Paper

Protecting Our Own: A Method for Reducing Breast Radiation Exposure in Healthcare Workers

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Abstract—**Standard lead aprons do not protect the female breast adequately from radiation exposure, which has been associated with breast cancer in healthcare workers. A novel lead shield was designed to reduce radiation to the breast, axilla, and thyroid (BAT). A procedure room was simulated with an anthropomorphic phantom representing the operator. Dosimeters were positioned on the outer quadrant of each breast, the chest, the thyroid, and deep inside of a phantom acrylic female torso with neck and head. Standard lead vest plus a thyroid shield was used as control and compared to standard lead vest plus BAT shield. Three operator and two image receptor positions were tested. The reductions in radiation exposure were calculated. The standard vest plus BAT shield provided significant reductions in radiation exposure for all anatomic locations compared to control. When averaging all operator positions, the BAT provided reductions of 91% ($p < 0.0001$) for near breast. Reductions for far breast, chest, thyroid, and deep tissues were 76% ($p = 0.016$), 94% ($p < 0.0001$), 52% ($p = 0.026$), and 60% ($p = 0.004$). With operator 90° to the table using a cross-table lateral beam, the BAT provided a 97.7% reduction in radiation to the near breast and significant reduction in radiation to the chest, thyroid, and deep tissues. The BAT shield reduces radiation exposure to the breast, chest, thyroid and deep hematopoietic tissues. Such shields could benefit healthcare workers to reduce the risk of breast cancer and other radiation-associated cancers.**
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Key words: breast; cancer; occupational safety; radiation protection

INTRODUCTION

BREAST CANCER remains the world's most prevalent cancer (WHO 2022). At the end of 2020, there were 7.8 million women alive who were diagnosed with breast cancer in the past 5 y (WHO 2022). Decades of research have led to the identification of a number of lifestyle and environmental breast cancer risk factors, each typically explaining a modest proportion of the variation in disease risk (Maas et al. 2016). Several studies have documented the link between occupational radiation exposure and breast cancer (Mohan et al. 2002; Yoshinaga et al. 2004; ICRP 2007). In 2007, the International Commission on Radiological Protection estimated an increased risk of radiation-induced breast cancer death that was twice as high as its 1977 and 1991 estimates, suggesting that the risks of ionizing radiation to the breast may be higher than previously perceived (ICRP 2007). With women continuing to increase as a percentage of the physician workforce, it is important to ensure adequate occupational protection, specifically for diseases with sex predilection such as breast cancer (Verdi et al. 2022).

As medical therapies gravitate to more non-invasive approaches, the utility of radiation and fluoroscopy grows. Fluoroscopy is not only used in the field of radiology but has also expanded into other medical specialties, including cardiology and gastroenterology, as well as surgical specialties such as orthopedic, vascular, and hepatobiliary surgery. It is estimated that there are 2.3 million medical radiation workers worldwide (UNSCEAR 2000). In the United States, medical radiation workers constitute 44% of all radiation exposures, providing an opportunity to study breast cancer risks in a healthy population that has chronic exposure to radiation (Mohan et al. 2002). A study of 90,957 radiologic technologists from 1994 through 2008 reported a significant elevation in the incidence of breast cancer among technologists who performed fluoroscopically guided interventional procedures (Rajaraman et al. 2016). In addition to radiologic technicians, orthopedic surgeons also have a higher rate of breast cancer, with studies reporting a 2.9-fold increase in prevalence when compared with women of similar age and race (Chou et al. 2022). Several studies have described a higher rate of breast cancer in radiologic technologists, orthopedic surgeons, and female physicians as a whole (Chou et al. 2022; Lee et al. 2015; Rajaraman et al. 2016).

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The upper outer quadrant of the breast, which is the most common site of all breast cancers, is especially exposed to higher scatter radiation doses (Valone et al. 2016). The standard lead vest or apron does not provide adequate intraoperative protection against radiation to the upper outer quadrant of the breast (Van Nortwick et al. 2021). Studies have called for the use of axillary supplements and sleeves to improve protection; however, such devices are often uncomfortable with motion restriction, require special fitting or attachments to specific lead aprons, and are often discontinuous in the axillary portion where protection is needed most. The purpose of this study was to test a novel lead shield designed to adequately protect the breast, axilla, and thyroid (BAT) while ensuring mobility and comfort for the operator and universal compatibility with standard lead aprons or vests without attachments or modifications.

MATERIALS AND METHODS

A standard fluoroscopic procedure room setting was simulated using an anthropomorphic phantom with female torso, neck, and head to simulate the operator (Fig. 1). Ten acrylic slabs simulate the patient (Table 1). Both the phantom and acrylic slabs are accepted simulations of human tissue for studies of scattered ionizing radiation (Valone et al. 2016). Institutional Review Board approval was not required for this phantom study, as no human research subjects were present in the fluoroscopy suite. A standard Philips Allura Clarity C-arm fluoroscope (Philips, Andover, MA) was used in high dose fluoroscopic mode using standard manufacturer settings employing automatic brightness control. Electronic dosimeters (RAD-60R; RADOS Technology, Turku Finland, measurement range 1 μSv–9.99 Sv, semiconductor type) were attached to the outer quadrant of each breast equidistant from the center of the breast (labeled as near breast and far breast relative to the radiation source), the chest near the intersection of the lead apron and thyroid shield, and the thyroid. The location of the radiation sensor within the dosimeters was identified and placed carefully in the area of interest. An additional dosimeter (Thermos Radeye; Thermo Fisher Scientific, Waltham, MA) was placed in a small cavity deep inside of the phantom in the approximate location of simulated spinal hematopoietic tissue. This dosimeter was used specifically due to the location deep inside the phantom, which prevented visualization and its capability of saving exposure per time values for viewing following test completion. After placement of dosimeters on the phantom, protective garments were applied. All dosimeters had been calibrated to standard sources before the experiment.

The control was a standard lead vest and thyroid shield (Fig. 2a) with 0.50 mmPb equivalence based on the phantom's dimensions and the manufacturer's (Burlington Medical, Newport News, VA) size chart for best fit. This was compared to a standard lead vest plus BAT shield. The BAT shield consisted of sleeves with flanges that overlap the standard lead vest, thyroid shield, and chest piece that bridges between the thyroid shield and standard lead vest (Fig. 2b). The chest piece provided additional coverage to the thyroid as well as to mediastinal organs and spinal hematopoietic tissue. The BAT was 0.35 mmPb equivalence for all lead areas except for the thyroid shield portion, which was 0.525 mmPb equivalence to approximately match standard thyroid protection.

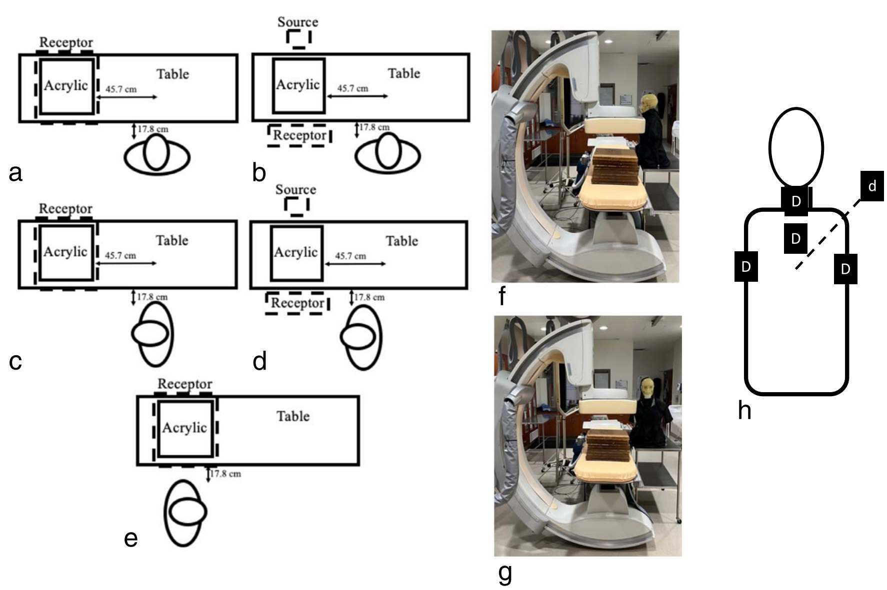

Fig. 1. The different beam orientations and operator positions relative to acrylic slabs or hypothetical patient are depicted in these schematic figures and photographs. Anterior-posterior beam (AP), operator facing table at region of patient's lower torso (A and F); cross-table lateral beam (XTL), operator facing table at lower torso (B); AP, operator 90° to table at lower torso (C and G); XTL, operator 90° to table at lower torso lower torso (D); AP, operator 90° to table adjacent to acrylic (E); Location of external dosimeters labeled "D" and deep dosimeter labeled "d" on phantom (H).

Table 1. Setup parameters.

Projection of image receptor	Anteroposterior	Cross Table Lateral
Peak kilovoltage (kV)	80	125
Current (mAs)	22	32
Field of view (cm)	48	48
Source to image receptor distance (cm)	108	120
Table height (cm)	83	90
Acrylic phantom to image receptor distance (cm)	18	10
Acrylic phantom dimensions (cm)	38x38x24	38x38x24
Operator top of head height (cm)	165	165

The testing setup was similar to a previously reported method (Valone et al. 2016; Van Nortwick et al. 2021). A total of five combinations of three different operator positions and two image receptor positions were tested and described in Fig. 1. These were selected to represent situations that occur in clinical use. Operator height was set to correspond to an average female operator height of 165 cm. Other setup parameters are depicted in Table 1.

For all dosimeters corresponding to all anatomic locations except deep, the total dose after 5 min of fluoroscopy were recorded in milliroentgens and converted to micro sieverts (μSv). The deep dosimeter recorded in μSv h^{-1}, which were converted to μSv 5-min^{-1}, to approximately correspond to the measurements from the other dosimeters. Measurements were obtained in a single setting to ensure controlled experimental conditions. No modifications were performed to the setup or equipment during measurement acquisition aside from changing the garments draped around the phantom and those depicted in Fig. 1. The setup parameters were kept constant by periodic checking of the control panel settings and digital display of the C-arm equipment during acquisition. The dosimeters were reset after every 5-min test except for the deep dosimeter, which did not require this because it was capable of saving exposure per time values for viewing after test completion.

Data on radiation exposure levels were recorded in tables. For each operator, machine position and location, a paired difference of percent radiation exposure reduction was obtained between BAT and standard protection. The mean and 95% confidence intervals were obtained, and one sample t-test was used to test the null hypothesis of no differences between paired difference of the two protection methods. Data analysis was performed with R version 4.0.3 statistical software. All statistical tests were two-sided with statistical significance level set at p values <0.05.

RESULTS

Radiation exposures are shown in Tables 2 through 4. All anatomic areas (near breast, far breast, chest, deep, thyroid) had a significant reduction in radiation exposure with the BAT shield compared to standard protection, ranging from 19.4% to 100% (Table 2). Notably, the median radiation dose to the near breast of 110.5 μSv was significantly reduced to 6.1 μSv with the BAT shield (91% reduction, $p < 0.0001$). The near breast had exposures reduced by 97.4%, 71.4%, 93.9%, 97.7%, and 95.3% depending on setup (Tables 3 and 4).

With anterior-posterior (AP) beam and the operator facing the table (Fig. 1a and Table 3a), the radiation exposure of the near breast was 34.20 μSv with standard protection and 0.88 μSv with the BAT shield (97.4% reduction). It should be noted that in this position, the deep tissue experienced a reduction in radiation exposure from 4.00 μSv to 1.39 μSv (65.2% reduction) with the BAT shield.

In the AP projection with the operator standing in the same position, near breast exposure changed little when the operator turned from facing the table to facing 90° from the table (34.2 to 28.9 μSv, Table 3). With the operator facing 90° from the table (Fig. 1c), the near breast experienced a 93.9% reduction in radiation with the BAT shield

Fig. 2. Standard lead aprons universally available. Gaps for radiation exposure to the upper outer quadrant of the breast, axilla, and chest (A). The breast, axilla thyroid (BAT) shield worn over the same lead vest. Improved coverage of the breast, axilla, and chest (B).

Table 2. Radiation exposure (μSv) for each anatomic location in all scenarios.

	Standard vest + thyroid shield Median (Interquartile range)	Standard vest + BAT shield Median (interquartile range)	Mean percent reduction (95%CI[a])	p-value
Chest	8.8 (4.4,325.4)	0.88 (0, 30.7)	94% (88%, 100%)	**<0.0001**
Deep	13.0 (4.0, 52.6)	1.4 (1.2, 16.7)	60% (31%, 89%)	**0.004**
Far breast	0.88 (0.88, 10.5)	0 (0, 3.51)	76% (26%, 100%)	**0.016**
Near breast	110.5 (34.2, 130.7)	6.1 (1.75, 7.89)	91% (77%, 100%)	**<0.0001**
Thyroid	2.6 (1.75, 54.3)	0.88 (0.88, 43.85)	52% (10%, 93%)	**0.026**

[a]Upper and lower confidence intervals. Upper CI is truncated at 100%.

(Table 3c). Notably, in this position, the far breast did not receive a detectable level of radiation with either standard protection or the BAT shield. Across all other anatomic areas, there was a significant reduction in radiation exposure (p = 0.019) when the phantom was wearing the BAT shield.

As expected, exposures were considerably higher for cross-table lateral beam projection. In all setup scenarios, median near-breast exposures were the highest of all anatomic sites. In all anatomic locations, the reductions in exposure when BAT was used compared to standard protection was significant, ranging from 34.6% for deep tissues to 100% for far breast.

In the cross-table lateral testing with the operator facing the table (Fig. 1b and Table 3b), the near breast and the chest experienced the highest exposures and greatest absolute reductions with the BAT for all anatomic areas (p = 0.020).

In the cross-table lateral testing with the operator facing 90° to the table (Fig. 1d and Table 3d), the near breast experienced a 97.7% reduction in radiation exposure with the BAT shield. The chest, deep, and thyroid tissues also experienced significant reductions with values of 88.9%, 68.3%, and 22.7%, respectively. Across all anatomic sites, the reduction of radiation was significant (p = 0.0061) when the phantom was wearing the BAT shield.

In the cross-table lateral projection, near breast exposure approximately tripled when the operator turned 90° to the table (110.5 to 336.8 μSv, Table 3).

Placing the operator near the acrylic slabs (Fig. 1e), as opposed to placing the operator toward the foot of table (Fig. 1a–d) with the beam in the AP projection, resulted in substantial increase in near breast exposure to 130.67 μSv

Table 3. Exposure (μSv) with operator standing at patient's lower torso.

	Operator facing table			
	Standard vest + thyroid shield	Standard vest + BAT shield	Percent reduction	p-value
A. Anteroposterior				**<0.0001**
Chest	8.8	0.88	90.0%	
Deep	4.0	1.4	65.2%	
Far Breast	0.88	0.0	100.0%	
Near Breast	34.2	0.88	97.4%	
Thyroid	2.6	0.88	66.7%	
B. Cross Table Lateral				**0.020**
Chest	442.0	30.7	93.1%	
Deep	55.6	36.3	34.6%	
Far Breast	12.3	7.9	35.7%	
Near Breast	110.5	31.6	71.4%	
Thyroid	54.4	43.85	19.4%	
	Operator 90° to the table			
C. Anteroposterior				**0.019**
Chest	4.4	0.0	100.0%	
Deep	2.0	1.2	40.5%	
Far Breast	0.0	0.0	NA	
Near Breast	28.9	1.8	93.9%	
Thyroid	1.8	0.88	50.0%	
D. Cross Table Lateral				**0.0061**
Chest	325.4	36.0	88.9%	
Deep	52.6	16.7	68.3%	
Far Breast	10.5	3.1	66.7%	
Near Breast	336.8	7.9	97.7%	
Thyroid	57.9	44.7	22.7%	

Table 4. Radiation exposure (μSv) with operator 90° to the table, adjacent to acrylic slabs.

	Standard vest + thyroid shield	Standard vest + BAT shield	Percent reduction	p-value
Anteroposterior				**<0.0001**
Chest	1.8	0.0	100.0%	
Deep	13.0	0.90	93.1%	
Far breast	0.88	0.0	100.0%	
Near breast	130.7	6.14	95.3%	
Thyroid	0.88	0.0	100.0%	

with standard protection, which was reduced by 95.3% with the BAT (Table 4). Again, there was a significant reduction in radiation with the BAT shield when compared to standard protection across all anatomic sites ($p < 0.0001$).

Far breast exposure was generally low overall (Tables 2 and 3).

DISCUSSION

Physicians, trainees, and medical staff often use the standard lead aprons purchased by the healthcare facility. Given the lack of customization and appropriate sizing, these aprons are often ill-fitting, leaving gaps for radiation exposure to the axilla, breast, thyroid, and manubrium. This can be especially problematic for smaller-framed women using the stock radiation protection typically available, which may be too large. This problem is depicted in Fig. 2a.

Other studies have shown that the addition of lead sleeves or axillary supplements to a standard lead vest significantly decreases radiation exposure to this area (Van Nortwick et al. 2021). Currently available modifications to the standard lead vest include lead wings and sleeves; however, these modifications may be underutilized due to motion restriction and lack of comfort (Van Nortwick et al. 2021). The modifications are designed to be fixed and attached to the standard apron or vest with Velcro, snaps, or buttons, resulting in restrictive arm motion for the operator, which is disadvantageous during a procedure. In order to overcome such restriction, some products have gaps in the axillary region, leaving the axilla and lateral breast vulnerable to scatter radiation, which projects in an upward direction from the source (Fig. 3). Additionally, the available attachments are often manufacturer- and product-specific and often not available to users, especially if they do not own their own lead apron and are using one provided by the facility.

The literature has called for the development of an axillary supplement placed underneath the arm (Van Nortwick et al. 2021). The BAT shield was developed to address these concerns and was found to be effective in radiation reduction to the upper outer quadrant of the near breast with median exposure reductions of 91%. In addition to reducing radiation, the BAT shield addresses the problems with standard sleeves attached to aprons. First, the BAT shield does not fix or attach to the vest or apron, facilitating range of motion and comfort, while providing universal compatibility with all standard vests and aprons (Fig. 2b). Second, the BAT shield was designed without an underarm gap, thus protecting the lateral breast from the upward-directed scatter radiation. In order to reduce the number of supplemental pieces to the standard vest or apron, the BAT shield incorporates thyroid protection. This study showed reduced exposures to thyroid gland compared to standard garments. The cause cannot be determined but might be related to slightly higher Pb equivalency of the thyroid shield or because reductions to surrounding tissues resulted in reduced tertiary scatter to the thyroid. The limited protection of the lens of the eye with lead glasses is well documented and due in part to the effects of tertiary scatter from tissues to nearby tissues (Moore et al. 1980; Fetterly et al. 2017).

In addition to breast and thyroid protection, the BAT shield provided a statistically significant 60% reduction in exposure to the deep tissues in the chest. This finding is important as the hematopoietic tissues are radiosensitive and

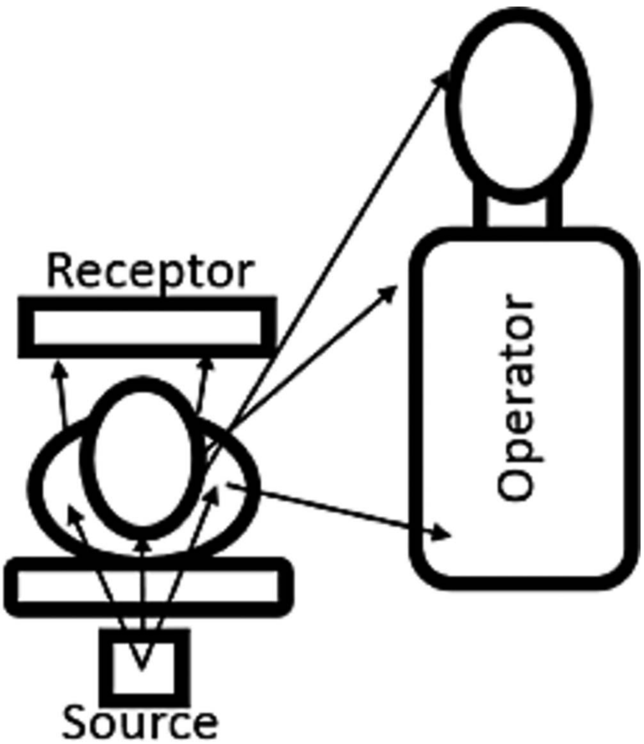

Fig. 3. Schematic depiction of direction of scatter to operator. Scatter emanates from patient in all directions. The scatter reaching the axilla has a predominately upward angle. For this reason, shielding positioned in the axilla and under the arm is an important aspect of protection of the outer breast.

relate to risk of leukemia and lymphoma. Protection of the proximal humerus by BAT also has potential implications related to the presence of hematopoietic bone marrow in this location (Niklason et al. 1993).

The standard lead apron was developed in 1950 to protect the wearer against the harmful effects of x rays (Lubow 1950). Although still effective in its most basic purpose, radiation protection now deserves modifications to account for significant changes in the medical landscape over the past five decades, such as the great increase in the involvement of women, who in 2019 comprised 50.5% of enrollees in US medical schools. This shift in the workforce calls for a close examination of traditional practices and determination of areas where improvements and adaptations are needed.

The present study has limitations. Extrapolation of actual exposures to real situations is not possible because of different positions of the operator, operator movement during a procedure, variable fluoroscopy positioning and settings, and different radiation scatter patterns of actual patients. The phantom also did not have arms, which may affect radiation exposure to the breast in certain operator positions. The phantom only allowed testing of one size of breast, and it is possible that different breast sizes may yield different results. Our study does not demonstrate a causality between radiation exposure and breast cancer. The exposures for deep location were recorded with a different type of dosimeter than the others, so direct comparisons between locations may not be possible, although percent reductions with the BAT shield are still valid for all locations. Additional studies should be performed to further elucidate the relationship and to establish annual dose limits for occupational radiation exposure to the breast.

The BAT shield provided significant reductions to anatomic locations of the chest, thyroid, and breast, which are important in the current era of highly prevalent noninvasive interventional medical therapies and involvement by women. The universal compatibility with standard garments allows for potential widespread use, potentially benefitting the growing number of women who are placed at risk of occupational radiation exposure.

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