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Fetal dose estimates and the ICRP abdominal dose limit for occupational exposure of pregnant staff to technetium-99m and iodine-131 patients

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Abstract. The International Commission on Radiological Protection has recently recommended a supplementary dose limit of 2 mSv to the abdominal surface of a pregnant member of staff in order to provide protection to her fetus comparable to that in members of the public, whose annual limit is recommended to be 1 mSv. In order to determine whether this apparent attenuation factor of 50% is appropriate for nursing and imaging staff exposed to nuclear medicine patients, estimates were made of the ratios of the maternal abdominal surface to fetal dose appropriately weighted for time, distance and dose rate. Thermoluminescent dosimeter (TLD) measurements were made at various depths in an anthropomorphic phantom irradiated at different distances by a distributed source of either technetium-99m or iodine-131 in order to determine the corresponding attenuation factors at the average fetal midline depth. Dose estimates were based on these factors and on published values of dose rate and exposure times for nursing and imaging staff at these distances from the patient. Fetal doses to nursing staff caring for an adult ^{99m}Tc patient were estimated to vary from 86 μSv to 1.6 μSv, with the corresponding ratio of the abdominal surface to fetal dose varying from about 1.8:1 to 1.5:1 as the patient became less dependent on nursing care and the mean distance from the patient increased. Fetal doses to imaging staff varied from 1.12 μSv to 0.17 μSv for three types of ^{99m}Tc scan, but the ratio only varied from 1.4:1 to 1.3:1. Fetal doses to imaging staff were estimated to be 6.7 μSv and 9.0 μSv for a whole-body scan of a thyroid cancer patient after ^{131}I ablation and therapy respectively, and the ratio was 1.3:1 for both types of scan. It was concluded that for a pregnant ward nurse or imaging technologist exposed to an adult or paediatric patient administered ^{99m}Tc or ^{131}I, a dose limit of 1.3 mSv to the maternal abdominal surface will restrict their fetal dose to 1 mSv. A pregnant imaging technologist should perform no more than six adult ^{99m}Tc studies or one ^{131}I whole-body scan per day, and may have to wear a more sensitive personal dosimeter than a film badge.

Key words: Fetus – Dose – Limit – Technetium-99m – Iodine-131

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Introduction

The International Commission on Radiological Protection (ICRP) has recommended that for occupational exposure of a pregnant member of staff, the protection provided for her fetus should be comparable to that in members of the public [1]. Once the pregnancy is declared, this protection is to be achieved by the application of a supplementary dose limit of 2 mSv to the surface of the woman's abdomen. For members of the public, ICRP has recommended an annual limit of 1 mSv. Although this apparent attenuation factor of 50% has been shown to be adequate for fluoroscopy [2], the National Radiological Protection Board has implied that it may not be appropriate for external photon radiation of energy greater than 100 keV, and that expert advice should be sought on the necessity of a lower dose restriction to the abdominal surface [3]. With the exception of thallium-201, the energies of the principal photons emitted by the radionuclides commonly used in nuclear medicine exceed 100 keV. The necessity for a lower dose restriction in a particular situation can be decided by deriving the corresponding ratio of the dose at the maternal abdominal surface to the dose at the fetal mid-plane.

The critical members of staff likely to receive the greatest abdominal exposure from a nuclear medicine procedure are a ward nurse caring for a radioactive patient and a technologist who images a radioactive patient

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[4]. Exposure of other members of staff to radioactive patients will usually be of a much shorter duration, and exposure of any group of staff to inanimate sources can be limited by shielding and by restrictions of time and distance. The advent of the electronic personal dosimeter has allowed direct measurements of the surface dose received by a member of staff just from one radioactive patient. However, the fetal dose from this type of occupational exposure cannot be estimated by multiplying such a measurement by a tissue attenuation factor, because the radiation emitted from a patient is a diverging beam, and therefore the attenuation at the fetal depth will vary with distance from the patient. Hence the ratio of the maternal surface to fetal dose will vary according to the occupational levels of time and distance spent by the member of staff near to the patient. This ratio must be based, therefore, on a knowledge of the surface doses received at different distances from the patient and on the corresponding different attenuation factors.

The dose to the abdominal surface at a particular distance from a radioactive patient can be estimated simply from published values of the dose rate [5–7] and of the time [8, 9] spent at that distance by nursing and imaging staff. However, there are few published data to describe the attenuation in tissue applicable to the occupational exposure of a nurse or imaging technologist to a nuclear medicine patient. The attenuation at the fetal depth cannot be derived from the linear attenuation coefficient because the exposure does not occur under narrow beam conditions. Not only does this attenuation vary with the distance from the patient, but it also depends on the primary and scattered radiation energy spectrum incident to the abdominal surface, on the variation of the beam intensity in the plane orthogonal to the beam axis, and on the depth of the fetus below the surface.

The aim of this study was to estimate the maternal abdominal surface and fetal doses to pregnant nursing and imaging staff from occupational exposure to patients administered technetium-99m or iodine-131, and from the ratio of these two doses, to make recommendations of the appropriate dose limits to their abdominal surface which would restrict the fetal dose to 1 mSv. The fetal dose estimates were based on attenuation factors for the fetal midline depth derived from measurements of the dose at the surface and at depths in an anthropomorphic phantom exposed at various distances to distributed sources of ^{99m}Tc or ^{131}I. These distances corresponded to the values at which exposure times and dose rates for these groups of staff were either already available or could be easily derived.

Materials and methods

Phantom measurements. The radioactive sources consisted of a glass vial containing 15–18 GBq of ^{99m}Tc in 20 ml saline or 0.7–2.7 GBq of ^{131}I in 100 ml saline located behind a rectangular perspex block of 8 cm thickness. Lithium fluoride thermoluminescent dosimeter (TLD) sachets were positioned on the anterior surface and in slots located at depths of 6 and 9 cm along the central axis of four alternate slices at the level of the uterus in a Rando anthropomorphic phantom (Alderson Research Laboratories Inc, Stamford, Conn., USA) [10]. Measurements were made with the anterior abdominal surface of the phantom at distances of 0.2, 0.5 and 1.0 m from each source. To minimise the exposure of staff and other individuals to radiation from the unshielded sources, the measurements were conducted over a weekend to give a total TLD irradiation time of about 60 h.

^{99m}Tc dose estimates. The fetal dose D_f received by a nurse or imaging technologist was estimated by adding the separate exposures received at n positions, each of distance x_i from a patient undergoing a ^{99m}Tc procedure:

$$D_f = \sum_{i=1}^{n} d_i a_i t_i, \quad (1)$$

where d_i is the average dose rate over the exposure time t_i spent at the i-th position, and a_i is the corresponding attenuation factor at the depth of the fetal midline.

Data published from an ultrasound study have shown that the mean midline fetal abdominal depth along an anteroposterior projection, averaged over the full period of pregnancy, is 7.1 cm (range 6.0–8.5 cm) [11]. The TLD measured doses at 6 and 9 cm depth in each slice were normalised to their respective incident surface dose. The average normalised dose was calculated at each of these two depths, and then a simple linear interpolation was made between the two values to derive the attenuation factor a_i at a depth of 7.1 cm.

For nursing staff, values of t_i were taken from published periods of time spent at distances of 0.1, 0.5 and 1.0 m from patients classified according to their requirements for nursing care (Table 1) [8]. Maximum values of time-averaged dose rates (over 8 h from the end of the study) at 0.1, 0.5 and 1.0 m (Table 1) recorded from patients who had undergone a wide range of adult ^{99m}Tc procedures were substituted for d_i in the above equation [6]. The estimate of D_f was based on a distance of 0.2 m rather than 0.1 m be-

Table 1. Data used for estimation of maternal abdominal surface and fetal doses to pregnant nursing staff caring for ^{99m}Tc patients

Distance (m)	Time spent near patient (min)[a], according to patient category					
	Totally helpless	Partially helpless	Chairfast /bedfast	Semi-ambulant	Totally ambulant	Time averaged[b] dose rate (μSv·h^{-1})
0.1	67	17	5	0	0	98
0.5	128	91	56	7	5	20
1.0	30	56	32	31	8	4.7

[a] Taken from [8]
[b] Taken from [6]

Table 2. Data used for estimation of maternal abdominal surface and fetal doses to pregnant imaging staff carrying out a ^{99m}Tc bone, liver or dynamic renal scan, and a whole-body ^{131}I scan on a patient after ablation or therapy treatment

Distance (m)	Time spent near patient (min)[a]			Dose rate (μSv·h^{-1})		
^{99m}Tc scan:	Bone	Liver	Dynamic renal[c]	Bone[b]	Liver[b]	Dynamic renal[b, c]
0.5	0.5	0.4	0.6	30	5	5.6
1.0	8.5	6	1.5	5.5	1.2	1.7
2.0	21.5	16	37	1.4	0.3	0.4

Distance (m)	Time spent near patient (min)[a]		Dose rate (μSv·h^{-1})	
^{131}I scan:	Ablation	Therapy	Ablation[d]	Therapy[d]
0.5	0.5	0.5	119	133
1.0	8.5	8.5	34	46
2.0	21.5	21.5	8.5	12

[a] Taken from [9]
[b] Taken from [6]
[c] ^{99m}Tc-diethylene triamine penta-acetic acid
[d] Barrington, personal communication

cause the attenuation factor had been derived at 0.2 m. It was assumed that the exposure time at this distance was the same as had been observed at 0.1 m, and from the results of a previous study of the variation of dose rate with distance [12], the dose rate at 0.2 m was taken to be equal to one-half of the value published for 0.1 m.

For imaging staff, values of t_i were taken from published observations of the time spent at distances of 0.5, 1.0 and 2.0 m from adult patients undergoing a ^{99m}Tc bone, liver or dynamic renal scan (Table 2) [9]. Since the exposure times per patient for imaging staff were shorter than for nursing staff, maximum values of departure dose rate (rather than time-averaged values) recorded at 0.5 and 1.0 m from adult patients undergoing these scans were substituted for d_i in the above equation [6]. The published dose rate data did not include measurements made at a distance of 2.0 m from the patient. However, it has been shown that the dose rate at 2.0 m from a patient can be estimated by an inverse square law extrapolation of the value at 1.0 m [12].

TLD measurements were not conducted at a source to phantom distance of 2.0 m because the maximum activities of ^{99m}Tc and ^{131}I available would have produced a dose too close to the threshold value for LiF (0.05 mSv) [13]. For a source whose area was greater than that used in the above phantom measurements, the dose rate decreased with increase in distance according to the inverse square law from a distance of 0.5 m and beyond [12]. Therefore to estimate the attenuation factor for the exposure of imaging staff at a distance of 2.0 m, it was assumed that a_i at the fetal midline depth r in the phantom depth r in the phantom varied over this range of distances according to the following equation:

$$a_i=(x_i/(x_i+r))^2\cdot e^{-\mu r} \quad (2)$$

where μ is the broad beam attenuation coefficient. The term $e^{-\mu r}$ was calculated for the fetal midline depth of 7.1 cm from the above equation using the attenuation factor derived from the TLD measurements at a distance of 0.5 m. The attenuation factor at a distance of 2.0 m was then obtained from Eq. 2 using the calculated value of $e^{-\mu r}$. The process was repeated using the results from the TLD measurements made at a distance of 1.0 m. The contribution to the total fetal and maternal surface doses for imaging staff due to their exposure at a distance of 2.0 m was estimated from the average value of these two attenuation factors.

The maternal abdominal surface dose D_s was estimated from the equation:

$$D_s = \sum_{i=1}^{n} d_i t_i \quad (3)$$

using the corresponding data described above.

^{131}I dose estimates. In the absence of any published observations of the time spent by nursing or imaging staff at different distances from patients administered ^{131}I, the exposure times for a ^{99m}Tc bone scan [9] were used to estimate the fetal and maternal abdominal surface doses to imaging staff carrying out a whole-body scan on a patient who had completed their first ^{131}I (ablation) treatment after thyroidectomy or subsequent ^{131}I follow-up (therapy) treatment. To obtain the worst case values, the fetal and abdominal doses were estimated from Eqs. 1 and 3 respectively using the 95% upper confidence limit of the mean values of dose rate per unit activity [Barrington, personal communication] at 0.5 and 1.0 m on the 2nd day after administration, which was assumed to be the shortest time interval before the residual activity in the patient could be imaged (Table 2). Separate doses were estimated for an ablation and a therapy patient administered 3.0 and 5.5 GBq respectively. Dose rates and attenuation factors at 2.0 m from the patient were derived as before.

Results

The average doses at 6 and 9 cm depth in the four phantom slices, normalised to the incident surface dose, are given in Table 3 for both sources. The attenuation factor a_i interpolated at 7.1 cm depth for the ^{99m}Tc source was 0.51±0.06, 0.66±0.08 and 0.72±0.04 at distances of 0.2, 0.5 and 1.0 m respectively, and for the ^{131}I source the corresponding attenuation factors a_i were 0.53±0.10, 0.65±0.04 and 0.76±0.05 respectively. Values of 0.83±0.10 and 0.81±0.05 were derived for the term $e^{-\mu r}$ at a depth of 7.1 cm for the ^{99m}Tc source at a distance of 0.5 and 1.0 m respectively, giving an average attenuation

Table 3. Normalised dose measured at depths in the phantom irradiated by the ^{99m}Tc and the ^{131}I source at different source to phantom distances

Source to phantom distance (m)	Normalised dose (%)[a]					
Source:	^{99m}Tc			^{131}I		
Depth in phantom (cm):	0	6	9	0	6	9
0.2	100	56±5	41±9	100	60±9	42±6
0.5	100	71±7	56±8	100	69±3	58±4
1.0	100	79±3	60±7	100	80±5	68±2

[a] Mean value ±1 SD of measurements in four phantom slices

Table 4. Estimates of maximum maternal abdominal surface and fetal doses for occupational exposure of nursing staff caring for ^{99m}Tc patients

Patient category	Maximum dose from one patient (μSv)		Dose ratio[a] (maternal:fetal)
	Maternal surface	Fetus	
Totally helpless	155	86	1.8:1
Partially helpless	63	37	1.7:1
Chairfast/bedfast	29	18	1.6:1
Semi-ambulant	4.7	3.3	1.5:1
totally ambulant	2.3	1.6	1.5:1

[a] Maternal abdominal surface dose corresponding to a fetal dose of 1 mSv

Table 5. Estimates of maximum maternal abdominal surface and fetal doses to imaging staff from carrying out a ^{99m}Tc bone, liver or dynamic renal scan, and a whole-body ^{131}I scan on a patient after ablation or therapy treatment

Scan	Maximum dose from one patient (μSv)		Dose ratio[a] (maternal:fetal)
	Maternal surface	Fetus	
^{99m}Tc: Bone	1.53	1.12	1.4:1
Liver	0.23	0.17	1.4:1
Dynamic renal	0.35	0.26	1.3:1
^{131}I: Ablation	8.9	6.7	1.3:1
Therapy	11.8	9.0	1.3:1

[a] Maternal abdominal surface dose corresponding to a fetal dose of 1 mSv

factor a_i of 0.77±0.05 at a distance of 2.0 m. For the ^{131}I source at a distance of 0.5 and 1.0 m, $e^{-\mu r}$ was calculated to be 0.82±0.05 and 0.85±0.06 respectively, giving an average attenuation factor a_i of 0.79±0.04 at a distance of 2.0 m from the phantom. All these uncertainties were based on the standard deviations of the average normalised doses given in Table 3, and the systematic uncertainties in each TLD measurement were ignored.

The maximum value of maternal abdominal surface dose to a nurse varied from 155 μSv when caring for a totally helpless adult ^{99m}Tc patient to 2.3 μSv for a ^{99m}Tc patient classified as totally ambulant (Table 4). The corresponding fetal doses were estimated to be 86 μSv and 1.6 μSv respectively. Also given in Table 4 are the ratios of the maternal abdominal surface to fetal dose when the latter was equal to 1 mSv. The ratio decreased from about 1.8:1 to 1.5:1 as the ^{99m}Tc patient became less dependent on nursing care.

The maximum value of maternal abdominal surface dose to an imaging technologist varied from 1.53 μSv to 0.23 μSv for the three types of ^{99m}Tc scan (Table 5). The corresponding range of fetal doses was estimated to be 1.12 μSv to 0.17 μSv respectively. The ratio of the maternal abdominal surface to fetal dose when the latter dose was equal to 1 mSv only varied from about 1.4:1 to 1.3:1.

The 95% upper confidence limit of the maternal abdominal surface dose to an imaging technologist was 8.9 μSv and 11.8 μSv for a whole-body scan of an ^{131}I ablation and therapy patient respectively (Table 5). The corresponding fetal doses were estimated to be 6.7 μSv and 9.0 μSv respectively. The ratio of the maternal abdominal surface to fetal dose when the latter was equal to 1 mSv was about 1.3:1 for both types of patient.

Discussion

The precision of the TLD results and the uncertainty over the appropriate analytical function to describe the variation of dose with depth at a distance of 0.2 m justified deriving the attenuation factor at the fetal midline

depth by a simple linear interpolation between the measurements at 6 and 9 cm depth. The close agreement between the values calculated for the term $e^{-\mu r}$ at 0.5 m and 1.0 m distance for each source supported the use of Eq. 2 as a valid means of deriving the attenuation factor at a distance of 2.0 m. Under narrow beam conditions, the depth in tissue of 6.3 cm for 50% attenuation of the primary gamma radiation from ^{131}I (360 keV – 79%) is 1.8 cm greater than the equivalent depth of 4.5 cm for ^{99m}Tc (140 keV – 90%). However, for the same source to phantom distance, no significant difference was found in the variation of dose with depth (Table 3) or in the attenuation factor for the fetal midline depth between the ^{99m}Tc and the ^{131}I sources. Although the precision of the TLD measurements may have prevented these differences from being resolved, two physical effects were considered to have contributed to a reduction in the difference between the penetration of the radiation from these two sources.

Firstly, the measurements were conducted without any restriction to the area of the incident beam, and as this area increases, the difference between the penetration of two different energy radiations will decrease even though the penetration of each beam will actually increase. Secondly, both sources emitted photons other than their primary emissions. Of the radiations produced directly by nuclear transitions, only those emitted from ^{131}I are sufficiently energetic to escape from the source, but they are unlikely to reduce the mean photon energy incident to the phantom because they have energies both greater and less than that of the primary emission and they are of a lower intensity (80 keV – 2.2%, 280 keV – 6.3%, 640 keV – 9.3%, 720 keV – 2.8%). However, the ^{131}I source also produced bremsstrahlung radiation from absorption of its beta particle emissions within the saline and glass vial. The mean energy of the beta particles emitted by ^{131}I is 246 keV [14], but the mean energy of the bremsstrahlung radiation from absorption of the beta particles in these media will be considerably less and would have occurred at the low photon energies where the response of the LiF TLD is enhanced [13]. Although no data could be found to indicate the relative intensity of this type of radiation incident to the phantom, consideration of the count rate from gamma camera imaging of bremsstrahlung radiation from patients administered other beta particle emitting radionuclides, such as phosphorus-32 [15] or holmium-166 [16], suggests that it may be sufficient to reduce the mean energy of the photon radiation incident to the phantom from the ^{131}I source below that of the primary emission. For the level of activities available, TLD measurements lacked the precision to identify the separate effects of source distribution, irradiation geometry and bremsstrahlung, and it is recommended that they should be investigated further with a Monte Carlo computer code such as MCNP [17].

The magnitude of the abdominal surface and fetal dose estimates for pregnant nursing staff increased as a ^{99m}Tc patient became more dependent on nursing care due to the greater time spent in close proximity. A pregnant ward nurse would have to care for 11, 55 or 625 adult ^{99m}Tc patients classified respectively as totally helpless, chairfast/bedfast or totally ambulant before their fetal dose exceeded 1 mSv. Using the same values of nursing times as before [8] and maximum time-averaged dose rates from paediatric patients administered ^{99m}Tc radiopharmaceuticals [5], maternal surface and fetal doses for pregnant nurses were estimated to be about one-half to one-third of the corresponding values for adult patients given in Table 4. On this basis, the number of paediatric ^{99m}Tc patients which would have to be cared for by the same pregnant nurse before the fetal dose exceeded 1 mSv is at least twice the corresponding number of adult patients. Hence a pregnant ward nurse caring for adult or paediatric ^{99m}Tc in-patients is unlikely to incur a dose to their fetus of more than 1 mSv during the period after their pregnancy is declared, even though paediatric patients may require longer periods of close nursing. Doses to pregnant imaging technologists from carrying out scans on children were not estimated because of the absence of available data to describe the extended periods of time in close contact which may be necessary to reassure and restrain them.

The ratio of maternal abdominal surface to fetal dose also increased as a ^{99m}Tc patient became more dependent on nursing care because the proportion of the total nursing time spent close to the patient increased (i.e. the mean working distance from the patient decreased). Because the variation in the maximum values of dose rate with distance from paediatric patients [5] did not differ greatly from that from adult patients [6], and because the same set of exposure times was used for both sets of patients, the ratios estimated for pregnant nursing staff caring for paediatric patients were no different to the values given in Table 4 for adult patients. For pregnant imaging staff, similar ratios were found for each type of adult ^{99m}Tc scan (Table 5), because the mean working distance for each scan varied only from 1.7 to 1.9 m and the variation of dose rate with distance, did not alter significantly with the type of scan (Table 2). The maternal abdominal surface dose which will result in a fetal dose of 1 mSv for pregnant imaging staff carrying out scans on paediatric patients will be more than the values for adult patients because a greater proportion of the total time for the procedure will have to be spent close to the patient.

Lack of occupational data prevented an estimate of the surface and fetal doses for pregnant nursing staff caring for an in-patient being treated with ^{131}I for thyroid carcinoma. However, occupational exposure in this situation is restricted by the use of local shielding, and by the issue of strict instructions which limit time and distance on the basis of direct dose rate measurements. Assuming equivalent exposure times for ^{99m}Tc bone scans allowed the abdominal and fetal doses to be estimated for pregnant imaging staff carrying out a whole-body scan for thyroid cancer, which is the most likely exposure of this group of staff to ^{131}I patients. Dose rates from these pa-

tients were about an order of magnitude greater than from ^{99m}Tc procedures (Table 5), and they produced correspondingly higher estimates of maternal and fetal dose. Similar variations in dose rate with distance and the similar magnitude of attenuation factor at each distance resulted in the same value of the ratio of maternal to fetal dose for exposure to ^{99m}Tc and ^{131}I patients.

In order to minimise handling of the high activities necessary for the TLD measurements, the ^{99m}Tc and ^{131}I were not subdispensed into larger sources for further measurements to investigate the effect of source area. The use of a wider area source for the phantom measurements would have resulted in a lower estimate of the ratio of the maternal surface to fetal dose at distances of less than 1.0 m from the patient [12]. Because imaging staff produced a lower ratio than nursing staff, the abdominal surface dose limit for pregnant staff must be based on the ratio for the former group. However, the maternal and fetal dose estimates for pregnant imaging technologists were dominated by the contributions at distances of 1.0 m and beyond, where there is little difference in the variation of dose rate with distance and in the ratio of maternal to fetal dose between different sized sources [12]. Thus the ratio for pregnant imaging staff exposed to a patient administered a radiopharmaceutical with a widespread anatomical distribution is unlikely to differ from the values given in Table 5.

It was concluded that a dose limit of 1.3 mSv to the maternal abdominal surface of a pregnant ward nurse or imaging technologist exposed to an adult or paediatric patient administered any ^{99m}Tc radiopharmaceutical or ^{131}I iodide will restrict the fetal dose to 1 mSv. On the assumption that the duration of pregnancy is 7 months from the time the employer is informed, then the dose to the maternal abdominal surface of a pregnant imaging technologist from adult ^{99m}Tc patients should not exceed 0.2 mSv per month in order that the fetal dose should not exceed 1 mSv. This monthly limit is the same as the detection threshold for a film badge, and therefore it may be necessary for a pregnant imaging technologist to wear a more sensitive device such as an electronic personal dosimeter, particularly if she will be carrying out procedures which yield a higher than average abdominal surface dose.

For the average abdominal surface dose to an imaging technologist of 1.5 μSv found by Clarke et al. [18] from a wide range of ^{99m}Tc procedures, the average fetal dose per adult ^{99m}Tc procedure corresponding to the limiting ratio of 1.3:1 is 1.2 μSv. Assuming 20 working days per month, a pregnant imaging technologist should not carry out more than six adult ^{99m}Tc studies or one ^{131}I whole-body scan per day in order to restrict the total fetal dose to 1 mSv. A workload of six studies per day per gamma camera is less than the European average [19], and hence the technologist's duties may have to be altered, particularly if the workload involves paediatric patients or procedures known to produce high abdominal doses. Observations of the exposure time of imaging staff at different distances from paediatric patients would allow workload recommendations to be derived specific to the occupational exposure of pregnant imaging technologists to children undergoing a diagnostic nuclear medicine procedure.

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