray absorptiometry *Br. J. Radiol.* **69** 1196

Njeh C F, Apple K, Temperton D H and Boivin C M 1996 Radiological assessment of a new bone densitometer—the Lunar Expert *Br. J. Radiol.* **69** 335–40

NRPB 1988 *Guidance Notes for the Protection of Persons Against Ionizing Radiations Arising from Medical And Dental Use* (London: HMSO)

Patel R, Blake G M, Batchelor S and Fogelman I 1996 Occupational dose to the radiographer in dual x-ray absorptiometry: a comparison of pencil-beam and fan-beam systems *Br. J. Radiol.* **69** 539–43

Patel R and Blake G M 1996 Occupational dose to the radiographer in dual x-ray absorptiometry (reply to Letter to the Editor) *Br. J. Radiol.* **69** 1196

Shrimpton P C, Wall B F and Fisher E S 1981 The tissue-equivalence of the Aldo Rando anthropomorphic phantom for x-rays of diagnostic qualities *Phys. Med. Biol.* **26** 133–9

Spencer D, Kuang C and Perks C 1994 Monte Carlo calculations of radiation dose to patients from DXA *Current Research in Osteoporosis and Bone Mineral Measurement III* ed E F Ring, D M Elvins and A K Bhalla (London: British Institute of Radiology) p 69

Wall B F, Harrison R M and Spiers F W 1988 Patient dosimetry techniques in diagnostic radiology *The Institute of Physical Sciences in Medicine Report* 53 (York: IPSM)