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Fetal radiation dose from CT pulmonary angiography in late pregnancy: a phantom study

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ABSTRACT. Pulmonary embolism (PE) is the leading direct cause of maternal mortality in the UK. Accurate diagnosis is important but, even though CT pulmonary angiography (CTPA) is the recommended imaging modality for PE in the general population, there is limited guidance for pregnant patients. Knowledge of the radiation doses to both the mother and the fetus is therefore important in the justification of CTPA in this situation. Dose measurements were made on three helical CT scanners, with an anthropomorphic phantom representing the chest and abdomen in late gestation. Estimated fetal doses from CT scans of the maternal chest were in the range of 60–230 μGy. Fetal dose reduction strategies (mA modulation, shielding with a lead coat, and a 5 cm shorter scan length) were investigated. These reduced the fetal dose by 10%, 35% and 56%, respectively. Fetal doses from a scan projection radiograph (SPR) of the maternal chest were insignificant when compared with the dose from a CT scan. However, if the SPR was not stopped before the ''fetus'' was directly irradiated, the dose measured on one scanner was 20 μGy.

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Pulmonary embolism (PE) during pregnancy presents a significant risk to the mother, with pregnancy limiting the range of therapeutic options [1–3]. Additionally, a diagnosis of venous thromboembolism (VTE) may lead to the requirement for prophylaxis in future pregnancies [4]. An objective diagnosis of VTE is therefore particularly important in the pregnant population, and the Royal College of Obstetricians and Gynaecologists' (RCOG) guidelines state that *''Any woman with signs and symptoms suggestive of VTE should have objective testing performed expeditiously…Individual hospitals should have an agreed protocol for the objective diagnosis of suspected VTE during pregnancy''* [5].

The tools available for the diagnosis of VTE include clinical assessment, imaging of the lower limbs and lungs, and other non-imaging tests. Lung imaging modalities for non-massive PE include radionuclide perfusion scanning (with or without ventilation) and conventional pulmonary angiography. More recently, the development of helical CT scanners has facilitated the development of CT pulmonary angiography (CTPA).

British Thoracic Society guidelines on the diagnosis of (non-pregnant) patients with suspected VTE/PE recommend CTPA as the first-line lung imaging modality, but give limited information on the specific case of the pregnant patient [6]. The RCOG has recently recommended CTPA as an option for diagnosis of VTE during pregnancy [5]. These guidelines were based on a number of published estimates of dose to the fetus from CTPA.

Nijkeuter et al [7] applied published conversion factors to estimate the dose to the uterus and hence the fetus in early pregnancy. The equivalent dose to the fetus was in the range of 0.013–0.026 mSv. Cook and Kyriou [8] reported a comparable absorbed dose to the fetus of 0.01 mGy.

A UK survey of patient doses found that the mean and maximum fetal (uterine) absorbed doses were 0.06 mGy and 0.96 mGy, respectively [9]. These values are reported in the guidance ''Advice on Exposure to Ionising Radiation during Pregnancy'' [10]. Although this survey and guidance pre-date the widespread use of multidetector-row CT, the guidance is commonly used as a first-line estimate of fetal dose.

Estimates of fetal doses in later pregnancy are provided by Winer-Muram et al [11]. They determined maternal–fetal geometries in 23 healthy pregnant women of varying body mass index and gestation, and used these to produce simplified geometries for simulation. For six women in the third trimester, the mean dose in the volume representing the fetus was 0.051–0.131 mGy. These estimates were used in a recent article specifically addressing the question of the most appropriate imaging protocol for pregnant patients [12].

Most published estimates of fetal dose from CTPA rely on Monte Carlo simulation. However, Hurwitz et al [13] used measurements in an anthropomorphic phantom to determine fetal doses from a range of multidetector-row CT investigations in the early stages of pregnancy. They reported absorbed doses at the uterus for a PE investigation in the range of 0.24–0.66 mGy between conception and 3 months gestation.

This body of literature points to relatively low fetal doses from CTPA. However, there are no published measurements of the dose from CTPA in a phantom which are specific to later pregnancy, when the dose will be highest. The aim of this work is to measure the fetal dose in an anthropomorphic phantom representing late gestation.

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Methods and materials

The phantom used in this work was originally developed by Badr et al [14] for a study of X-ray pelvimetry, and a full description is given in that paper. It consisted of a water-filled plastic ''bump''-shaped shell (moulded from the shape of a pregnant woman of 39 weeks' gestation). This was placed on a female Alderson ''Rando'' phantom of the pelvis, augmented with three water-equivalent slabs containing discs of bone-equivalent material to represent the L1, L2 and L3 vertebrae. The water-filled bump contained a central circular channel into which was inserted a rod with cut-outs for thermoluminescent dosemeters (TLDs) at 2.5 cm intervals. The phantom was designed to allow reproducible placement of the TLD-containing rod; to this end, the water-filled ''bump'' fitted snugly to the Rando phantom, and the TLD rod was located against a stop at the end of the channel.

In order to use this phantom for CTPA, it was necessary to add a chest. This was achieved by using the chest part of a male Alderson Rando phantom. The extent of the phantom to be used was determined by the vertebrae. Water-filled balloons of 10 cm diameter were used to simulate breasts. The resulting phantom was positioned in a supine position, as illustrated in Figure 1. The distance between the scan volume and the TLDs was measured on the scan projection radiograph (SPR) views; this was verified by physical measurement.

Dose measurements were made with LiF:Cu,Mg,P TLD chips (Harshaw TLD100H, Thermo Scientific, Waltham, MA). These had previously been demonstrated to have a response that was independent of X-ray energy (within 5% over the range 50–120 kV_p) and linear with dose. All TLDs used were known to have variations in sensitivity of $<\pm 5\%$ compared with the batch mean.

Calibration and background measurements were made using groups of TLDs from the same batch. The TLDs were calibrated against an ionization chamber with a calibration traceable to national standards.

The minimum detectable dose for the TLDs used in each set of dose measurements was taken to be twice the standard deviation in the corresponding background readings. Each dose measurement was made using a single scan of the phantom, as it was determined that the doses thus measured lay above the minimum detectable dose and within the part of the dose response which had been demonstrated to be linear with dose.

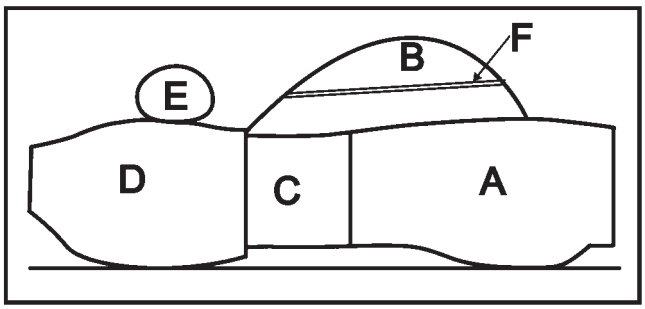

Figure 1. Illustration of the composite phantom used in this work. A, female pelvis ''Rando'' phantom; B, water phantom; C, additional water-equivalent slabs; D, male chest ''Rando'' phantom; E, water-filled balloons; F, rod-containing thermoluminescent dosemeters.

The phantom was scanned in a number of CT scanners. CT scans were planned on SPR views of the composite phantom. Unless stated otherwise, the imaged scan volume was from the apices to the bases of the lungs. The bottom of the scan volume corresponded to the bottom of the male (chest) phantom and to the top of the water phantom. The water-filled ''bump'' was therefore not included in the CT image volume.

The position of a typical fetus at term was determined from two publications, both of which used ultrasound to make measurements on healthy pregnant patients. Winer-Muram et al [11] measured the distance between the fundus of the uterus and the pubic symphysis (the ''fetal height'') and that between the fundus and the xiphoid process (approximating the bases of the lungs). For six patients in the third trimester, the mean xiphoid–fundus distance was 7 cm (range, 4–10 cm) and the mean fetal height was 33 cm (range, 27–37 cm).

Osei and Faulkener [15] measured the mean fetal depth, defined as the average of the mean fetal skull depth (*i.e.* the distance between the anterior surface of the maternal abdomen and the midline of the fetal skull, along a ray perpendicular to the maternal abdominal surface) and the mean fetal abdominal depth (similarly defined). For nine women in the latest stages of pregnancy (35–40+ weeks), the mean value was 10.2 cm (range, 9.9–10.6 cm). From these results, the assumption was made that the fetus lay at a mean depth of 10.2 cm from the anterior abdominal surface, at a distance of 7–40 cm from the bottom of the scan volume. The fetus was assumed to have uniform cross-section.

Initial measurements

In order to obtain dose measurements of the CT and SPR components separately, the TLDs needed to be inserted into the phantom after the SPR scan had been performed. However, any movement of the phantom whilst doing this would render the SPR less accurate for planning the CT scan. Reassembling the phantom in exactly the same position after placing TLDs in the Rando phantom proved difficult. It was, however, straightforward to remove the TLD rod and reinsert it in the same reproducible position without disturbing the rest of the phantom. It was therefore desirable to measure dose only in the TLD rod. However, the distance between the TLD rod and the maternal abdominal surface was a maximum of ~7 cm, *i.e.* it was slightly more anterior than the mean fetal depth of 10 cm.

Initial measurements of dose from CT were carried out using a Volume Zoom scanner (Siemens, Erlangen, Germany). TLDs placed into the TLD rod (*i.e.* in the water filled ''bump'') and also distributed throughout the Rando pelvis. These demonstrated that the variation in dose in the transaxial plane was relatively unimportant (R^2=0.98 for the correlation of –ln(dose) with cranio-caudal distance from scanned volume, with measured doses in the range 0.04–1.00 mGy). Given the difficulties in positioning TLDs anywhere in the phantom other than the rod, it was decided that measurements made using

this TLD rod would be used to estimate the dose to a fetus lying slightly more posteriorly.

It should be noted that the position in the transaxial plane is significant in the assessment of dose from the SPR.

CT scan

The phantom was scanned in three further CT scanners (Scanners A, B and C). The scan protocols used were the standard protocols for non-pregnant patients. At the hospitals concerned, CTPA is not undertaken on pregnant patients routinely, and so no pregnancy-specific standard protocols exist. However, the equipment users have reported that the same protocols are used on the rare occasion when a pregnant patient is scanned. Details of the CT scanners and standard protocols are shown in Table 1.

Dose reduction strategies

There are a number of measures available that potentially reduce the dose to the fetus. CT scans using modified protocols were carried out on Scanner A to investigate the effect of these measures on the fetal dose. The modifications to the standard 120 kV protocol were as follows:

1. The CT scanner's mA modulation capability was used. This reduces the tube mA for those projections where there is less attenuation, thus reducing the radiation dose.
2. Some protocols recommend the shielding of the abdomen [16]. A lead coat was draped over the ''bump'', up to the level of the bottom of the scan, as a readily achieved initial investigation. Although the ''fetus'' was not shielded posteriorly, the location of the fetus nearer to the anterior than the posterior surface suggests that anterior shielding is more important. The lead coat would shield the fetus from (i) radiation scattered from the breast tissue, (ii) extra-focal radiation and (iii) other multiply scattered radiation entering the abdomen anteriorly.
3. It has been suggested that emboli in the sub-segmental arteries may not contribute significantly to morbidity and mortality [17]. Protocols that ensure coverage of the segmental arteries, but not necessarily the whole lung, have therefore been proposed [18]. A scan was performed with a 5 cm shorter scan length, leaving the bases of the lungs unexamined and unexposed.

Scan projection radiograph

Limited measurements were made of doses from posteroanterior (PA) and anteroposterior (AP) SPRs. The protocols used for SPR views are given in Table 2. Measurements were carried out for SPR views covering the same length as the CT scans. A PA scan covering the whole length of the phantom was also carried out on Scanner C.

Results

CT scan

The dose distribution in the water phantom was found to decrease exponentially with distance along the z-axis from the scanned volume (Figure 2).

The dose, D, at a particular distance, z, from the scanned volume can therefore by described by the equation

$$D = D_0 \exp\{-\mu z\} \tag{1}$$

D_0 and the linear attenuation coefficient, μ, are derived from the equation of the line fitted to ln(dose) *vs* distance using a linear least squares regression. The mean dose to a fetus of constant cross-section sited between 7 cm and 40 cm from the scanned volume is then given by:

$$D = \frac{1}{(40-7)} \int_{7}^{40} D_0 \exp\{-\mu z\} dz \tag{2}$$

Table 1. Standard protocols used to scan the phantom

Scanner	Manufacturer and model	Maximum number of detector rows	Tube potential (kV)	mAs per rotation	Pitch	mAs per rotation/pitch[a]	Nominal beam collimation (mm)	Detectors used (mm)	Reconstructed slice width (mm)
A (120 kV protocol)	Siemens Sensation 16	16	120	125	1.25	100	9	12 × 0.75	5 and 1
A (100 kV protocol)	Siemens Sensation 16	16	100	150	1.25	120	9	12 × 0.75	5 and 1
B	Siemens Somatom Emotion	1	130	240	2	120	3	1 × 3	3
C	Marconi MX8000	4	120	250	1.25	200	10	4 × 2.5	3.2

[a]mAs per rotation/pitch is denoted ''effective mAs'' or ''mAs per slice'' by different manufacturers.

Table 2. Protocols for the SPR views

Scanner	Projection	Tube potential (kV)	mA	Collimation (mm)	Table travel speed (mm s^{-1})
A	AP	120	50	1	98
B	PA	120	30	3	87
C	PA	120	30	1	95

Table 3. Mean fetal absorbed dose (to the nearest 10 μGy) estimated for each of the standard protocols

Scanner	Protocol	Mean fetal absorbed dose (μGy)
A	120 kV	100
A	100 kV	60
B	130 kV	90
C	120 kV	230

Table 4. Percentage reductions in mean fetal absorbed dose using modified protocols on Scanner A

Modified protocol	% dose reduction
mA modulation	10
Lead coat	35
Short scan	55

The mean fetal doses thus calculated for the standard protocols are shown in Table 3.

Dose reduction strategies

The dose reductions afforded to the fetus by the three modified protocols investigated are shown in Table 4. It can be seen that the greatest dose reduction is given by not scanning the lower portion of the lung.

Scan projection radiograph

The doses measured for SPR views are shown in Figure 3. On Scanner B, doses to the midline of the water phantom were measured for both AP and PA scans. The dose from the AP scan was considerably higher than for the PA scan, especially for locations close to the scan volume. The values tended to converge with increased distance from the scan volume (possibly because scatter made the dose distribution more homogeneous in the transaxial plane). Although the position of a typical fetus extends more posteriorly than the TLD rod, the fetal dose from a PA SPR will be less than for an AP SPR for a typical fetus, whose mean depth is more anterior than the maternal midline. Additional shielding would be afforded by the maternal spine.

The absorbed dose at the midline of the water phantom for a PA SPR covering the ''fetus'' on Scanner C was approximately 20 μGy. Again, because of the position of the TLD rod, this is likely to be an underestimate for a PA SPR. Conversely, it can reasonably be assumed that the dose from an AP exposure would be higher.

Discussion

For a fetus assumed to be of uniform cross-section and extending from 7 cm to 40 cm from the scanned volume, the estimated mean fetal dose from a CTPA lung scan was 0.06–0.23 mGy. This is well below the 100 mGy threshold reported to be relevant for deterministic effects, and represents an excess risk of cancer death in childhood of ~1 in 100 000 [19]. In terms of fetal mean absorbed dose, we have considered the worst-case scenario. This is the case of a nearly full-term pregnancy as the fetus grows towards the lungs (*i.e.* the scanned volume) and before it engages and descends into the pelvis before birth.

The fetal doses have been measured for the standard protocols currently in use on each scanner. Each protocol produces images of acceptable diagnostic quality; however, there is a two-fold difference in the measured doses. Much of the difference in dose is attributable to the significant differences in mAs seen between scanners. Although some of the other variations in scan protocol are due to the differing capabilities of the scanners (*e.g.* the number of detector channels available), the relation-

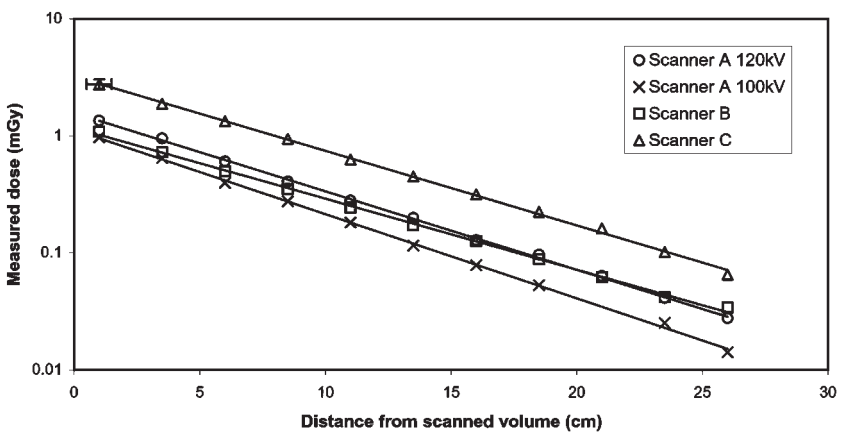

Figure 2. Variation in measured dose with distance from the scanned volume. Data are shown for the standard protocols for each scanner. Representative error bars are shown for one point. Distance error bars represent the uncertainty in positioning the thermoluminescent dosemeters within the phantom and planning the CT scan from the SPR ($\pm$0.5 cm). Dose error bars are $\pm$2 standard deviations from the calibration readings ($\pm$10%).

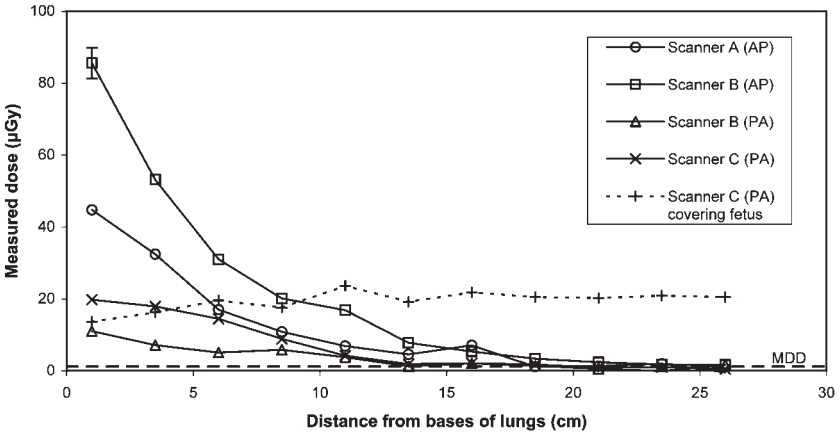

Figure 3. Variation in measured dose with distance from the bases of the lungs for SPR views. This is equivalent to the distance from the inferior edge of the scanned length, except for the SPR covering the fetus, which extended past the phantom. MDD, minimum detectable dose (given by two standard deviations for the background measurements).

ship between exposure parameters and image quality will depend on the required slice width and the reconstruction algorithm used. This suggests that there is likely to be scope for dose optimization. Such a process would require a comparison of objective image quality associated with each scan protocol and consideration by clinicians of the acceptable level of image quality for diagnosis. This was not attempted in this study.

Winer-Muram et al [11] calculated doses of 0.05–0.13 mGy using Monte Carlo methodology for third trimester pregnancies. The simulated scan protocol in that study was similar to our 120 kV_p standard protocols, but used a lower mAs per rotation (100 mAs *c.f.* 125–250 mAs) and a lower pitch (1 *c.f.* 1.25). Nevertheless, the values measured here are comparable. Hurwitz et al [13] reported measured doses in the range of 0.24–0.66 mGy in the first trimester. It would be expected that the dose would be lower earlier in pregnancy, when the fetus is smaller and further from the scanned volume. However, the upper limit of this range is above our estimate. This may result from differences in the scan protocols (*e.g.* Hurwitz et al used 140 kV_p and 304 mAs per rotation).

CTPA and ventilation/perfusion (V/Q) lung scanning using ^{81m}Kr gas and ^{99m}Tc macro aggregates of albumin (MAA) are often viewed as alternative imaging modalities. The Administration of Radioactive Substances Advisory Committee (ARSAC) guidance gives an estimated dose to the uterus of <0.001 mGy from ^{81m}Kr gas, and 0.3 mGy from ^{99m}Tc MAA [20]. This can be used as an estimate of fetal dose in early pregnancy. However, there are no estimates available for late pregnancy. In clinical practice, the fetal dose may be decreased by reducing the administered activity and encouraging the mother to void frequently. Therefore, although there are large uncertainties in the estimation of fetal dose in late pregnancy from V/Q, it appears that the doses are comparable to those from CTPA.

Measured fetal dose for a PA SPR covering the abdomen was 20 μGy, although this is likely to be an underestimate owing to the position of measurement. However, our measurements indicate that dose from AP SPRs may be higher than for PA SPRs, even where the fetus is not in the direct beam. Consequently, it is important to use a PA SPR where possible and to ensure the abdomen is not directly irradiated.

In addition to the dose to the fetus, the dose to the mother must be considered in the justification of CTPA in pregnancy. Recent publications have also highlighted the dose to the breast from CTPA [8, 21]. If CTPA is justified, considerable dose savings to the fetus may be achieved by the use of simple measures such as shielding the maternal abdomen; however, further investigation into the optimum form of shielding is warranted.

Conclusions

The fetal dose from CTPA is an order of magnitude less than the UK average annual background radiation, and similar to that from a V/Q scan. Fetal radiation dose alone is therefore unlikely to preclude CTPA in the pregnant patient. Other factors such as the availability and diagnostic utility of CTPA and other scans, the safety of contrast media and the dose to the mother (particularly to the breast tissue) are likely to be more important in the decision-making process.

If, and when, the use of CTPA is justified, the scan must be optimized so that the required information is collected with the lowest practicable dose to mother and fetus. To this end, the effects of various dose reduction strategies have been investigated. The SPR scan should utilize a PA projection where this is possible, and be stopped before the fetus is directly irradiated. The CT scan should cover the smallest possible volume, taking into account the clinical utility of information from the smaller arteries. A further significant reduction in fetal dose may be afforded by shielding the maternal abdomen.

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