Reduction of Radiation Dose to the Female Breast: Preliminary Data with a Custom-Designed Tungsten-Antimony Composite Breast Shield

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ABSTRACT

Objective: This purpose of this study was to estimate the radiation dose to the female breast incurred during chest computed tomography (CT) and to determine if that dose can be reduced by the external application of a custom-designed tungsten-antimony breast shield.

Materials and Methods: A 6.0-cm thick breast tissue equivalent slab phantom (53% adipose/47% water) was placed on the chest wall of an anthropomorphic head and torso phantom. Thermoluminescent dosimeters (TLDs) were positioned on the breast phantom surface at the 12 o'clock, 3 o'clock, and 6 o'clock positions; at the nipple level equivalent; and underneath the breast phantom on the chest wall. The phantom combination was scanned four times on a 16-head multi-detector CT, with identical TLD positioning, and imaging parameters simulating our pulmonary embolus protocol. The first and third scans employed no breast shielding. The second scan used a commercially available bismuth breast shield. The fourth scan utilized our custom-designed tungsten-antimony composite (0.25 lead equivalent) breast shield. An automated TLD reader read the exposed TLDs.

Results: The unshielded breast phantom radiation dose ranged from 84.8 to 122.9 mGy. The bismuth shield reduced the dose 37% at the 12 o'clock position, 56% at 3 o'clock, 30% at 6 o'clock, 42% at the nipple level, and 28% at the chest wall. Our tungsten-antimony composite breast shield reduced the unshielded dose by 55% at the 12 o'clock position,

73% at the 3 o'clock position, 57% at the 6 o'clock position, 43% at the nipple level, and 55% at the chest wall.

Conclusions: The unshielded breast tissue equivalent phantom incurred a dose of 84.8-122.9 mGy. Our custom-designed Tungsten-Antimony composite breast shield reduced this dose between 43% and 73%.

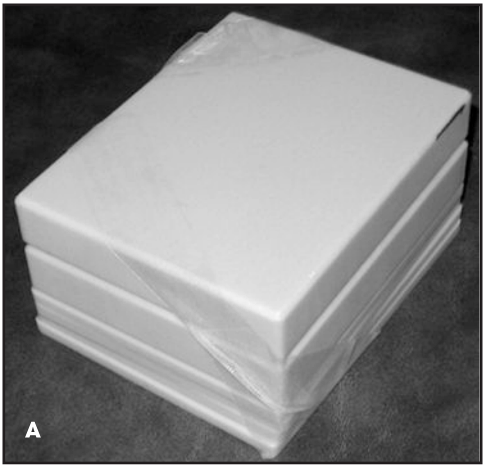
INTRODUCTION

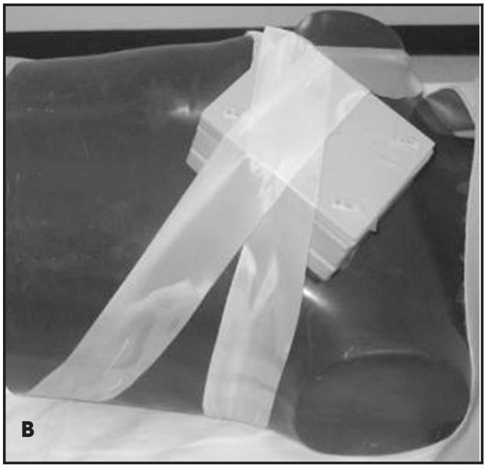
More than 35 million computed tomography (CT) scans are performed annually in the United States.[1] It is estimated that CT is responsible for approximately 13% of all radiologic procedures performed in the United States and that it accounts for 30% of the medical diagnostic radiation dosage to patients.[1-3] Single-detector row, and more recently multi-detector row CT scanners (MDCT), have markedly increased the clinical indications for CT. However, as the use of CT has increased, so have concerns about the associated increased radiation exposure to patients.[4-8] The American College of Radiology, the International Council on Radiological Protection (IRCP), and the European Commission's Radiation Protection Actions Committee have all raised concerns about the increasing radiation exposure from CT and its potential stochastic effects on patients and on radiosensitive tissues.[6-11] The health effects of low doses of ionizing radiation have also been addressed recently in the Biological Effects of Ionizing Radiation (BEIR) VII report released by the National Research Council, the principal research division of the U.S. National Academy of Sciences and the U.S. National Academy of Engineering.[12] Chest CT is a commonly ordered test, but few requesting physicians are aware that this diagnostic exam imparts a radiation dose of 20-50 mGy or more to the breasts of an average-sized woman.[6-8,13-15] We present the preliminary results from the first phase of an on-going project. The purpose of this phase was to determine if we could reduce this radiation dose by the external application of a thin layered radioabsorbent, lead-free custom-designed breast shield. The second phase will assess potential image degradation, photon flux, and loss of lesion conspicuity created by the use of a breast shield.

MATERIALS AND METHODS

We constructed a 6.0-cm thick block of breast tissue equivalent material (53% adipose/47% water) (Figure 1A) to simulate the female breast, and placed this breast slab phantom on the left anterior chest wall of an anthropomorphic tissue equivalent adult head and torso phantom (Figure 1B) (Computerized Imaging Reference System, Norfolk, Virginia). Four sets of four thermoluminescent dosimeters (TLDs) (TLD-100; Harshaw Bicron, Solon, Ohio) (Figure 1C) were labeled and attached to the breast tissue equivalent phantom. Four TLDs were positioned on the surface of the breast phantom at the 12 o'clock position, 4 TLDs were placed at the 3 o'clock position, and 4 were placed at the 6 o'clock position. Four TLDs were also applied at the nipple level equivalent and 4 were placed underneath the center of the breast phantom on the anterior chest wall of the anthropomorphic torso phantom.

To maintain consistency between the individual CT scans, the breast tissue equivalent slab and TLD positions were mapped and recorded. The anthropomorphic torso phantom with the applied breast tissue equivalent was then scanned on our 16-head MDCT (Sensation 16; Siemens Medical Solutions, Munich, Germany). The selected imaging parameters simulated our pulmonary embolus protocol: 120kV, 130mAs, collimation 16 x 0.75





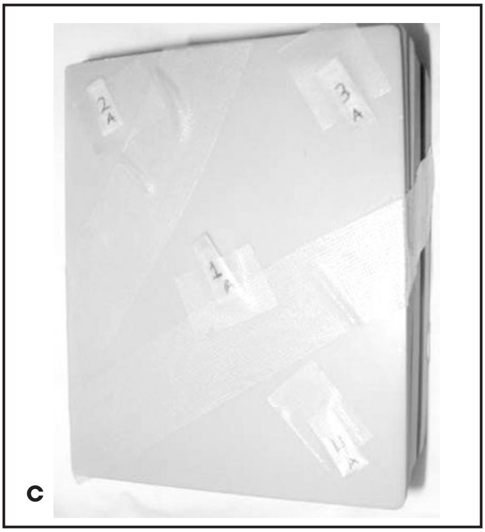


Figure 1. (A) A 6.0-cm thick block of breast tissue equivalent material (53% adipose/47% water and) simulating the female breast. **(B)** A 6.0-cm thick breast slab phantom with applied thermoluminescent dosimeters (TLDs) (TLD-100; Harshaw Bicron, Solon, Ohio) attached to the left anterior chest wall of an anthropomorphic tissue equivalent adult head and torso phantom (Computerized Imaging Reference System Norfolk, Virginia). **(C)** TLDs labeled and attached to the 6.0 cm breast slab phantom and positioned at the 12 o'clock, 3 o'clock, 6 o'clock positions and at the nipple level equivalent. An additional set of 4 TLDs (not shown) was placed underneath the center of the breast slab phantom on the anterior chest wall of the anthropomorphic torso phantom.

Figure 2. Tungsten-antimony composite breast shield (RADPAD; Worldwide Innovations & Technologies, Inc., Overland Park, Kansas) draped over the combination breast tissue equivalent and anthropomorphic adult head and torso phantom.

mm, rotation time 0.5 second, and pitch 1.25. The phantom combination was scanned a total of four times and the four-recorded TLD exposure doses at each of the five anatomic locations were then individually averaged. The first CT run employed no shielding and served as the control. During the second run, a commercially available bismuth breast shield (AttenuRad; Dyna Medical Corporation, London, Ontario) was placed over the breast phantom. The third run also employed no shielding and again served as a control. During the fourth and final run, our custom-designed tungsten-antimony composite

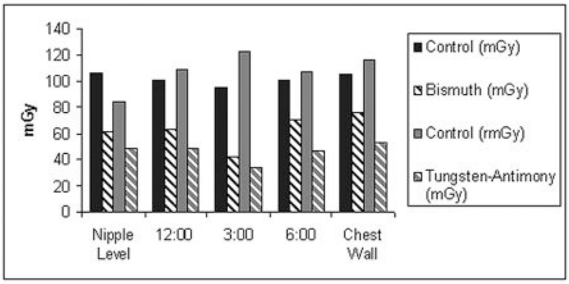


Figure 3. Comparative doses to the breast phantom at each of five anatomic locations without shielding and reductions in dose with the use of two different breast shields

(0.25 lead equivalent) breast shield (RADPAD; Worldwide Innovations & Technologies, Inc., Overland Park, Kansas) was draped over the breast phantom combination (Figure 2). All TLDs were selected to a have uniform response to radiation. An automated TLD reader read the exposed TLDs.

RESULTS

The unshielded breast phantom radiation dose during our first CT run ranged from 95.1 to 105.7 mGy. The estimated dose at each of the 5 anatomic levels averaged as follows: 100.6 mGy (12 o'clock), 95.1 mGy (3 o'clock), 100.9 mGy (6 o'clock), 105.7 mGy (nipple level equivalent), and 105.2 mGy (anterior chest wall) directly underneath the breast slab phantom. The commercially available bismuth breast shield reduced the dose at each respective anatomic location to the following averaged TLD readings: 63.1 mGy (12 o'clock), 42.1 mGy (3 o'clock), 70.8 mGy (6 o'clock), 61.2 mGy (nipple level equivalent), and 76.2 mGy (anterior chest wall). The bismuth breast shield reduced the dose to the breast slab phantom by 37% at the 12 o'clock position, 56% at 3 o'clock, 30% at 6 o'clock, 42% at the nipple level equivalent, and 28% at the anterior chest wall. (Table 1).

The third CT run also served as a control to estimate the unshielded dose to the breast slab phantom. During the third CT run, the radiation dose ranged from 84.8 to 122.9 mGy. The dose at each of the 5 anatomic levels during this run averaged as follows: 108.9 mGy (12 o'clock), 122.9 mGy (3 o'clock), 107.4 mGy (6 o'clock), 84.8 mGy (nipple level equivalent), and 117.2 mGy (anterior chest wall). Our custom-designed tungsten-antimony composite breast shield was then applied and the phantom combination was rescanned with identical imaging parameters and TLD positioning. The composite breast shield reduced the dose at each respective anatomic location to the following averaged TLD readings: 48.5 mGy (12 o'clock), 33.5 mGy (3 o'clock), 46.3 mGy (6 o'clock), 48.1 mGy (nipple level equivalent), and 52.2 mGy (anterior chest wall). Our breast shield design reduced the dose by 55% at the 12 o'clock position, 73% at 3 o'clock, 57% at 6 o'clock, 43% at the nipple level equivalent, and 55% at the anterior chest wall (Table 2).

A comparison of the unshielded doses and the averaged TLD readings at each of the 5 anatomic locations employing both the bismuth and tungsten-anti-

Table 1. Dose (mGy) to the Breast Phantom Before and After the Application of the Bismuth Shield*

TLD Location	Control (No Shield)	Bismuth Shield*
Nipple level	128.5	72.6
	129.3	60.7
	68.2	68.5
	96.8	42.9
	105.7 (average)	**61.2 (average)**
12 o'clock position	123.1	74.1
	69.3	80.2
	95.7	56.2
	114.3	42.0
	100.6 (average)	**63.1 (average)**
3 o'clock position	84.3	46.4
	119.2	39.7
	123.1	44.8
	53.8	37.3
	95.1 (average)	**42.1 (average)**
6 o'clock position	57.0	69.9
	123.2	74.7
	122.4	69.0
	101.1	69.4
	100.9 (average)	**70.8 (average)**
Chest wall	112.5	71.6
	91.9	77.4
	108.7	76.3
	107.5	79.3
	105.2 (average)	**76.2 (average)**

TLD=thermoluminescent dosimeters
*AttenuRad; Dyna Medical Corporation, London, Ontario

mony composite breast shields are provided in the histogram in Figure 3.

DISCUSSION

Chest CT is not performed to obtain diagnostic information about the breast itself, but rather information about the lung parenchyma and the mediastinum. The radiation dose delivered to the breast is an unwanted by-product of their superficial location on the anterior chest wall of the thorax. Few physicians are aware that standard diagnostic helical chest CT imparts a radiation dose of 20-50 mGy or more to the breasts of an average-sized 60-kg woman. We specifically choose the imaging parameters employed for our CT pulmonary angiography because 60% of the pulmonary embolus CT studies performed at our institution are on female patients.[16] This is the population that we believe is at the highest risk for potential stochastic effects. The radiation doses associated with CT angiography have typically been reported in the same range as

Table 2. Dose (mGy) to the Breast Phantom Before and After the Application of the Tungsten-Antimony Composite Breast Shield*

TLD Location	Control (No Shield)	Tungsten-Antimony Shield*
Nipple level	67.2	52.0
	111.3	49.8
	74.9	42.8
	85.6	47.9
	84.8 (average)	**48.1 (average)**
12 o'clock position	139.8	55.5
	100.9	42.7
	72.6	52.1
	122.5	43.7
	108.9 (average)	**48.5 (average)**
3 o'clock position	126.5	34.9
	124.6	36.9
	119.5	32.3
	120.8	29.7
	122.9 (average)	**33.5 (average)**
6 o'clock position	74.5	45.1
	125.6	52.1
	128.4	35.2
	101.2	52.8
	107.4 (average)	**46.3 (average)**
Chest wall	114.9	53.1
	111.8	48.9
	118.5	53.9
	123.4	53.0
	117.2 (average)	**52.2 (average)**

TLD=thermoluminescent dosimeters
*RADPAD; Worldwide Innovations & Technologies, Overland Park, Kansas

those associated with standard helical chest CT, 20-50 mGy.[6-8,13-15] However, our phantom studies suggest the doses may be even higher, in the range of 85-123 mGy, with MDCT. To put this in perspective, the lower range of this CT dose is roughly equivalent to 10-25 two-view mammograms and up to as many as 100-400 chest radiographs.[4,8,17,18]

One might question why our doses are higher than those reported in the literature and why there was not a uniform dose across the phantom itself and a uniform reduction in radiation dose across the breast phantom with shielding. It is well known that there are variations in radiation dose between single-row and MDCT scanners. Variations in radiation dose are also well known between not only different but even the same model MDCT scanners. The dosages associated with one CT protocol from one particular manufacturer may also differ from the same protocol associated with another manufacturer.[19-22] Our particular CT

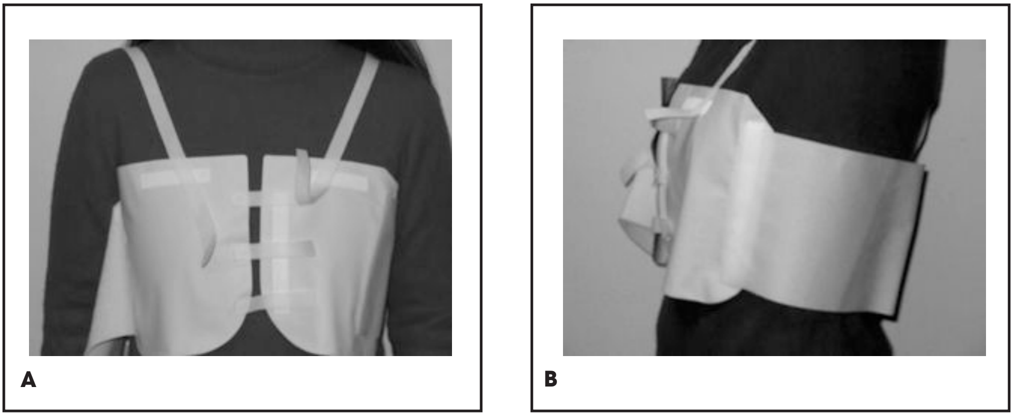


Figure 4. (A) Head-on and **(B)** side view photographs illustrating the bismuth (AttenuRad; Dyna Medical Corporation, London, Ontario) breast shield applied to a model. Notice the numerous straps and fasteners.

scanner was a new, state-of-the-art, recently installed scanner. It had been calibrated by both the manufacturer and our physicists, and was in full compliance with state and federal guidelines. A diagnostic evaluation is performed anytime the scanner is inactive for more than one hour. We strategically used 4 sets of 4 TLDs in 5 different anatomic locations and averaged their values to compensate for potential mishandling or damage to the TLDs. The TLDs were positioned in a manner to simulate the quadrants of the female breast and deep to the breast at the anterior chest wall. The variation in breast dose based on anatomic location, both without and with applied shielding, is likely related to a combination of the geometry of the x-ray beam itself, the geometry of the rectangular slab breast tissue equivalent phantom as opposed to a "mound-shaped breast" morphology, the conformation of the shield to a rectangular breast phantom equivalent as opposed to a mound-shaped breast equivalent, the starting and stopping points of the x-ray tube relative to the TLD positioning, and the orientation of the TLDs relative to the beam. We plan to repeat our study using a commercially available mound-shaped female breast phantom. Nonetheless, the reduction in dose with the application of our shield was substantial, ranging from 43% to 73%.

The increasing radiation exposure from CT and its potential adverse effects on both patients and radiosensitive tissues is a real concern. In late January 2005, the Department of Health and Human Services added medical ionizing radiation to their list of potential carcinogens.[23] Stochastic events occur at all doses, but the probability of stochastic effects depends on the amount of radiation absorbed. There is no threshold dose below which the radiation-induced effects do not occur. According to the International Commission on Radiological Protection (IRCP) Special Task Force Report 2000, the radiation doses employed in CT often approach or exceed those levels known to increase the probability of non-fatal and fatal cancers.[3,24,25] Available data for radiation-induced cancers suggest that 1 mSv of radiation exposure may lead to 5 additional cancers in 100,000 exposed patients.[10,24,26] Assuming a linear relationship between increasing radiation dose exposure and the stochastic effects of ionizing radiation on biologic tissue, one can extrapolate a possible additional 100-250 cancers per 100,000 exposed individuals, and perhaps as many as 500 additional cancers, from diagnostic helical chest CT. Land et al predict that the delivery of 1 rad of radiation to the breast of a woman younger than 35 years increases her lifetime breast cancer risk by 13.6% over the expected spontaneous rate for the general population.[13]

Most physicians would agree that the benefit of any one given chest CT exam outweighs the risk of the study. However, collectively, the risk of several thousand or possibly a million CT scans, often several in the same patient, could become a public health issue. When CT cannot be avoided, attempts should be made to reduce the level of exposure. Radiologists typically do this by reducing the tube current (normally between 80 and 300 mAs), increasing the table increment (pitch), reducing the exposure time, and, therefore, the exposure level, and by reducing the tube voltage.[27-30] However, each manipulation is associated with some compromise in image quality and, potentially, diagnostic information.

An externally applied breast shield may be another potential means of reducing the radiation dose to the female breast. The concept of radioprotective shielding is not new to diagnostic imaging. Thick leaded radioprotective shielding has been used to completely block x-rays through an area not of diagnostic interest since shortly after Wilhelm Conrad Roentgen's invention in 1895. However, we are suggesting a means of reducing, not blocking, the radiation delivered to a region of the body of diagnostic interest, namely the thorax. The commercially available, thin-layered bismuth radioprotective breast garment consists of two large panels, one for each breast, connected and secured by reinforced Velcro (VELCRO USA, Manchester, NH) straps (Figure 4). This bismuth shield effectively reduced the dose by 28-56% in our breast phantom study. However, our CT technologists found this device cumbersome to use and apply to patients. The application of this brassiere was a particular issue for our male CT technologists. Additionally, because this bismuth brassiere is only available in a large and medium size, we also encountered problems properly fitting it to many of our patients of varying body habitus. Furthermore, because of the numerous reinforcing Velcro straps, we could not adequately disinfect the device to our satisfaction between patients. As a result of these issues, our technologists abandoned the use of this device shortly after its introduction at our institution.

It is our goal to eventually develop not only a more effective but also more user-friendly radioprotective breast shield. Tungsten is the hardest metal in existence. Tungsten heavy alloys have very high melting point and have a density twice that of steel and are more than 50% heavier than lead. Due to their high density, tungsten alloys offer greater radiation shielding than lead and are non-toxic.[31] Antimony greatly increases the hardness and mechanical strength of metals.[32] Our tungsten-antimony composite was fashioned into a 0.25 lead equivalent breast shield and effectively reduced the dose to our breast phantom by 43-73%. Our proposed shield design is lightweight, adequately covers the anterior chest wall and axilla regardless of body habitus, can be easily applied as a drape by CT technologists, and will be covered in a durable, non-permeative Nylon sheath, providing easy disinfection between patients.

It is intuitive that the composite alloys will increase beam hardening which may possibly decrease contrast and lesion conspicuity in some patients. The decrease in flux of the radiation beam may be associated with an increase in noise and quantum mottle. That will be the focus of the second phase of our breast shield study.

CONCLUSIONS

Shielding of radiosensitive tissues such as the female breast may reduce the dose to this radiosensitive organ. Our preliminary data suggest that an externally applied custom-designed tungsten-antimony composite shield can potentially reduce the dose incurred during CT pulmonary angiography by 43-73%. The potential issues of photon flux and beam hardening artifact need to be further addressed before the routine use of such a shield can be advocated.

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