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Introducing SRF in Bismuth-Silicon and Polyurethane shields for breast dose reduction during chest CT

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ABSTRACT

Background: This study introduces Shield Reduction Factor (SRF) for breast dose decline using two new Bismuth-polymer composites shields in chest CT.
Method and Materials: SRF of Bismuth -Silicon (Bi-Si) and -Polyurethane (Bi-PU) were measured after chest CT by a multi-detector CT (MDCT, 16 detectors) and a single-detector CT (SDCT) for breast at spiral and axial modes using female chest phantom.
Result: Higher effectiveness was observed in the use of the Bi-Si shield with an SRF of 1.25 and 1.66, and in the use of the Bi-PU shield with an SRF of 2.31 and 2.06 in SDCT and MDCT (100 mAs), axial mode, respectively. Experiments by 80 mAs at spiral/axial mode induced lower SRF by Bi-Si and Bi-PU shields.
Conclusion: This study showed that Bi-Si and Bi-PU shields are new composites, light and economical, carrying promising potentials for breast dose reduction during chest CT in spiral and axial modes at 80 and 100 mAs, single and 16 MDCT.

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KEYWORDS

Bi-Si ,Bi-PU shields ,breast dose , SDCT, MDCT

INTRODUCTION

The number of CT tests have almost doubled in the United States, Germany and Japan, (Kubo et al., 2008) with the number of CT examinations amounting to about 67 million in 2006 (Mettler et al., 2009). What is, therefore, to be expected is the range of detrimental effects caused by ionizing radiation from chest CT to sensitive organs such as the lung and breast, leading to much tangibly felt concern. The amount of radiation dose in radiography of chest is around 0.7 mSv; which is 5.1-11.1 mSv lower than chest CT (Wenyun et al., 2014). Furthermore, applying 10 mGy to the breast of women under 35 leads to an increase in the risk of cancer close to 14 percent, overall (Angel et al., 2009). The evaluated received radiation on breast tissue regarding CT; with absorbed dose to the breast tissue in MDCT reported between 4.77 and 9.22 cGy (Hurwitz et al., 2007) or mean dose of lung (23 mGy); are other reasons for the need of organs protection in chest CT field of radiation.
An overview of the three principal methods of radiation protection includes keeping distance, exposure factors and using protective equipment in CT. These lead to the fact that the distance between tube and isocenter usually is fixed in CT, but changing the exposure factors, supine or prone position of chest and using a shield results in a reduction of organ dose in CT (Akhlaghi et al., 2014; Araghian et al., 2015). In radiation protection, Dose Reduction Factor (DRF) is generally used for the expression of the dose of radiation in the presence and absence of radio-protector drug; however, in this study, we suggest using Shield Reduction

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Factor (SRF) for dose of radiation evaluation, with and without the shield.

Lead shields, as the most common protective equipment, have been used in conventional radiography and fluoroscopy for decades. But they cannot be used in primary fields of CT scan due to their omitting visual information and flash artifacts. Bismuth shields were proposed for CT scan in 1990 to reduce the dose in surface and anterior organs of the body such as the breast, eye lens and thyroid. Different studies have shown that Bismuth shields lead to dose reduction in surface organs sensitive to x-ray like the breast, leading to a 29 and 27-52 percent decrease in dose in pediatrics and adults, respectively, depending on the shield thickness, breast size and imaging method (Fricke et al., 2003). Meanwhile, using this shield can lead to decreased observed dose in the heart, esophagus and lungs. The observed decrease in bismuth shields during MDCT were 34, 33 and 10 % in the breast, skin and anterior lung (Huggett et al., 2013); while using other shields like Tungsten-Antimony shows possible decreases in the amount of absorbed dose up to 43-73 percent (Parker et al., 2006). Previous studies have looked at Bismuth shields used for breast causing CT number displacement, noise and star artifact, which can be solved by increasing the distance between the shield and the phantom (Kelsey et al., 2003). A study showed that increasing the distance between the shield and phantom does not lead to considerable changes in the amount of surface dose. Thus, the negative impact of shield on image quality is minimized, while a fixed level of dose reduction is maintained by increasing the distance between shield and phantom (Kalra et al., 2009).

Bismuth is a metal, atomic number 83, which is trivalent, white crystalline, heavy and fragile with a pink tinge; chemically similar to Arsenic and Antimony. Bismuth is the most magnetic metal which has, meanwhile, the least thermal conductivity among elements except Mercury (Bismuth 2016). Composites are compound or multi-structure materials involving matrix and reinforcing phases, with at least 5% of the second phase used. Thus, the composition matrix and fibers (or reinforcing material) under 5 percent are called composites. There are three composites: A) ceramic matrix composites, B) metallic matrix composites and C) polymer matrix composites.

In this research, polymer matrix composite forms of Bismuth Silicon (Bi-Si) and Bismuth Polyurethane (Bi-PU) shields are used. Breast dose reduction in the presence and absence of shields at spiral and axial modes in single and 16 slicer chest CT was evaluated by Thermo Luminescence dosimetry (TLD).

MATERIALS AND METHODS

The materials used were Polymer matrix composites including two polymers of Silicon and Polyurethane matrixes 210 × 210 × 1 mm^3 with 1 mm thickness, 1% Bismuth grains with the size of 50 micrometers in Bismuth Silicon R_2SiO_n (Bi-Si) and Bismuth Polyurethane R-N=C=O + OH_n (Bi-PU). Shield reduction factor (SRF) was calculated by the following formula:

$$\text{SRF} = \frac{\text{Dose of radiation without shield}}{\text{Dose of radiation with shield}}$$

In the Bismuth shield, foam must be used for spacing between shield and skin; six mm foam used for Silicon and ten mm foam for Polyurethane shields created free-artifact images, which was inferred after various trials with different thicknesses of foams. These shields were placed on the Phantoms of water and female chest, to evaluate CT image quality by the CT numbers extraction in the CT scanning images, in both with and without the shields, and standard deviation (SD) of measured CT numbers was recorded for image noise evaluation.

DIADOS (PTW) dosimeter system, was used to measure linear attenuation coefficient for both shields. Dose was measured in the air with one and two mm thicknesses of Bi-Si and Bi-PU shields in FFD=100 cm, mAs=100 and kV=80, 100 and 120 kV. The linear attenuation coefficient (μ) was calculated by the following formula:

$$\mu = \frac{\ln N_2 - \ln N_1}{X_2 - X_1}$$

N_1 is dose without shield, N_2 is dose with shield, X_2 and X_1 are shield thicknesses in N_2 and N_1, respectively. The 16 slicer scanner (MDCT), (Siemens, Germany) and single slicer (SDCT), (GE, hi-Speed) were used for comparison purpose. The exposure and scanning parameter of chest CT at axial and spiral modes were 120 kV, pitch 1.3 and slice thickness 10 mm with 100 and 80 mAs, respectively. Dose was measured by Thermo Luminescence dosimetry (TLD) placed in superior and 4^{th} layers of breast phantom in 6 and 12 o'clock location in the presence and absence of Bi-Si and Bi-PU shields to evaluate the dose values of breast layers. The analysis was performed by SPSS Software, T-test, mean Witntly and Tukey tests.

RESULTS

Linear attenuation coefficient (μ_L) and CT images using Bi-Si and Bi-PU shields at 80, 100 and 120 kV

The Linear attenuation coefficient of Bi-Si shield was 0.12, 0.073 and 0.071 cm^{-1} at 80, 100 and 120 kV, respectively. In the Bi-PU shield, μ_L was 1.21, 0.78 and 0.46 cm^{-1} at 80, 100 and 120 kV, respectively. Therefore, an increase in tube energy from 80 to 120 kV causes 41% and 61% decrease in μ when using Bi-Si and Bi-PU, respectively. The linear attenuation coefficient (μ) declined by photon energy increasing and varied by shield material.

The effect of Bi-Si and Bi-PU shields on the CT images of water and female chest phantoms are shown in Figure 1.

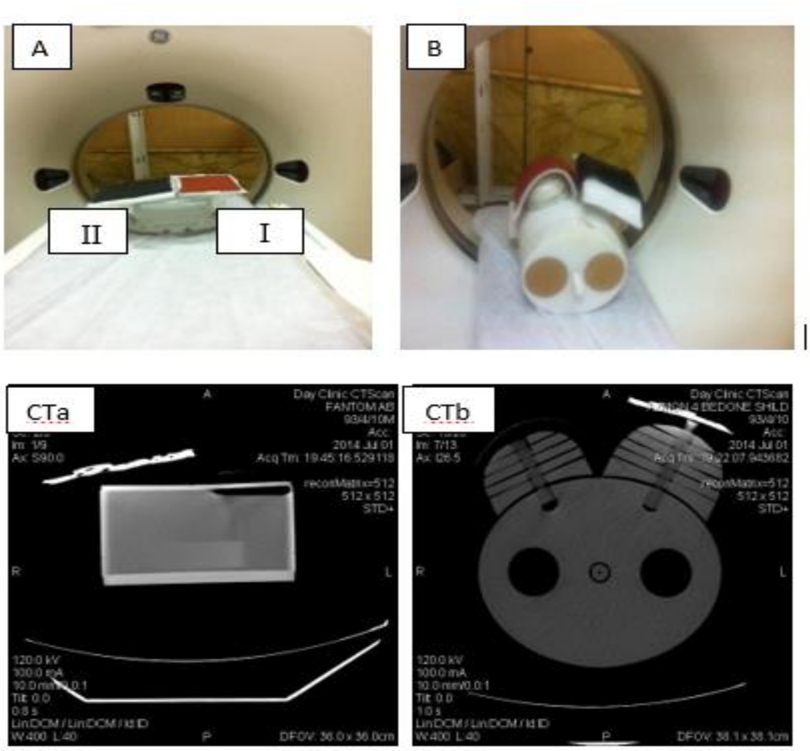

Fig.1: Photo of Silicon (I) and Polyurethane (II) shields position on the A: water phantom, B: woman chest phantom. CTa: image of two shields on the water phantom, CTb: image of two shields on the woman chest phantom, which are presented in accepted images.

The quality of CT images did not change in experiments by shields. Also, star or flash artifacts were not observed and an acceptable contrast was approved by a radiologist.

The average breast dose by spiral/axial mode at 80 and 100 mAs, 120 kV

Breast dose was measured in skin and 4 cm depth, with and without Bi-Si and Bi-PU shields on the female chest phantom as shown in Table 1 and Table 2 for SDCT and MDCT.

Table 1: Breast dose (mSv) in skin and 4th layers of woman chest phantom measured by TLD during single slice chest CT with and without shielding in spiral and axial modes at fixed 120 kV, 80 or 100 mAs. (*) is position of TLD at 6 and (**) is at 12 o'clock on the breast phantom. Experiments for each positions of TLD had been repeated three times and their average was written.

	Spiral				Axial			
	80 mAs	average	100 mAs	average	80 mAs	average	100 mAs	average
without shield skin dose depth dose	10.5*, 8.10** 7.62, 6.51	9.3 7.1	12.00*, 11.34** 7.47, 5.91	11.7 6.7	14.9*, 10.72** 10.82, 9.6	12.8 10.2	16.7*, 15.02** 13.07, 12.40	15.9 12.7
with Bi-Si shield skin dose depth dose	7.90, 7.28	7.6 6.4	7.67, 7.10 6.34, 5.69	7.4 6.0	12.02, 11.05	11.5 9.7	14.25, 11.75 10.76, 7.78	13.0 9.3

	6.20, 6.56				10.04, 9.29			
with Bi-PU shield skin dose depth dose	6.76, 6.10 5.34, 4.69	6.4 5.0	6.91, 6.03 5.37, 3.99	6.5 4.7	8.67, 7.5 6.31, 5.06	8.1 5.7	8.93, 6.8 5.40, 3.10	7.9 4.3

Table 2: Breast dose (mSv) in skin and 4th layers of woman chest phantom measured by TLD during 16 slice chest CT with and without shielding in spiral and axial modes at fixed 120 kV, 80 or 100 mAs. (*) is position of TLD at 6 and (**) is at 12 o'clock on the breast phantom. Experiments for each positions of TLD had been repeated three times and their average was written.

	Spiral				Axial			
	80 mAs	average	100 mAs	average	80 mAs	average	100 mAs	average
without shield skin dose depth dose	9,45* 8,26** 7,32 6,90	8,9 7,1	15,06* 13.69** 12.88, 11.62	14.4 12.3	8.57*, 6.36** 6.16, 5.18	7.5 5.7	10.77*, 10.03** 8.76, 7.57	10.4 8.2
with Bi-Si shield skin dose depth dose	6.40, 6.18 4.71, 3.81	6.3 4.3	12.14, 11.20 5.74, 5.98	11.7 5.9	5.19, 5.01 5.1, 4.04	5.1 4.6	6.31, 5.75 5.45, 4.69	6.0 5.1
with Bi-PU shield skin dose depth dose	6.76, 6.10 5.34, 4.69	5.9 3.4	9.75, 8.11 4.75, 3.83	8.9 4.3	4.3, 3.76 3.55, 3.37	4.03 3.5	5.11, 5.67 4.1, 3.48	5.4 3.8

SDCT

1) Spiral mode at 80 mAs

In Table 1, the average breast skin and depth doses without shields were 9.3 and 7.1 mSv, respectively. The calculated SRFs (Table 3) of Bi-Si and Bi-PU shields for average breast dose were 1.17 and 1.43, respectively.

Table 3: The SRF of Bi-Si and Bi-PU Shields calculated from total average of breast dose in SDCT and MDCT by spiral /axial mode at 80 and 100 mAs, 120 kV.

	SRF Spiral 80 mAs	SRF Spiral 100 mAs	SRF Axial 80 mAs	SRF Axial 100 mAs
Bi-Si Shield SDCT MDCT	1,17 1,50	1,36 1,51	1,08 1, 35	1,28 1,67
Bi-PU Shield SDCT MDCT	1,43 1,70	1,63 2,02	1, 66 1,75	2,34 2,02

2) Axial mode at 80 mAs
By axial mode, the average breast skin and depth doses were 12.81 and 10.2 mSv. In Table 3, use of Bi-Si and Bi-PU brought out SRFs 1.08 and 1.66 of average breast dose, respectively.
3) Spiral mode at 100 mAs
Increasing tube current to 100 mAs changed average breast skin and depth dose to 11.34 and 6.7 mSv by spiral mode without shielding. Covering the breast by Bi-Si and Bi-PU shields induced 1.36 and 1.63 SRF of average dose of breast, respectively.
4) Axial mode at 100 mAs
By axial mode, the average breast skin and depth doses were 15.9 and 12.7 mSv. In Table 3, the SRF of Bi-Si and Bi-PU shields of the average breast dose were 1.28 and 2.34, respectively.

MDCT
1) Spiral mode at 80 mAs
In Table 2, the average breast skin and depth doses without shields in MDCT were 8.9 and 7.1 mSv, respectively. In Table 3, using Bi-Si and Bi-PU shields presented 1.50 and 1.70 SRF for average breast dose.
2) Axial mode at 80 mAs
By axial mode, the average breast skin and depth doses were 7. 46 and 5.67 mSv. Using Bi-Si and Bi-PU pointed to 1.35 and 1.75 SRF of average breast dose, respectively.
3) Spiral mode at 100 mAs
Increasing tube current to 100 mAs changed average breast skin and depth dose to 14.4 and 12.3 mSv by, respectively. In Table 3, covering the breast by Bi-Si and Bi-PU shields induced 1.51 and 2.02 SRF of average breast dose, respectively.
4) Axial mode at 100 mAs
By axial mode, the average breast skin and depth doses were 10.4 and 8.2 mSv. The SRF of Bi-Si and Bi-PU shields of the average breast dose were 1.66 and 2.02, respectively.

A comparison between effectiveness of scanning parameters and using Bi-Si or Bi-PU shields on the average breast dose reduction
A comparison of the average breast dose between 80 and 100 mAs at 120 kV in SDCT without shielding is presented in Figure 2.

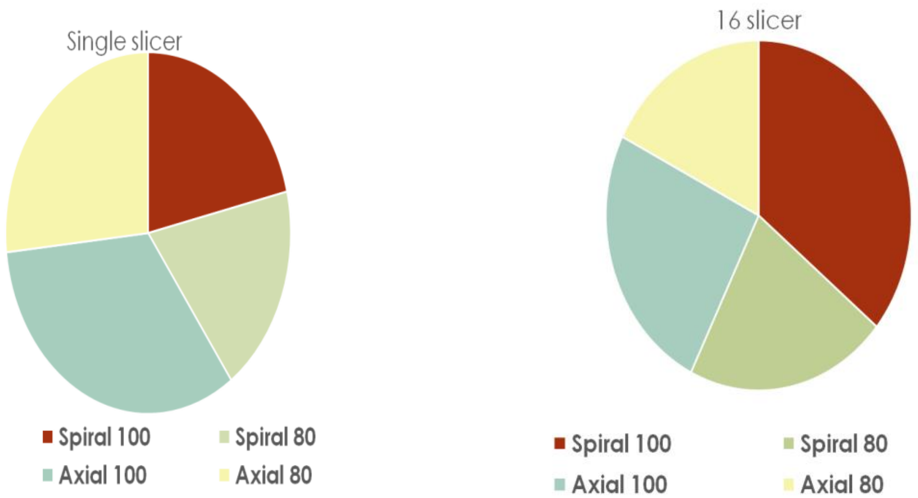

Fig.2: Percentage values of breast dose in single and 16 slices CT by changes on the mA and scanning modes at fixed 120 kV without shielding.

As recorded for the breast, the selection of axial mode at 100 mAs induced a higher dose, and the selection of spiral mode at 80 mAs induced a lower dose. In other words, about 43% reduction in breast dose was due to the selection of spiral mode at 80 mAs.
When the breast was covered by Bi-Si and Bi-PU shields, decreases of breast dose were observed with both shields.
In SDCT, in both 100 and 80 mAs, the highest (2.34) and lowest (1.08) SRF was in axial mode and belonging to Bi-PU and Bi-Si, respectively. Nevertheless Bi-PU shield triggers 34% and 45% more than Bi-Si dose reduction at 80 and 100 mAs, respectively. This difference was 18% and 16% in spiral mode at 80 and 100 mAs, respectively (Figure 3).

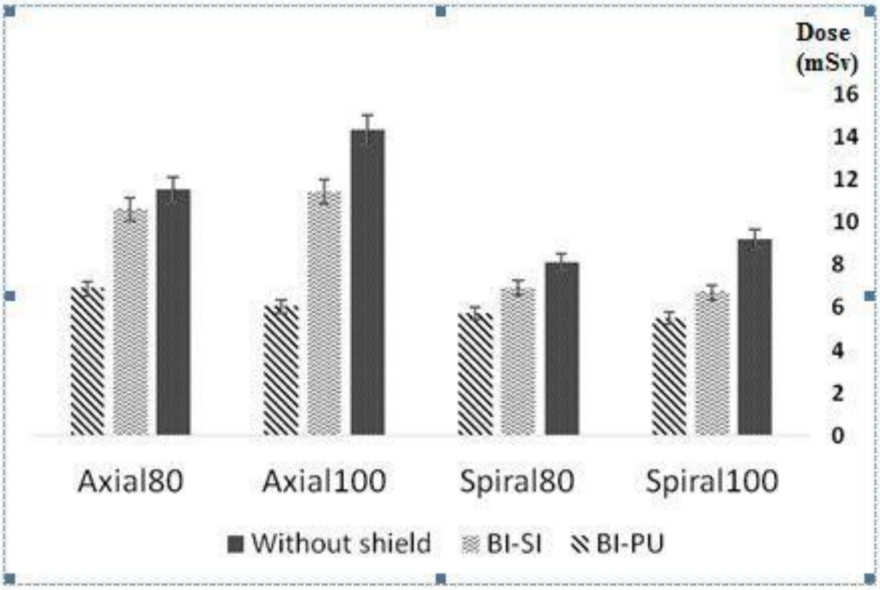

Fig.3: Breast dose in SDCT by Axial/spiral mode at 80 and 100 mA, 120 kV with and without shielding.

In MDCT, spiral mode and 100 mAs induced a higher breast dose, while a lower dose was seen at 80 mAs by axial mode (Figure 2). The highest SRF (2.02) for Bi-PU was at 100 mAs, axial and spiral modes, and a lower SRF (1.35) was observed in the axial mode, 80 mAs for Bi-Si. This indicates that, at axial mode, 100 mAs, Bi-PU causes 50% breast dose reduction in comparison to Bi-Si that causes 40% dose reduction (Figure 4).

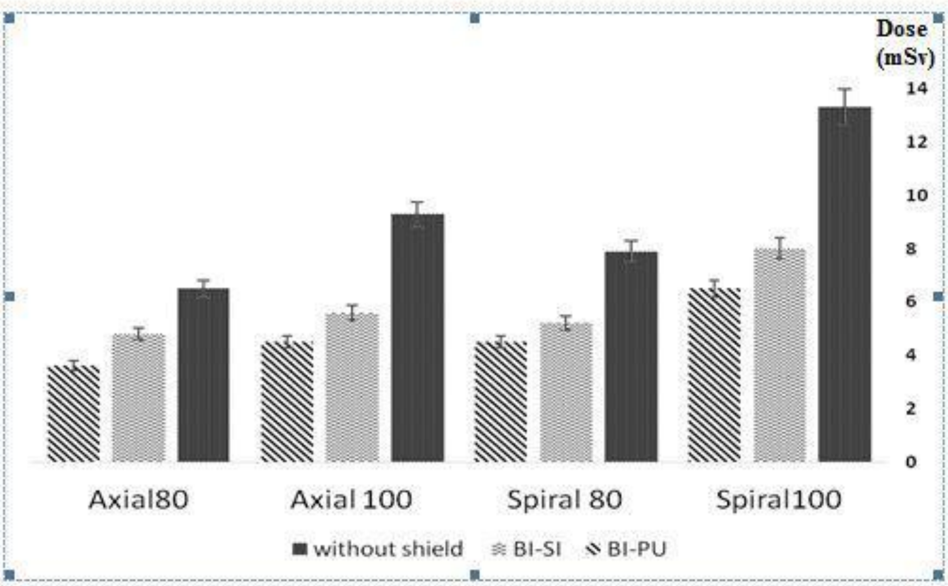

Fig.4: Breast dose in MDCT by Axial/spiral mode at 80 and 100 mA, 120 kV with and without shielding
Mean noise increased 21.07% (from 6.29 to 7.97 HU) with Bi-Si shield and in the case of Bi-PU shield 13.81% (from 6.49 to 7.53 HU).

DISCUSSION

Managing x-ray dose in chest CT tests is of great importance, since photon-sensitive organs such as the breast are directly exposed when such tests are performed. Meanwhile, breast cancer is one common and deep concern. As a result, when it comes to x-ray imaging procedures, the protection of the breast gains inevitably paramount importance.

This study argued for the fact that the two composites of Bismuth Silicon (Bi-Si) and Bismuth Polyurethane (Bi-PU) are effective in the reduction of breast dose during chest CT.

The linear attenuation coefficient of Bi-PU was seen to be higher than Bi-Si shield. However, the attenuation coefficient decreases in both types of shields when the voltage increases from 80 to 100 and 120 kV. This is an indication that increasing tube potential leads to penetrability of the x-ray, which, in turn, makes for increases in its power to pass through shields. Bismuth shields have much lower attenuation coefficient in comparison to lead, but lead shields cause image noise and omission of information of interest when the organs are placed under the shield in CT scanning field. Also, lead in CT field of view induces higher dose if automatic mAs was used which is often the case in conventional CT. Bismuth -Silicon and -Polyurethane shields have the attenuation coefficient of 1-2 cm^{-1}. Thus, as an important advantage, these shields allow highest energy photon spectrums to pass, although low energy photons that are important sources of superficial and skin absorbed dose and do not contribute to creating the image were eliminated by the shield.

In this paper, we talked about SRF which can be used to compare shields effectiveness in different shields materials, as well as the ability of the shield for radiation protection. When the breast was shielded by Bi-Si and Bi-PU at spiral mode, 100 mAs, SRF was 1.25 and 2.31, respectively.

In this research, first the role of scanning parameters such as tube current, scan mode and scanner type were studied in breast dose reduction as shown in Figure 2. Data showed that, in the axial mode, the breast received higher dose than in the spiral mode in SDCT; however, in MDCT spiral mode, 80 or 100 mA induced higher dose to the breast. In both detectors, increasing tube current has a direct effect on the breast dose increasing. Also, the selection of the scan protocol modes for the delivery of lower dose to the breast in chest CT is dependent on CT detector as well as mA.

In study of 64 MDCT angiography by axial/spiral modes using bismuth shield, a higher dose was reported for spiral mode, which was in agreement with our data at 16 slicer (Einstein et al., 2012). Also, they presented maximum reduction for breast dose (51%) by bismuth shielding. This study showed that the amount of absorbed dose of breast in multi-slice devices based on spiral mode is higher than in the axial one. This increase took place in order to obtain helical data from the first and last slices, requiring additional information at the end of imaging volume, so that each additional rotation leads to dose increase compared with the one-slice scanner (Lewis 2005). This subject is also considered another reason for increasing dose in multi-slice scanner compared to single slices beside its other advantages in particular in term of image quality; meanwhile, the increase in bandwidth (volume and field of scanner) is more than in the case of the single-slice one especially in effective dose (Dougenia et al., 2012).

Breast dose in 16 MDCT has been reported with a decline of 26% using bismuth shield (MDCT axial mode 80 mAs), which was the lowest breast dose reduction in our studied references, but it has been demonstrated that if tube current modulation is used within bismuth shields, the breast dose reduction will be up to 52% (Coursey et al., 2008); this variation in breast dose reduction has obtained by 80 mAs with our data too.

Bismuth shield, in pure form or mixed with other metals, are used for breast radiation protection, but the details of shield components have not been fully explained in the literature. Also, bismuth polymer composite shields, referred to as Bismuth Silicon and Bismuth Polyurethane, have not been used in previous studies. This study introduced Bi-Si and Bi-PU shields for breast protection during chest CT.

A comparison between Bi-PU and Bi-Si shields with MDCT showed a decrease of the breast dose in the vicinity of 43-55 % and 26-40 %, respectively. This decrease, in addition to dependence on tube current, scan mode and scanner type, was significantly associated with Bi-Si and Bi-PU shields, as held up by SRF.

Evaluating the results of axial and spiral scanning modes, as well tube current modulation at 16 MDCT, indicates that in both modes, the highest dose reduction of the breast was with Bi-PU shield; at the axial mode and at 80 mAs and 100 mAs, it was about 43% and 55%, respectively.

Yilmaz et al. evaluated the effect of Bismuth shield at coronary arteries imaging with 16-MDCT, 120 kV, where the amount of breast absorbed dose was reduced 37 %, while no difference was observed between shielded and unshielded image of lungs (Yilmaz et al., 2007). In the present study that had a similar imaging condition to Yilmaz et al.'s study, the decline of breast dose using Bi-Si shield was similar (37%), while using Bi-PU shield resulted in a higher percentage of reduction, i.e. 43%.

Parker et al. estimated the amount of absorbed dose of breast 14-20 mGy; in chest CT, 16-MDCT helically, 120 kV, 130 mAs when using Tungsten,

Antimony shield led to 56-61 % reduction of breast dose (Parker et al., 2008).
Another study presented dose of breast at 16-MDCT in chest CT helical scan, 80 and 60 mAs, 120 kVp, which was 5.3 and 4.1 mGy when using Bismuth shield; the decrease in breast dose was up to 3.7 mGy (Patrick et al., 2013). However, this study showed that using Bismuth shields is more effective than decreasing the dose by tube current. Furthermore, the present study confirmed the efficiency of Bi-PU and Bi-Si shields in comparison to tube current modulation. Nonetheless, if they are used simultaneously, they will lead to a better protection result. In this study, simultaneous with using current reduction, Bi-Si shield is able to decrease breast dose up to 53.4%. Also, using Bi-PU shield leads to a percentage of 59.7 in spiral imaging method. Simultaneous use of current reduction and Bi-Si shield is able to decrease breast dose up to 37.7%; meanwhile, using Bi-PU shield leads to a percentage of 53.3% for the absorbed dose of breast in axial imaging method.
There is an ongoing debate among the researchers about the existence of noise using bismuth shield in CT imaging. Fricke et al. showed no increase with the use of bismuth shielding in patients' images (Fricke et al., 2003). Also reported was preservation of image quality in CT with shielding (Midgley et al., 2012). Another study showed increases in image noise and increasing attenuation values as well as image noise (Kalra et al., 2009; Geleijns et al., 2006). In this study, the problem of the artifact and invisibility of under-shielded organs was improved by selecting an optimum foam between the shield and the breast. The foam size was 6 mm and 10 mm for Bi-Si and Bi-PU, respectively. The image with two shields was acceptable in chest CT observed by two expert radiologists. Therefore, Bismuth composite shields are recommended, especially in young women and children, because low energy photons of poly energy spectrum of x-ray are usually absorbed in surface organs and the existence of Bismuth shields causes decreases in breast dose and improvements in the visibility of the organ under the shield in comparison to lead shields
Overall, this research introduced Bismuth-Silicon and Bismuth-Polyurethane shields which are new composites, light and economical, and offer other advantages. Also, scanning factors such as mA, modes and detectors are studied within the new shields.

CONCLUSION

This study showed that Bi-Si and Bi-PU shields have a good potential for breast dose reduction and SRF is benefit factor for showing shields dose reduction ability during chest CT in spiral and axial modes at 80 and 100 mAs, single and 16 MDCT. This decline was seen to be more with Bi-PU, 100 mAs and 16 MDCT.

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