The British Journal of Radiology, *81* (2008), 499–503

SHORT COMMUNICATION

Modelling the effect of lead and other materials for shielding of the fetus in CT pulmonary angiography

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ABSTRACT. The aim of this work is to construct and validate a model to describe the variation in fetal dose as a function of the thickness of abdominal lead shielding used during CT pulmonary angiography and to determine the optimal shielding material. An anthropomorphic phantom was modified to contain a 15 cm^3 ionization chamber at the site of the uterus. Fetal dose was measured with varying thicknesses of lead shielding at four values of tube potential (kV_p). Data generated by the proposed model were compared with experimental data to determine the validity of the model. The effect of lead shielding has been modelled accurately and results have shown that, although alternative materials could be used, lead is an effective and practical shielding material. In conclusion, lead remains a suitable shielding material and a pair of conventional lead aprons provides significant shielding for the fetus; we recommend that aprons should be reserved specifically for this purpose. However, it is possible that a dedicated and specifically designed lead shield could reduce fetal dose more effectively whilst also reducing patient discomfort.

Received 25 September 2006
Revised 2 July 2007
Accepted 9 August 2007

DOI: 10.1259/bjr/66819221

Pulmonary embolism occurs with a frequency of 1–6 per 2000 pregnancies [1–3]. The British Thoracic Society guidelines state that CT pulmonary angiography (CTPA) is currently the recommended imaging modality for the diagnosis of pulmonary embolism [4]. The fetal dose from CTPA has been estimated in a study by Hurwitz et al [5] using anthropomorphic phantoms. They reported typical fetal doses of 0.2–0.7 mGy.

Prior to the authors' own work [6], there was no agreement in the literature as to whether the use of lead shielding was justified, although Doshi et al [7] suggest that a dose reduction is possible in CTPA. A possible dose reduction to the uterus and ovaries was also investigated by Hidajat et al [8], who subsequently reported no such reduction. This occurred because the scan volume was closer to the uterus than a CTPA scan and only a small amount of lead was used for shielding. As such, their results are not directly comparable with the clinical situation under investigation in this study.

In earlier work, we have established the use of lead shielding for the reduction of fetal dose resulting from CTPA. This work considered the effect of a variety of scan parameters, along with the use of different thicknesses of lead and their positioning. The recommendations made were that lead aprons containing the equivalent of 0.7 mm lead should be placed around the patient and positioned up to the caudal edge of the scan volume. Dose reductions of up to 55% were seen [6].

Bateman et al [9] and Murphy et al [10] have reported that lead aprons show a large variation in their equivalent thickness. Their results mean that the extent of dose reduction provided for a fetus may vary widely when lead aprons are used. It was also noted during our previous experimental work that the available lead aprons did not provide a consistent covering for the phantom. The shape of the aprons meant that gaps and folds appeared, which resulted in areas of the phantom being inadequately shielded and other areas being affected by the extra weight of overlapping aprons. This can be seen in Figure 1. The aprons were also longer than required for this application and, as such, they resulted in weight being placed on the patient for no dose reduction benefit. It also results in unnecessary moving and handling for radiographic staff.

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Aims of this work

The aim of this work is to construct and validate a model to describe the variation in fetal dose as a function of the thickness of lead shielding. The model will be constructed using measured data and will identify the relative magnitudes of the different contributors to total fetal dose. This model will then be used to determine whether any alternative shielding materials offer an advantage over lead aprons. The need for a dedicated shield for the fetus will also be discussed.

Figure 1. Experimental set-up showing the RANDO phantom, the positioning of the lead aprons and clearly demonstrating the folds and gaps in the aprons.

Methods

The method for collecting data has been previously described [6]. A RANDO phantom (Alderson Laboratories, Stamford, CA) was modified to enable the fetal dose to be measured using a 15 cm^3 ionization chamber at the position of the uterus. A Siemens SOMATOM Sensation 16 CT scanner (Siemens AG, Erlangen, Germany) was used for all measurements and the phantom was positioned supine on the couch, as shown in Figure 1. Lead aprons used as shielding were checked for damage and were positioned on both the anterior and posterior sides of the phantom aligned at the position of the lower costal margin. The fetal dose was measured for lead thickness of up to 2.2 mm at tube potentials of 80 kV_p, 100 kV_p, 120 kV_p and 140 kV_p.

Knowledge of the sources of scattered radiation that contribute to the fetal dose, coupled with analysis of experimental data, has enabled us to propose a model that describes the variation in fetal dose with thickness of any attenuating material. These different sources of scattered radiation are shown diagrammatically in Figure 2.

The proposed model is described below:

$$\text{Fetal dose}\,(\mu\text{Gy}) = C + [I_0 e^{-\mu_x t_x} e^{-\mu_t t_t}] + [(I_I(1 - e^{-\mu_x t_x}))e^{-\mu_t t_t}] \quad (1)$$

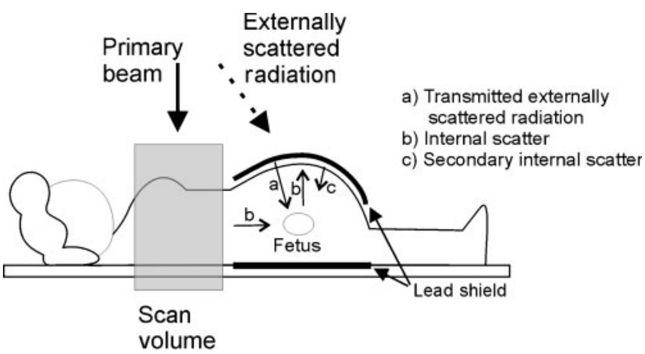

Figure 2. Diagram showing the three sources of scattered photons that contribute to the fetal dose.

where C is the contribution to the fetal dose that arises from internally scattered radiation (µGy); I_0 is the dose at the surface of the phantom, owing to externally scattered radiation, in the absence of any shielding (µGy); μ_x (cm^{-1}) is the attenuation coefficient of the shielding material; t_x (cm) is the thickness of the shielding material; μ_t (cm^{-1}) is the attenuation coefficient of the tissue; t_t (cm) is the thickness of the tissue; and I_I is the dose at the phantom side of the shielding, which arises from internally scattered radiation (µGy)

The first term in Equation 1 represents the contribution to the fetal dose of internal scatter from the scanned volume. This was assumed to be constant, irrespective of the thickness of lead (or other shielding material) that is placed on the patient. The second term represents the contribution to fetal dose of the externally scattered radiation, and the third term describes the fetal dose contribution from secondary internally scattered radiation.

From the measured fetal doses, we determined the maximum possible percentage dose saving for each kV_p setting. As the lead shielding was placed on the outside of the patient, we assumed that this dose saving was a result of blocking the externally scattered radiation.

With no lead shielding present, the dose from secondary internal scatter (I_I) is zero, and so the dose to the fetus is the sum of the internally and externally scattered radiation. Therefore, we set the external scatter term (as a percentage of the fetal dose with no lead) to be equal to the maximum possible percentage dose saving, which allowed the value of I_0 to be calculated. From this, we also determined the percentage value of the internal scatter, C, as this is equal to 100% minus the maximum possible percentage dose saving.

These values for C and I_0 were entered into the model and adjusted to fit the measured data at small thicknesses of lead (for which I_I is minimal). I_I was then adjusted to achieve an optimal fit to the data at larger thicknesses of lead, when secondary internal scatter becomes a larger contributor to fetal dose. Further adjustments were made to C, I_0 and I_I to optimize the fit to the measured data across the whole range of lead thicknesses.

Once a good fit to the data had been achieved using this manual method, the final values of C, I_0 and I_I were determined using a formalized mathematical function solving tool in Microsoft Excel ("Solver"; Microsoft Excel ™, Microsoft Corporation, Redmond, WA). The following constraints were used in this process:

- The values of C, I_0 and I_I must be $\geqslant 0$.
- The percentage difference between the experimentally measured and the calculated dose values with zero lead must be equal to zero.
- The mean percentage difference between the experimentally measured and the calculated dose values across the full range of lead thicknesses must be equal to zero.

Once the relative contributions of C, I_0 and I_I had been determined, the model was used to determine the typical dose savings that could be achieved with several alternative shielding materials by entering the µ values for each material into Equation 1.

Table 1. Mass of 1 m^2 of a number of materials needed to give the same attenuation as 0.7 mm lead

Element	Mass of each material required at each kVp setting (kg)			
	80 kVp	100 kVp	120 kVp	140 kVp
Bismuth	7.59	7.80	7.94	7.94
Copper	24.28	25.39	24.87	24.13
Gadolinium	3.59	3.22	3.24	3.41
Gold	8.84	8.71	9.21	8.59
Lead	7.94	7.94	7.94	7.94
Molybdenum	9.31	9.36	9.69	9.65
Rhodium	7.59	7.60	7.77	7.74
Silver	6.80	7.00	7.32	7.21
Tungsten	13.46	11.04	10.82	2.73
Zinc	22.52	22.97	22.71	21.63

Results

Figure 3a shows the experimentally measured data alongside the data predicted by the model for the same scanning parameters and thicknesses of lead for 140 kV_p and 120 kV_p. Figure 3b shows equivalent data for 100 kV_p and 80 kV_p.

A non-parametric Spearman rank correlation showed that the model devised displays no significant difference from the experimental data at the 95% significance level, with an R_S value of 0.98 for $p<0.0001$.

The relative contributions of the three sources of scattered radiation at 140 kV_p are shown in Figure 4; the exact proportions of the internal, external and secondary internal scatter vary with tube potential and may also vary from scanner to scanner.

A simplified version of the model has also been developed that does not account for the contribution from secondary internally scattered radiation, as this has a small effect on the total dose. A non-parametric Spearman rank correlation showed that the simplified model also displayed no significant difference from the experimental data at the 95% significance level, with an R_S value of 0.98 and $p<0.0001$.

This simplified model was applied to a number of stable, commercially available materials that could be considered as alternative shielding materials; the thickness of each material that would provide equivalent shielding to 0.7 mm lead was calculated for each kVp setting on the CT scanner. From these results, the mass of a 1 m^2 area of the required thickness of each material was calculated. Table 1 shows the results for materials that yielded a required mass of <25 kg.

Figure 3 shows that increasing the thickness of lead, which is used as the shield, increases the dose saving; similarly, decreasing the thickness of lead reduces the dose saving. It was therefore postulated that using a greater thickness of lead at the posterior of the patient (*i.e.* on the scanner couch) would yield a small increase in the achievable dose saving. Reducing the thickness of lead that is placed on the anterior side of the patient would yield a small decrease in the achievable dose saving. If both of these changes in the shield thickness were implemented simultaneously, it should be possible to approximately balance out the relative increase and decrease in the dose saving, thus obtaining overall dose savings that are similar to those achieved with a constant thickness of lead, whilst reducing the weight being placed on the abdomen of the patient. Interpretation of the data shown in Figure 3 suggests that, with careful choice of the lead thickness being used, fetal dose reductions of up to 99% of those achieved with the same thickness of lead on the anterior and posterior of the patient can be achieved. This is obviously dependent on the tube potential that is used for the clinical scan. Further tests showed that, even at 140 kV_p, using this variable thickness technique yielded 95% of the fetal dose reduction that was achieved with a constant thickness of lead around the patient.

Discussion

An analysis of the components of Equation 1, as detailed in Figure 4, shows that the externally scattered radiation is exponentially reduced as the thickness of lead is increased, and is decreased to approximately a quarter of its original intensity by 0.35 mm lead. The contribution to the fetal dose of secondary internally scattered radiation increases with increasing lead thickness but reaches a plateau at thicknesses of lead beyond ~1.5 mm. If these two curves are subtracted from the curves describing experimental data, as shown in Figure 3, the remaining contributor to the experimental data, which represents the internal scatter, is a constant. This validates the initial assumption that the dose from internal scatter was independent of the thickness of lead used as shielding.

The results illustrate that the component resulting from secondary internally scattered radiation is much smaller in magnitude than the other two components of the curve. This component decreases with increasing primary beam energy, whilst the component resulting from externally scattered radiation increases with primary beam energy.

The form of the curves is dependent on the value of μ for the material used as shielding and also the thickness used; in turn, the value of μ is dependent on the energy of the primary beam and, as such, is dependent upon the scanner and tube potential used. The value of μ for tissue is approximately constant over the energy range that was used; the thickness of the tissue present was also constant, as the same phantom was used for all of the tests.

From the results shown in Table 1, it can be seen that four of the elements can provide equivalent shielding to 0.7 mm lead but with less weight being placed on the patient. Tungsten also offers a weight reduction at high

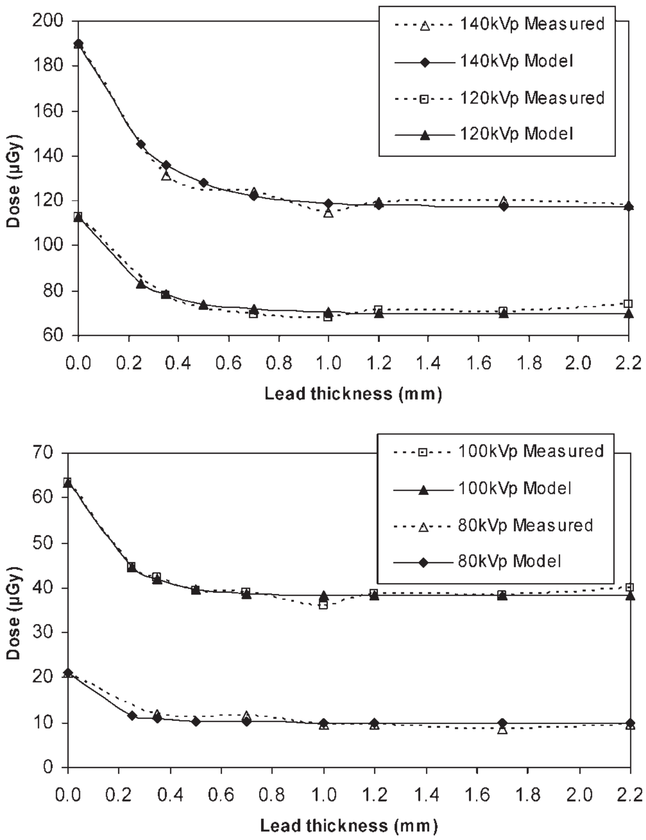

Figure 3. (a) Experimental data and modelled data for tube potential settings of 140 kVp and 120 kVp. (b) Experimental data and modelled data for tube potential settings of 100 kVp and 80 kVp. Errors on all values in Figure 3 are 1%.

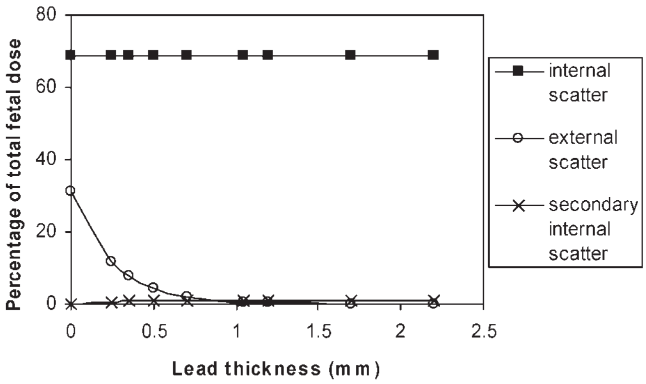

Figure 4. The relative contributions of the three sources of scattered radiation to the total fetal dose as calculated using the proposed model at 140 kV_p. (The indicated dose levels are illustrative, as the exact values will vary from scanner to scanner.)

primary beam energies owing to a K-edge in the range of energies used. A reduction in the weight of the shielding material, especially the weight placed on the front of the patient, will reduce patient discomfort and also reduce potential moving and handling issues for radiographers.

Of these four elements, gadolinium, although it reduced the weight of the shielding needed by more than any other element, tarnishes in air, and silver and rhodium may be expensive. Bismuth offers a small advantage at low beam energies and is practical.

The work of Bateman et al [9] and Murphy et al [10] showed that lead aprons which are available in the clinical setting may not be of sufficiently high quality to provide shielding to the fetus. The results presented by Bateman et al [9] showed that the protection given by both lead and lead-free aprons was less than the stated value for scattered radiation, despite being similar to the stated value for primary radiation. In this case, where pregnant women are undergoing CTPA examinations, the fetus is subjected only to scattered radiation and, as such, the protection that is provided by the shielding may not be that which is expected from the stated lead equivalence of the apron. It is therefore postulated that a dedicated custom-built fetal shield, which fits neatly around the patient and allows no externally scattered radiation to enter the body, would be preferable. In previous work, the dose reduction seen when the phantom was covered up to the lower costal margin was 40%; this increased to 55% when the phantom was covered up to the caudal edge of the scan volume [6]. This suggests that any such dedicated shield would be most effective if it was used to shield up to the lower edge of the scan volume rather than up to the lower costal margin. We recommend that any such shield should be capable of covering up to the bottom of the scan volume and should extend only as far as the middle of the patient's thigh. This would provide sufficient shielding material and also reduce the total weight of the shielding that is placed on the front of the patient. Furthermore, we have shown that use of a thicker shield behind the patient and a thinner shield on the patient's abdomen can yield up to 99% of the dose reduction that can be achieved with the same shield thickness both behind and in front of the patient; this will further reduce patient discomfort.

The use of a dedicated shield may also be appropriate for all upper-body CT scans. The doses to organs under the shield will be reduced and there will be an associated reduction in the effective dose. The doses to organs towards the anterior of the patient may be higher than if a shield with a constant thickness of lead had been used but will still be lower than if no shielding had been employed.

Conclusions

A simple model for the behaviour of scattered photons when using protective shielding has been proposed. This was shown to have a significant correlation with the experimental data for lead using a Spearman rank correlation (R_S value of 0.98 and $p<0.0001$). The model was used to investigate the possible use of other shielding materials and has shown that, although other materials may be considered, lead is effective and should remain the material of choice as it is widely commercially available. It is postulated that a dedicated, specifically designed shield could be made available for this task, which would provide a more consistent covering for the patient and therefore yield a larger and more predictable dose reduction. Such a dedicated shield would also reduce patient discomfort, as well as moving and handling issues for radiographers. This is to be the focus of further work.

It is also recommended that if a specifically designed shield is not available, then lead aprons should be reserved specifically for this task and care should be taken to ensure that they do not become damaged or contaminated.

Acknowledgments

The authors would like to thank the Radiology Department at St James's University Hospital, Leeds, UK, for use of their CT scanner.

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