Internal Barium Shielding to Minimize Fetal Irradiation in Spiral Chest CT: A Phantom Simulation Experiment

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Purpose:
To use a phantom to prospectively examine the attenuating effect of barium sulfate as an internal shield to protect the fetus.

Materials and Methods:
In an adult-size phantom, 1- and 2-cm-thick acrylic slabs containing 315 or 630 mL of water, 2% or 40% barium sulfate suspension, and a 1-mm lead sheet were placed under the diaphragm. In 17 experiments, fetal dose was measured by using thermoluminescent dosimeters that were placed immediately under (near field) and 10 cm below (far field) the water slab (eight experiments), barium sulfate slab (eight experiments), and lead sheet (one experiment). In a pulmonary embolism protocol, the phantom was scanned with single-detector spiral computed tomography (CT) at 130 kVp and 230 mAs.

Results:
The control radiation dose was 3.60 mSv ± 0.54 (standard deviation) with the water slab at near field, where the uterus dome is at near term, and 0.507 mSv ± 0.07 with the water slab at far field, the uterus position during early gestation. Scattered radiation was attenuated 13% and 21% with 2% barium sulfate and 87% and 96% with 40% barium sulfate, as calculated in the near and far fields, respectively, and 99% with the 1-mm lead sheet. The extrapolated attenuations for 5%-40% barium sulfate suspensions indicated that beyond a 30% suspension, attenuation increased further only slightly.

Conclusion:
Study results in the phantom experiment suggest that fetal irradiation during maternal chest CT can be reduced substantially with barium shielding.

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Deep venous thrombosis occurs in 0.5–3.0 of every 1000 pregnancies in the United States (1,2), accounting for 10% of all hospital deaths of pregnant women and being a contributing factor in another 10% of such deaths (3). Fifty percent of all cases of pulmonary embolism (PE) in the general U.S. population are not diagnosed antemortem (4). During pregnancy, there is a five- to six-fold increased risk of PE (5,6), which continues to be the leading nonobstetric cause of death during pregnancy or the peripartum period (6–9) (Table 1). PE risk factors include increased lower-extremity venous stasis and relative hypercoagulability of the blood during the hyperestrogenic state (6,7). Although deep venous thrombosis is thought to occur mainly during the third trimester of pregnancy and immediately postpartum, others have observed an almost equal prevalence of the disease during all trimesters (10).

The challenge of diagnosing PE during pregnancy is in balancing the need for examinations that involve the use of ionizing radiation with both the potential risk to the fetus (11–16) and the likelihood of childhood cancer caused by pediatric computed tomography (CT), which have been publicized even further during the past 5 years (17–19).

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These concerns are the basis of ongoing debates among experts (20–25).

Currently, the following six examinations are available for diagnosing acute PE:

1. D-dimer assay has 97% sensitivity and a 99.6% negative predictive value (26). False-positive results may be caused by pneumonia, myocardial infarct, cancer, sepsis, pregnancy, and/or recent surgery (27).

2. Lower-extremity ultrasonography (US) for assessment of deep venous thrombosis may indicate a risk of PE and justify the use of anticoagulant treatment (26). The sensitivity and specificity of chest wall US in the detection of PE are 94% and 87%, respectively (28,29).

3. Contrast material–enhanced magnetic resonance angiography is not yet practical to perform because it lacks adequate spatial resolution and does not yield detailed information about the lung parenchyma (27).

4. Nuclear medicine examinations for the overall assessment of PE are now used less frequently (30,31) because their results are indeterminate in up to 73% of cases (32). Nonetheless, some still advocate performing perfusion scanning during pregnancy. Performing single photon emission CT lowers the indeterminate result rate (33).

5. Pulmonary angiography is recommended more often than it is performed (34,35). It is invasive and associated with occasional morbidity and mortality (36–38) and with interobserver agreement levels of 45%–66% (34,39). Therefore, pulmonary angiography is no longer the reference standard imaging tool for the detection of PE (39).

6. Spiral CT angiography, enabling direct visualization of the thrombus (40,41), is now preferred for diagnosing PE (27). Furthermore, up to two-thirds of patients suspected of having PE have disorders that simulate PE, including aortic dissection, pneumonia, lung cancer, and pneumothorax (42). The reported interobserver agreement with CT is 0.72, versus 0.22 with nuclear medicine examinations (32,43), and a diagnostic algorithm for PE that includes CT is more cost effective than other diagnostic schemes (44). Last, CT can correctly depict PE even in the presence of coexisting pneumonia or preexisting lung disease (45).

Unlike single-detector CT, which may not depict emboli in small peripheral vessels (46–49), multidetector CT can depict emboli in vessels down to the sixth-order branches (50), with interobserver agreement exceeding that achieved with selective pulmonary angiography (39,51,52).

The fetal radiation dose with single-detector CT has been estimated in various ways and during different trimesters; doses of 0.0033–0.8621 mSv derived by using low exposure factors (including 100 mAs) in one study (53), of 2 mSv in a second study (54), and of 1.2 mSv in a third involving the use of a phantom model (55) have been reported. Fetal radiation doses also vary according to the trimester during which the experiments are performed. If up to four-section multidetector CT is performed, the dose may increase by 30% (49,56) to 100% (57), and the dose to the uterus will increase by 92%–180% (58). Hence, use of multidetector CT technology may lead to a trade-off of radiation safety for improved diagnostic accuracy (59–61).

Since to the best of our knowledge, no internal protective shield had been designed before, the purpose of our study was to use a phantom to prospectively examine the attenuating effect of barium sulfate as an internal shield to protect the fetus.

### Materials and Methods

#### Phantom

An anthropomorphic phantom (Rando; Alderson Research Laboratories, Stan-

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**Table 1**

<table>
<thead>
<tr>
<th>Causes of Pregnancy-related Deaths in the United States</th>
<th>Percentage of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemorrhage</td>
<td>28.8</td>
</tr>
<tr>
<td>PE</td>
<td>19.9</td>
</tr>
<tr>
<td>Pregnancy-induced hypertension</td>
<td>17.6</td>
</tr>
<tr>
<td>Infection</td>
<td>13.1</td>
</tr>
<tr>
<td>Cardiomyopathy</td>
<td>5.7</td>
</tr>
<tr>
<td>Anesthesia complications</td>
<td>2.5</td>
</tr>
<tr>
<td>Other or unknown causes</td>
<td>12.8</td>
</tr>
</tbody>
</table>

Sources.—References 6–9, 1977 data.

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*Abbreviations:*

- **A**₀/ₐ — attenuation measurement of barium sulfate relative to water
- **PE** — pulmonary embolism
- **TLD** — thermoluminescent dosimeter

*Authors stated no financial relationship to disclose.*
ford, Calif) composed of 2.5-cm-thick tissue-equivalent contoured slabs was chosen as an in vitro model. The phantom had anteroposterior and side-to-side dimensions of 27.5 and 20.5 cm, respectively, and a circumference of 81.0 cm. Two Harshaw lithium fluoride thermoluminescent dosimeters (TLDs) (Landauer, Glenwood, Ill) weighing 0.04 and 0.23 g/cm² were chosen because (a) they could be easily positioned at various locations within the phantom; (b) a minimum radiation dose of 0.10 mGy could be measured according to the variability of the signal from nonirradiated detectors despite background noise; (c) the measurement precision was higher than 1.5% throughout the study; and (d) the energy response of these TLDs was known, having been previously investigated at various beam qualities. This last characteristic was particularly important because the energy spectrum of the scattered radiation is not well known. The TLDs were calibrated in a 6-MV phantom beam with a calibrated ionization chamber. A correction factor of 1.6 was applied to the 6-MV TLD calibrations to account for the energy response of the detector in the CT beam.

Experiments Performed
A total of 17 experiments were performed. Eight experiments were performed with 1- and 2-cm-thick slabs containing water (control), and eight others were conducted with slabs containing the 2% or 40% barium sulfate suspension in the near and far fields. For each experiment, a new set of TLDs was used. Experiment 17 was performed with the 1-mm-thick lead sheet placed between the thorax and the TLDs as the reference shield. A single-detector spiral CT unit (Philips Medical Systems, Cleveland, Ohio), the only system available in our laboratory at the time of these experiments, was used. The following exposure factors were used: 130 kVp, 230 mAs, 3-mm section thickness, a 1.7 pitch, and 30-cm collimation from the lung apices (T1 level) to the lung bases (T12 level). These factors remained constant throughout the 17 experiments. In none of the experiments was a scout CT image acquired.

Figure 1: Section of phantom shows location of 15 TLDs (identified by letters A–O) placed distal to the acrylic slab filled with either water or barium sulfate.

Figure 2: Anterior view of the phantom shows the 1-mm lead sheet held to the phantom by white adhesive tape and the hollow acrylic (Lucite) slab (arrow).
Attenuation measurements were performed at CT with 0.5- and 1.0-mm lead foils to obtain information about the energy of the scattered radiation, which was needed for TLD calibration and to derive an effective broad-beam attenuation coefficient.

An uncertainty analysis was performed because, when converting the measured TLD signal intensity to a radiation dose, four factors must be taken into account: the calibration of the TLDs at 6 MV, the individual sensitivities of the TLDs, the TLD energy exposure, and the background tissue signal intensity. This is consistent with finding that there was no difference in the dose measurements obtained between the two different-thickness detectors in this study.

### Results

The control radiation doses measured in eight different experiments with water slabs ranged from 3.06 to 4.14 mSv (mean, 3.60 mSv ± 0.54 [standard deviation]) in the near field and from 0.437 to 0.577 mSv (mean, 0.507 mSv ± 0.07) in the far field. Table 2 summarizes the attenuation measurements of barium versus water considering four variables: (a) the slab thickness containing water versus barium; (b) the barium solution concentration, 2% versus 40%; (c) the TLD slab placement at Z = 0 versus 10 cm from the water or barium slab (where Z is the distance from the fluid-filled slab to the TLD containing the Rando slab); and (d) the thickness, therefore, the weight of the TLDs, 0.04 g/cm² versus 0.23 g/cm². The section thickness was 3 mm on all occasions. These data are provided to give some perspective on the magnitude of scattered radiation that can be attenuated by barium sulfate. The $A_{\text{eff}}$ is equal to 1 minus the ratio of the radiation dose measured with barium sulfate ($D_b$) to the dose measured with an equivalent thickness—therefore, volume—of water ($D_w$) replacing the barium sulfate:

$$A_{\text{eff}} = 1 - \frac{D_b}{D_w}. \quad (1)$$

The results show that the different-thickness detectors yielded the similar results within the range of estimated experimental uncertainties, and the percentages of attenuation were similar at $Z = 0$ and $Z = 10$ cm. With the 0.04 g/cm² TLDs, the attenuation values measured for the 1- and 2-cm 2% barium sulfate slabs were 13% and 17% in the near and far fields, respectively. Corresponding values for the 0.023 g/cm² TLDs were 11% and 13%. With the 40% barium sulfate concentration—depending on the slab thickness, field, and TLD weight—the attenuation ranged between 86% and 98%. Assuming that the scattered radiation was attenuated by the barium sulfate as an exponential function of the barium sulfate concentration yielded the following relationship:

$$\frac{D_b}{D_w} = \exp(-\mu_{\text{eff}} \cdot B \cdot t). \quad (2)$$

where $\mu_{\text{eff}}$ is an effective linear attenuation coefficient, $B$ is the concentration of barium sulfate, and $t$ is the thickness of the barium sulfate layer. Using data from the attenuation values measured with the 2% and 40% barium sulfate concentrations, we obtained an effective linear attenuation coefficient of 5.9 cm⁻¹. Incorporating Equation (2) into Equation (1) yielded the following equation:

$$A_{\text{eff}} = 1 - \exp(-\mu_{\text{eff}} \cdot B \cdot t). \quad (3)$$

With this equation, the $A_{\text{eff}}$ rendered by the barium sulfate suspension in different concentrations and different slab thicknesses may be estimated. $A_{\text{eff}}$ values for barium sulfate concentrations of 5%–40%, in 5% increments, are listed in Table 3. As an example, with a 20% concentration, we calculated attenuations of 69% and 91%, respectively, for the 1- and 2-cm-thick barium sulfate slabs in the near and far fields. Derived by using the attenuation data for 2% barium sulfate, the composite exponential attenuation profiles for 1- and 2-cm-thick slabs containing concentrations of 2%–40% in the near and far fields are shown in Figure 3. The 1-mm lead sheet placed between the thorax and the abdomen attenuated 99% of the scattered photons. From the experiment involving the use of 0.5- and 1.0-mm lead foils, we established an effective energy of 60 keV for the scattered radiation.

In our analysis of the attenuation rendered by barium sulfate, we eliminated some of the uncertainties because we evaluated the ratio of the TLD signal intensities. However, four factors were involved in converting the measured TLD signal intensity to a dose measure-

### Table 2

| Summary of Attenuation Measurements of Barium Sulfate Relative to Water $A_{\text{eff}}$ in the Rando Phantom for 0.3-cm Helical CT at 130 kVp and 230 mA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.04 g/cm² TLD | | | 0.23 g/cm² TLD | | | | | | | |
| | 2% Solution | 40% Solution | 2% Solution | 40% Solution | 2% Solution | 40% Solution | 2% Solution | 40% Solution |
| Z Position* | 1 cm | 2 cm | 1 cm | 2 cm | 1 cm | 2 cm | 1 cm | 2 cm |
| 0 cm | 13 | 20 | 90 | 97 | 11 | 19 | 89 | 98 |
| 10 cm | 17 | 24 | 86 | 94 | 13 | 20 | 83 | 92 |

Note.—Attenuation measurement of barium sulfate relative to water ($A_{\text{eff}} = 1 - \frac{D_b}{D_w}$).

* Distance from the fluid-filled slab to the TLD containing the Rando slab.

### Table 3

| $A_{\text{eff}}$ Measurements with Various Concentrations of Barium Sulfate |
|---|---|---|
| Barium Sulfate Concentration (%) | 1-cm Slab* | 2-cm Slab* |
| 5 | 26 | 45 |
| 10 | 45 | 69 |
| 15 | 59 | 83 |
| 20 | 69 | 91 |
| 25 | 77 | 95 |
| 30 | 83 | 97 |
| 35 | 87 | 98 |
| 40 | 91 | 99 |

* Data are $A_{\text{eff}}$ values cited as percentages.
ment: the calibration at 6 MV, the individual sensitivity of the TLD, the TLD energy response, and the signal intensity of the background tissue. For each factor, 1 standard deviation of uncertainty, \( \sigma \), was calculated: \( \sigma \) values for calibration at 6 MV, individual TLD sensitivity, TLD energy response, and background signal intensity at \( Z = 0 \) cm and \( Z = 10 \) cm were \( \pm 2.0\% \), \( \pm 1.5\% \), \( \pm 7.0\% \), \( \pm 1.0\% \), and \( \pm 10.0\% \), respectively. Considering the individual uncertainties in quadrature, the estimated uncertainties in the attenuation measurements at 1 standard deviation, or at the 68\% confidence level, were \( \pm 8\% \) and \( \pm 13\% \) at \( Z = 0 \) cm and \( Z = 10 \) cm, respectively.

**Discussion**

Twenty-one percent to 39\% of all PEs cannot be detected in subsegmental arteries with single-detector CT, two-detector CT, or even electron-beam CT (46,49). Therefore, multidetector CT is now the scanning method of choice—but at the expense of a 30\% (49,56) to 100\% (57) higher fetal radiation dose and a 98\%–180\% higher organ dose (58). Because motion artifact, technical factors, and poor opacification may cause 5\%–10\% of CT scans to be nondiagnostic (53), patients may need to undergo either repeat CT or additional examinations such as lung scintigraphy or pulmonary angiography. In fact, the results of a multiinstitutional study indicate that although multidetector CT is the preferred imaging tool, multimodality imaging is still being used frequently (62). The frequent use of multimodality imaging will further increase fetal radiation doses and provoke anxiety in patients, their families, and their physicians. The radiation data given here may not apply to the newest and more efficient multidetector CT technologies (63), which are not available in all centers nation-wide or worldwide.

The perceptions of physicians regarding the teratogenic risks associated with radiography and CT during pregnancy are not realistic (64)—even at academic medical centers in the United States (65). These unrealistic perceptions may lead to the underutilization of new tests and jeopardize the health of mothers and fetuses. On the other hand, some physicians consider the reluctance of some radiologists to use multidetector CT in the work-up of pregnant patients to be an infringement of their right to examine and treat their patients (17). In addition, the estimated potential risk of childhood cancer due to fetal irradiation is not well known. It varies between one case per 1000 radiologic examinations in utero over the first 4 months of pregnancy (66), to 0.03\%–0.05\% per examination (67), to one additional cancer death per 1700 pregnancies, and one case per 10 000 radiologic examinations (20). Some suffice to say that “the risk for cancer is not zero at doses of the order of 10 mSv” (14).

In our experiments with water slabs, the control radiation doses were 3.06–4.14 mSv in the near field, the presumed position of the dome of the uterus in the third trimester, and 0.437–0.577 mSv in the far field, simulating the dose in the first trimester. The difference between our projected fetal doses and those reported by Winer-Muram et al (53) and Damilakis et al (55) can be explained in part by the exposure factors that we used, 130 kVp and 230 mAs (vs 120 kVp and 100 mAs), and our imaging of the entire thorax without excluding the lung apices and bases so that simulating disorders could be searched for. Our choice of field size was compatible with those used in daily practice. Other factors may have been differences (a) between the phantom sizes that were available to us and those that were available to the other investigators, (b) in the range of TLD sensitivities, and (c) in the calculation methods used (Monte Carlo technique used by Winer-Muram et al [53] versus our phantom method) and the uncertainties inherent of any analysis similar to ours.

The radiation dose with up to four-section multidetector CT would increase by 30\%–100\% (49,56,57), so our adjusted near-field radiation dose with use of this version of multidetector CT would be 4.68–8.28 mSv. These doses, without any additional radiation from scout imaging or other imaging examinations involving ionizing radiation, are almost equal to or higher than the 5-mSv limit set by the International Commission on Radiological Protection for the total 9-month occupational dose allowed for pregnant workers and are 10–16 times higher than the monthly radiation dose allowed for radiology personnel (62). The targeted gonadal...
dose in the third trimester, when the head is engaged in the pelvis and the gonads—specifically the testes—are in the near field, is markedly higher.

Our in vitro experiment results show that the protective effects of 40% barium sulfate measured with TLDs of two thicknesses were 90%–98% in the near field and 86%–94% in the far field. However, a 40% barium sulfate suspension need not be used in every patient. The extrapolated data that we have provided offer the pregnant patient several choices of barium volume and concentration. Both 630 mL of the 20% barium sulfate suspension and 315 mL of the 40% suspension will yield 91% attenuation. Even a 5%–10% barium sulfate concentration can reduce fetal radiation exposure by 45%–69%. At a 30% concentration, the attenuation curves will plateau, irrespective of the barium volume or TLD positions in the near or far field. Beyond a 30% concentration, further reductions in radiation will be only slight. Therefore, the effectiveness of a 30% or higher barium sulfate suspension is similar to the attenuating effect of a 1-mm-thick lead sheet. It is noteworthy that the attenuating effects of the 40% barium sulfate suspension during the actual experiment with the 1- and 2-cm-thick slabs were almost identical to those measured by using the extrapolation method (90%–98% vs 91%–99%). These results give credence to the extrapolation technique and to the projected data that we obtained.

In the far field (Z = 10 cm), the presumed position of the uterus during the first trimester, the radiation dose was 0.437–0.577 mSv. As low as this dose may seem, it is delivered during the critical phase of organogenesis when the fetus is most sensitive to radiation. The barium shield can attenuate the radiation dose to the fetus by 83%–94% during this critical period.

Although efforts to reduce the radiation dose by simply lowering the exposure factors had promising results initially (68–70), more recent study data contradict the earlier results (71). Furthermore, none of these studies included patients with PE in the study populations (68–71).

In terms of limitations, the specific dose reduction is a complex product that is affected by the maternal body habitus, fetal gestational age, position and orientation of the fetus, quantity and concentration of the barium sulfate suspension, and distribution of the suspension through the gastrointestinal tract. Furthermore, patients who are critically ill or may need to undergo a cesarean section may not be appropriate candidates for oral barium use. Last, a slab of barium sulfate in vitro is not precisely comparable to the anatomy of the gastrointestinal tract in vivo. In vivo protocols are currently being designed to address these differences.

In conclusion, the results of our phantom study show that a 30%–40% barium sulfate shield attenuates scattered photons almost as effectively as a 1-mm lead shield. The described radiation attenuation method is not rigid and gives the patient and the radiologist latitude in the choice of volume and concentration of barium without substantially altering the attenuation effect. With a concentration higher than 30%, any further decreases in radiation dose will be only slight. We believe this method is practical and can safeguard the health of the fetus, in accordance with the as low as reasonably possible philosophy. This method can potentially also be used for other imaging examinations that involve the use of ionizing radiation.

**Practical applications:** The use of oral barium sulfate is safe, effective, and intuitively logical, and it can potentially prevent one to 10 lifetime malignancies per 10000 pregnant patients who undergo chest CT examinations. The use of oral barium sulfate can alleviate the apprehension of acutely ill pregnant patients, their families, and their physicians—at practically no cost. After future in vivo application proves to be practical, the use of this method can be expanded to include pregnant patients who undergo lung scanning with use of nuclear medicine tracers, children who need to undergo repeated chest CT examinations for metastatic surveys, employees at workplaces with radiation hazards, and patients who need to undergo cardiac catheterization and interventional cardiothoracic procedures.

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