

Investigation into the effects of lead shielding for fetal dose reduction in CT pulmonary angiography

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ABSTRACT. This work aims to determine whether lead shielding can be used to decrease the radiation dose to the fetus during CT scans for the diagnosis of pulmonary embolism during early stage pregnancy. An anthropomorphic phantom was modified to contain a 15 cc ionization chamber at the site of the uterus to enable fetal dose to be measured. The effects of a range of scan parameters, positioning of lead and thicknesses of lead were investigated. Fetal dose was lower with lower values of kV_p and mAs. An increasing thickness of lead decreased the radiation dose to the uterus, as did increasing the proportion of the patient covered by the lead shielding. Fetal dose increased exponentially as the edge of the scan volume moved closer to the point of measurement. In no experiment was the dose to the fetus increased by the presence of the lead. It was found that the fetal radiation dose from a CT scan following a pulmonary embolism protocol can be effectively reduced by the use of lead shielding.

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Radiology

Pulmonary embolism (PE) is widely regarded in the literature as being the leading cause of maternal death during pregnancy [1–4], and it occurs with a frequency of 1–6 cases per 2000 pregnancies [3, 5, 6]. The 3 month mortality rate in the general population following a positive diagnosis of PE is 17.5% [7]. There are a number of factors that lead to an increased risk of PE during pregnancy, including increased venous stasis, an increase in venous distensibility and capacity, an increase in the levels of coagulation factors and bed rest [2, 8].

The British Thoracic Society guidelines state that computerized tomography pulmonary angiography (CTPA) is currently the recommended imaging modality for the diagnosis of PE, although ventilation/perfusion scanning is often used [9]. These guidelines do not include specific recommendations for pregnant patients.

The radiation dose to the fetus from CT scans aiming to diagnose PE has been estimated in a number of studies [1, 10–13]. In a study using anthropomorphic phantoms. Hurwitz et al [10] report a fetal dose of between 0.2 and 0.7 mGy. Fetal doses have been estimated using mathematical models [1], and doses of 0.003–0.130 mGy and 0.14 mGy have been reported [1, 11]. The fetal dose will increase during pregnancy both as the fetus grows in size and as it moves closer to the scan volume [1].

The developing fetus is sensitive to radiation because of the highly proliferating nature of the cells and processes of differentiation [14]. The risks of causing a range of different radiation effects vary with gestational age [15]. The expected doses involved in CT are not likely to meet the threshold for inducing malformations

or reduction in intelligence, so the most important consideration is the induction of childhood cancer. It is likely that this risk is constant over the entire term, and there is no evidence that the pattern of cancer induction varies with gestational age [14], or that the induction of cancer has a dose threshold. The excess risk of the induction of childhood cancer is reported as 1 in 33 000 per mGy [15].

The use of lead shielding

The use of lead shielding to provide protection from irradiation in CT has been well reported for a wide range of organs [13, 16–24]. In this work, we consider the case where the organ at risk, the fetus, is subject only to internally and externally scattered radiation. This means that the detrimental effects on image quality of placing the shielding within the primary beam are avoided.

The use of lead shielding for the protection of the uterus and the ovaries in CT scanning of the upper abdomen is considered by Hidajat et al [16]. No reduction in the dose to the uterus and ovaries was found through the use of the lead shield, although the authors make two important points: first, that (from their own observation) the internal dose is always greater than the surface dose for measurements outside the primary beam and, second, that the effectiveness of the lead shielding is dependent on whether the organ to be protected lies superficially or deep in the body.

Doshi et al [13], in their work measuring fetal doses during CTPA scans, report a reduction of approximately 30% when using a lead apron as shielding. The phantom used in their study was based on a pregnant patient at full term.

Dose reductions were observed in three studies considering the radiation dose to the male gonads using

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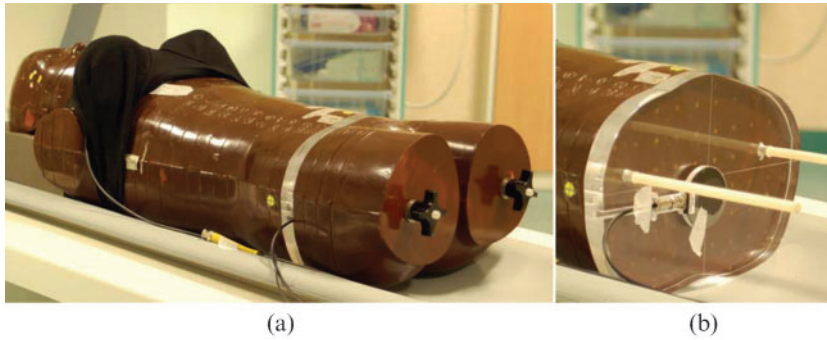


Figure 1. (a) Experimental set-up of the Rando phantom with Perspex slice and water balloons. (b) Perspex replacement slice.

a 1 mm lead shield designed to surround the testes [16, 17, 22]. Price et al [22] report dose reductions of 82% where the testes were 15 mm from the edge of the scan field and 77% where the testes were 10 mm from the edge of the scan field during pelvic CT scanning in a situation where the dose is only due to scatter. Hohl et al [17] found that the dose to the testes was reduced by 87% during routine abdominopelvic CT scanning, and Hidajat et al [16] used a phantom study to demonstrate a 95% reduction in the dose to the testes in abdominal CT examinations.

Shielding of the breasts during CT scanning of the head has been discussed by two studies [21, 23]. Beaconsfield et al [23] showed that the dose to the breast was reduced from 0.32 mGy to 0.042 mGy by the use of a lead shield, which represents a reduction of 87%. Brnic et al [21] also reported a reduction in breast dose of 57% through the use of a 0.35 mm lead shield. Measurements were also made by Brnic et al [21] to analyse the relative contribution from internal and external scatter. The results of these measurements imply that the relative contributions are approximately equal and that the ratio of internal to external scatter may be dependent on the depth of the measurements made.

Although no dose reduction was reported by Hidajat et al [16], the above, along with the work of Doshi et al [13], suggests that a dose reduction should be possible.

Aims of this work

This work aims to determine whether lead shielding can be used to decrease the radiation dose to the fetus during CT scans for the diagnosis of PE during early stage pregnancy. This information can be used to produce a protocol that will yield the minimum practically achievable dose to the fetus while preserving image quality within the scan volume.

Methods

Protocol determination

To establish the protocols used by local CT departments for PE and their use of lead shielding, a questionnaire was sent out to seven departments covering 11 CT scanners. Questions were asked regarding the exposure parameters that were used on each scanner, the extent of the scan volume in anatomical terms, whether the scan protocol was adapted for pregnant patients,

whether lead shielding was used, what thickness of lead shielding was used and how this was positioned on the patient. Results from these questionnaires were used to determine the range of scan parameters and other factors that were investigated in this study.

Designing the phantom

A Rando phantom (Alderson Laboratories, Stamford, CT) was modified to enable the dose to the fetus to be measured directly (Figure 1a). Information reported in Adams et al [12] was used to determine the distance of the top of the uterus from the top of the head. To verify the uterus position, the bones that were visible in the phantom were also matched to anatomical images [25]. These two methods indicated slice number 31, which had also been used by Hidajat et al [16], as the optimal position for the uterus. The organ dose to the uterus was taken as being equal to the fetal dose [15]. A Perspex replacement for slice 31 was machined with a well so that a 15 cc ionization chamber and the attached cables could be fitted (Figure 1b). Perspex is known to have a higher linear attenuation coefficient than the Rando phantom muscle material of the order of 10% at diagnostic energies and, as such, the replacement slice may have attenuated the scattered radiation more than the slice of the phantom that was removed. This study is designed to evaluate the relative change in fetal dose when lead shielding is used and, as such, the difference in attenuation between Perspex and the phantom material is thought to have had a minimal effect on the results.

Measurements of breast dose were used as a check of consistency between experiments. To enable the breast dose to be measured, an additional 15 cc ionization chamber was fitted to the surface of the chest of the phantom. This was positioned over slices 15 and 16 and underneath a balloon filled with water (similar to Doshi et al [13]) to represent a C cup breast, which was held in place by a bra. For a C cup, each breast should be 600 ml in volume (Alderson Laboratories, Stamford, CT; manufacturer's data). The two water balloons were each sealed in a plastic bag in case of leakage. The left breast weighed 615.2 g and the right breast weighed 592.5 g. The smaller breast was fitted over the ionization chamber.

Experimental set-up and protocol

A Siemens SOMATOM Sensation 16 CT Scanner (Siemens AG, Erlangen, Germany) was used for all the

scanning. The phantom was positioned supine on the couch with a foam headrest for support, as shown in Figure 1a. Keithley 35050A electrometers (Keithley Instruments Inc., Cleveland, OH) were connected to the ionization chambers to allow simultaneous read-out of fetal and breast dose.

The scan length was set to cover the whole lung field (302 mm) and, each time the patient was re-registered or the phantom was repositioned, a scan projection radiograph (topogram) was used to verify positioning.

All lead aprons used as shielding were checked for any tears, cracks, other damage or movement of the lead before use and were positioned in a straight line on the phantom at the boundary of slices 24 and 25, which marked the position of the lower costal margin. Scan projection radiographs showing the phantom with and without lead can be seen in Figure 2.

Experiments were performed with and without lead in the same session, and rearrangement of the phantom was kept to a minimum. For all experiments, no parameter was varied from the standard protocol apart from that specified. For consistency, a check measurement of uterus and breast dose was made at the beginning of each session using a standard scanning protocol.

The lead was positioned with one apron beneath the phantom and one apron on top. The two bottom edges of the apron were lined up with each other and with the phantom.

The following experiments were designed from the results of the protocol audit to determine the effect on fetal dose of scan parameters and the use of lead.

Scan parameters

Standard

An experiment was performed with five repeats using standard parameters: 100 kV_p, 140 effective mAs,

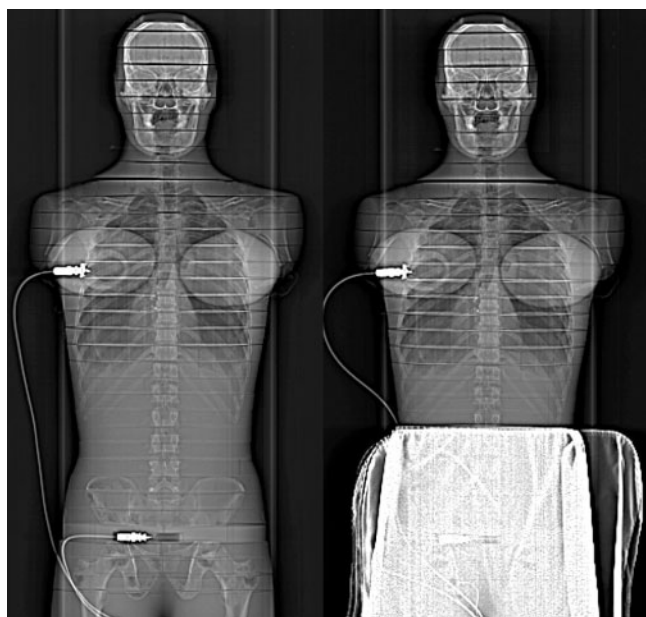


Figure 2. Scan projection radiographs showing the position of the ionization chambers and the lead shielding.

16 × 0.75 mm collimation giving 1 mm images, 0.5 s rotation, 10 mm feed per rotation (giving a pitch of 0.833) – this is the protocol that is used, as standard, on this CT scanner. All values of mAs used in this study are effective mAs values as displayed on the Siemens scanner. Effective mAs is defined as the tube mAs per rotation divided by helical pitch. Dose optimisation software was switched off. This experiment was designed to determine the reproducibility of the dose values obtained in the experiments.

kV_p

Measurements were made at beam energies of 80 kV_p, 100 kV_p, 120 kV_p and 140 kV_p.

mAs

The current time product was varied by progressively doubling the mAs setting from 25 mAs to 400 mAs with a constant rotation time of 0.5 s.

Rotation time

Rotation time was set to be 0.42 s, 0.5 s and 0.75 s as these were the steps available on the scanner.

Helical pitch

The doses were measured for helical pitches of 0.5, 1.0 and 1.5.

Collimation

The effect of doubling the beam collimation from 16 × 0.75 mm to 16 × 1.5 mm was observed.

Lead positioning and thickness

Coverage of patient

The effect of varying the amount of coverage of the phantom was investigated by performing one experiment with only the anterior of the phantom covered with the lead shielding.

Altering the volume covered by the lead

A series of measurements were made to investigate the effect of the position of the lead shielding relative to the scan volume. An initial measurement of fetal dose was made with no lead shielding on the phantom. Lead coats were then positioned above and below the phantom such that the superior edges of the shielding aligned with the superior edge of the uterus. The shielding was then moved towards the scan volume (cranially) in 2.5 cm steps, and a measurement of fetal dose was made at each position of the shielding.

Moving scan volume

The effect of moving the scan volume was measured in two separate experiments. First, the whole volume was moved closer to the uterus and, second, the end point of the scan was moved towards the uterus while the top edge stayed fixed. Both these sets of measurements were made in 2 cm steps with and without lead.

Lead thickness

The thickness of lead covering the phantom was varied from 0.25 to 1.0 mm lead equivalent in thicknesses that were readily achievable using lead aprons, and the doses were recorded as a function of thickness. This was performed at all four values of kV_p . The attenuation properties of the lead aprons were not assessed as part of this study.

The ion chamber that was used had a minimum detectable dose rate of $0.53 \mu\text{Gy s}^{-1}$ (Keithley Instruments Inc., Cleveland, OH; manufacturer's manual). For experiments in which a dose rate approaching this limit was expected, a correction factor was applied. This was determined from the experimental data obtained when changing only mAs where a linear response was expected.

Results

Local protocol information

Protocol information was gathered for five of the seven hospitals, and their responses regarding the use of lead shielding are shown in Table 1. The responses showed a large range in the exposure parameters that are used for CTPA examination; for example, kV_p values ranged from 100–140 kV_p , and mAs values varied from 90–210 mAs. Where possible, we used a range of values for each scan parameter that was greater than the range of values that was identified from the questionnaires. One hospital did not scan pregnant patients, and one hospital did not perform PE scans due to the fact that their available scanner was too slow for this application.

Scan parameters

Standard

The first experiment aimed to establish the reproducibility of the results obtained. The five repeats measuring the fetal dose without lead gave an average dose of $63.1 \mu\text{Gy}$ with a standard deviation of $0.36 \mu\text{Gy}$. The experiments with lead yielded an average fetal dose of $38.0 \mu\text{Gy}$ with a standard deviation of $0.39 \mu\text{Gy}$. These results represent an average dose reduction of 39.7%. The breast dose measured in these experiments showed a similarly small standard deviation. The standard deviations of the results were used to give an estimate of the error on all measurements, which is less than 1%. This formed a baseline for subsequent measurements to check the scanner during different experimental sessions.

kV_p

For the measurements made with increasing primary beam energy, it was found that the higher the value of kV_p , the higher the dose to both the fetus and the breast. The fetal dose was reduced by between 33% and 47% (Figure 3) through the use of a 0.7 mm lead apron for all energies; however, the magnitude of the dose reduction was energy dependent. A constant thickness of lead gave a smaller reduction at higher energies.

mAs

Fetal dose increases linearly with tube current. With the addition of lead, the absolute dose decreased, but the increase in dose due to an increase in the current was still linear. The dose reduction from the addition of the lead apron was constant for all values of current.

Rotation time

As rotation time was varied, no significant change in the fetal or breast dose was recorded, although the standard deviation of the results was larger than that found in other measurements.

Helical pitch

Fetal dose increased linearly with increasing helical pitch. When lead was added to the phantom, a reduction of between 41% and 45% was seen at all values of pitch (Figure 4). As the pitch increased, the percentage reduction in dose decreased.

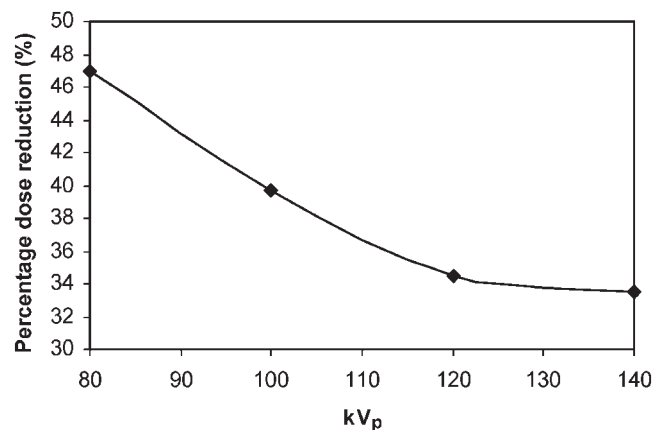


Figure 3. Percentage reduction in dose with 0.7 mm lead for varying kV_p . Each value has an error of 1%.

Table 1. Protocol for the use of lead during scanning of a pregnant patient presenting with symptoms of pulmonary embolism

Hospital	Use of lead
A	Not used
B	One lead apron placed beneath the patient and one above giving 0.7 mm on either side. Positioned from the lower costal margin down to cover the abdomen and pelvis
C	One lead apron placed around the patient giving 0.35 mm on either side. Positioned from the bottom of the ribs
D	One lead apron placed beneath the patient and one above giving 0.7 mm on either side. Positioned from the diaphragm down to the knees
E	One lead apron placed beneath the patient and one above giving 0.7 mm on either side

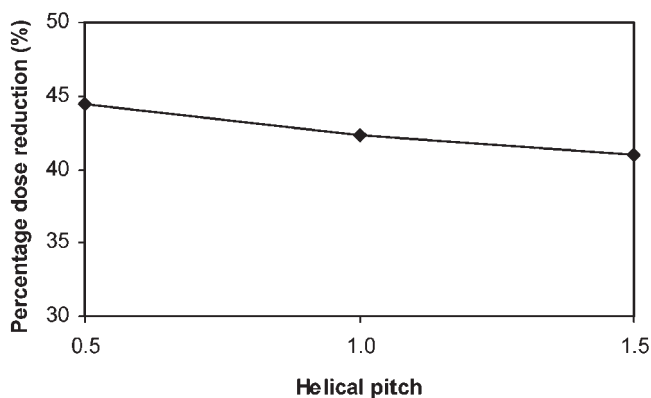


Figure 4. Percentage dose reduction with 0.7 mm lead as helical pitch is varied. Each value has an error of 1%.

Collimation

Doubling the collimation of the beam increased the dose to the uterus by $0.1 \mu\text{Gy} \pm 1\%$ without lead and by $1.9 \mu\text{Gy} \pm 1\%$ with the lead covering. The change of $0.1 \mu\text{Gy}$ for the unshielded measurements is within the experimental uncertainty.

Lead positioning and thickness

Coverage of patient

Covering only the anterior of the phantom gave 50% of the dose reduction that was found by covering all around the phantom with a given thickness of lead (*i.e.* a percentage dose reduction of $\sim 20\%$ with only the anterior of the phantom covered compared with $\sim 40\%$ with lead all around the phantom).

Altering the volume covered by lead

The variation in the dose to the fetus as lead aprons were moved progressively closer to the scan volume is shown in Figure 5, which shows that, when the shielding is moved towards the scan volume, a greater reduction in dose was seen. The fetal dose decreased linearly from $56.9 \mu\text{Gy} \pm 1\%$ with the superior edge of the shielding placed at the superior edge of the uterus to $25.9 \mu\text{Gy} \pm 1\%$ where the superior edge of the shielding was at the inferior edge of the scan volume (a linear fit to

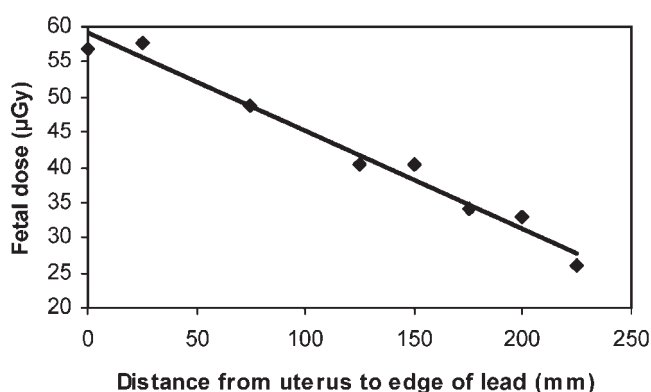


Figure 5. The variation in fetal dose as lead is moved along the body. Each value has an error of 1%.

the data is shown). The dose (in μGy) at any position of the shielding is given by $56.9 - 1.4 \times \text{distance to uterus (cm)}$ where 56.9 represents the dose when the superior edge of the shielding is aligned with the superior edge of the uterus (the measured dose was $63.3 \mu\text{Gy}$ when no shielding was present).

Moving scan volume

The fetal dose with no lead shielding increased exponentially as the end of the scan moved closer to the uterus. This is shown in Figure 6. With the addition of lead shielding, a greater reduction in fetal dose was seen as the scan moved further from the uterus. The edge of the lead apron was placed 150 mm from the uterus, so Figure 6 shows a region in which the lead was irradiated by the primary beam. Moving the whole scan volume closer to the position of the uterus gave an identical increase in fetal dose to moving only the bottom edge of the scan volume. However, the breast dose was reduced from $6.67 \text{ mGy} \pm 1\%$ to $5.22 \text{ mGy} \pm 1\%$ over the change in scan position.

Lead thickness

The variation in uterus dose with the thickness of lead at four different values of kV_p is shown in Figure 7. For the range of thicknesses shown, the uterus dose reduced as the thickness of lead covering increased.

Discussion

Local protocol information

The differences in protocol highlight the lack of standardization of the way in which pregnant patients are scanned for suspected/known PE. This could be as a result of the inconsistencies of the advice in current literature.

Experimental results

As expected, the fetal dose increased with beam energy and was reduced with the addition of lead at all energies. Using a lower value of kV_p would increase

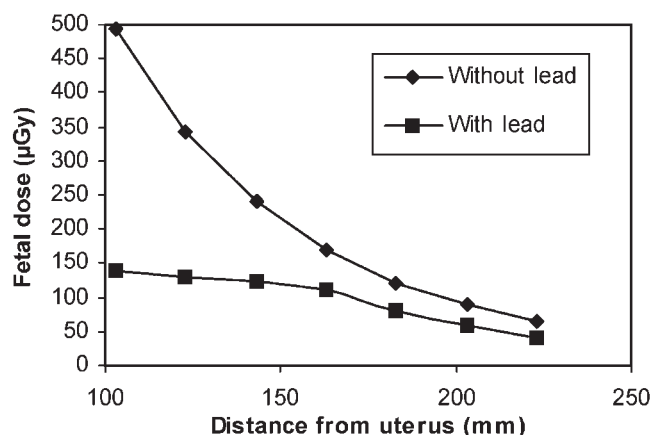


Figure 6. The variation in fetal dose with the distance of the scan edge from the uterus. Each value has an error of 1%.

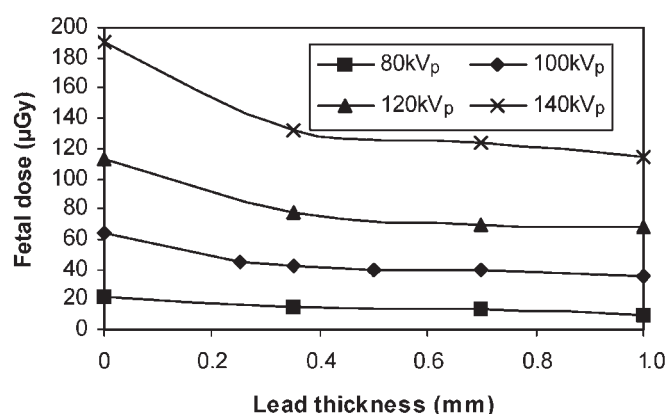


Figure 7. The variation in fetal dose with lead thickness for four different values of kV_p . Each value has an error of 1%. Extra data points are shown for 100 kV_p .

the contrast of the diagnostic images, but also increase patient dose.

The dose to the fetus increased linearly with tube current. With the addition of lead, the fetal dose (μGy) was reduced from $0.5 \times mAs$ to $0.3 \times mAs$ at 100 kV_p . Although using a lower value of tube current would decrease dose, it would also increase the noise in the images.

At low mAs settings, the measured dose deviated from the theoretically linear relationship between dose and mAs despite quality assurance tests on the scanner showing that the measured CT dose index values were linearly related to the mAs setting. This discrepancy was attributed to the measured dose rate approaching the minimum detectable dose rate of the chamber. As such, a correction factor was applied to the dose values at low mAs settings so that corrected dose values described a linear relationship with mAs settings. For all other experiments in which a dose rate approaching this limit was expected, the correction factor was applied to the measured dose values.

No significant changes were seen when the rotation time of the X-ray tube was varied as the value of mAs was kept constant. The small changes that were seen were attributed to mechanical tolerances.

The fetal dose was observed to increase as the helical pitch increased. The scanner that was used compensated for the pitch by changing the current to give a constant level of noise and hence a constant dose level (constant effective mAs). For the reconstruction of helical data, the scan was automatically lengthened as pitch was increased. This change in the distance of the nearest point of internal scattering to the uterus increased the dose by $15.5 \mu Gy \pm 1\%$. As such, the increase in the fetal dose with pitch setting for constant effective mAs setting is as expected for this type of scanner; this effect may not be seen on scanners that do not automatically adapt the mAs setting when the pitch is changed. Because only the externally scattered radiation is shielded by the addition of the lead apron, as the internal scatter increases, the component that can be reduced by shielding is proportionally less, and so the percentage dose reduction was seen to reduce from 44% to 41%. This indicates the importance of the distance between the end position of

the scan and the fetus in determining the dose received by the fetus.

A similar effect was seen when the collimation was increased. Widening the beam brings the closest point of internal scatter closer to the uterus, and this increased the radiation dose. A change in the dose of $1.9 \mu Gy \pm 1\%$ was seen and a change in the percentage dose reduction with the lead apron from 38% to 36%.

When only the anterior of the phantom was covered, the percentage dose reduction was half the value of that when the anterior and posterior of the phantom were covered due to the circular nature of the CT scan. The results indicate that, if a patient is unable to tolerate the weight of the lead placed on the lower abdomen, a significant dose reduction may still be achieved by placing lead underneath the patient and, if possible, using a lesser thickness of lead apron to cover over the abdomen.

Fetal dose varied linearly as the distance between the superior edge of the lead shielding and the superior edge of the uterus increased, as shown in Figure 5. The percentage reduction that was found varied linearly from zero, with no lead present, up to a maximum of 55%. At this point of maximum dose reduction, the lead apron covered the patient up to the edge of the scan volume. The internal scatter from the scan volume is not affected by the lead shielding and is therefore a constant percentage of the total fetal dose. The decrease in the fetal dose that was observed as the lead shielding was moved cranially is a result of the lead shielding blocking the externally scattered radiation that comes from the CT gantry and collimators. As the lead shielding is moved towards the scan volume, a higher percentage of this externally scattered radiation is blocked by the shielding, which therefore yields an increase in fetal dose reduction as the shielding is moved cranially. The results of these measurements show that there is an extra benefit to the patient of covering the greatest volume possible – up to but not covering the scan volume. However, comfort should also be taken into account, particularly if the patient has respiratory difficulties.

The increase in dose that was observed when the bottom of the scan volume or the whole scan volume was moved towards the uterus was exponential, as shown in Figure 6. With the addition of lead, an exponential relationship was still seen in the region where the scan volume did not cover the lead. The percentage reduction in dose is dependent on the distance of the scan volume from the uterus. As this distance increased, the percentage reduction possible increased from 34% to 38%. The implication of these results is that a reduction in fetal dose can be achieved by scanning only as far down the lung field as is necessary for the diagnosis of PE. There will also be an effect of gestational age as the fetus grows towards the scan volume, as shown in studies such as that by Winer-Muram et al [1]. This reinforces the need to minimize scanning of the lower lung field as far as possible. No significant difference was seen in the fetal dose between moving the bottom of the scan volume and moving the whole volume, but a reduction was seen in the dose to the breast due to a reduction in the primary beam irradiating this tissue. This implies that, beyond a certain distance from the point of measurement, the

contribution to the fetal dose from internally scattered radiation is negligible.

The variation in the dose to the fetus with thickness of lead at a number of values of beam energy is shown in Figure 7. The thicknesses used were conveniently available in the clinical setting by using lead aprons. As the thickness of lead increased, the dose to the uterus reduced. As can be seen from Figure 7, the dose reaches a point beyond which a further reduction is not seen. This is the point at which the component of the uterus dose that is due to the externally scattered radiation and which has an exponential dependence on thickness has been blocked. When the beam energy was increased, the fetal dose due to both internal scatter and externally scattered radiation was increased. The figures also show that the extra percentage dose reduction gained by adding a thickness of lead greater than 0.35 mm is small ($\sim 7\%$ at 100 kV_p) and that beyond 0.7 mm of lead, the additional dose reduction is negligible ($\sim 1\%$ at 100 kV_p). This implies that the optimum thickness of lead is 0.7 mm (*i.e.* a doubled-over 0.35 mm lead apron), although use of 0.35 mm of lead would still yield a significant reduction in fetal dose. We found no evidence of lead shielding increasing the fetal dose for thicknesses of lead up to 1 mm.

Clinical protocol

The results have indicated that optimal reduction of fetal dose can be achieved through the use of lead shielding and possibly through some modifications to the protocol used for acquiring the data needed to test for PE. An awareness of the effects of the parameters of the scan on fetal dose can be used to inform decisions about the use of individual scanners when considering pregnant patients.

It is possible to reduce the dose to the fetus by:

- Shielding the fetus using lead aprons. A thickness of lead greater than 0.7 mm is not recommended as this gives little benefit in terms of dose reduction, but increases patient discomfort.
- Positioning lead around the entire patient and covering up to the caudal edge of the scan volume.
- Shielding underneath the patient and using a lesser thickness of lead apron over the patient if a heavier apron cannot be tolerated. This still achieves a proportion of the maximum possible dose reduction.
- Minimizing scanning of the lower lung field to maximize the fetus-scan edge distance. This distance should be considered as the fetus grows and changes its position during pregnancy.
- Minimizing helical pitch. This changes the distance between the fetus and the edge of the scan volume, minimizing radiation dose.
- Reducing the kV_p or mAs; however, this should only be done bearing in mind the possible increase in dose to the patient, reduction in contrast or increase in noise.

The findings of this work are contrary to the results of Hidajat et al [16], who report that no dose reduction was achieved through lead shielding of the uterus. Hidajat et al

covered a smaller volume of the patient with the lead apron and performed a scan that was much closer to the uterus. Both these factors have been shown to increase the dose to the uterus and reduce the amount of dose reduction possible through the use of the lead shield. The experimental data collected were used to extrapolate to the position of the scan volume and lead used by Hidajat et al, and the resulting values agreed closely. A slightly greater reduction in dose was seen in the calculated values, but these were based on thicker lead and a lower kV_p, which account for the difference.

Conclusions

It was found that the fetal radiation dose from a CT scan following a PE protocol could be effectively reduced by the use of lead shielding. In considering a protocol for the examination of pregnant patients with known or suspected PE, the information contained within this text should offer guidance. Further work could consider the use of differently attenuating materials as shields, the effect of an increasing thickness of lead and the effect of gestational age.

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