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Theoretical Simulation of Improved Light Materials as a Shielding Apron for Medical Staff in Nuclear Medicine

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Abstract

Background*: Protecting medical stuff from different hazards is very important, especially those who are working in the nuclear field. So, this study is a trail to prepare light new composites materials used in making shielding apron against gamma and X-rays, and reduce the physical stress caused by wearing traditional lead aprons.*

Materials and methods: *The suggested new composite contains different elements such as Bismuth (Bi), Tin (Sn), Samarium (Sm), Antimony (Sb), and Tungsten (W) in certain proportions it is supposed to have lower density and toxicity than the common used aprons materials. To examine the suggested composite, human phantom has been simulated to the human body with geometrically approximated organs and tissues. The absorbed dose for each organ of the body has been evaluated, using simulation (MCNP-5) Mont Carlo Code and information of their respective chemical compositions. The effect of the apron thickness on the equivalent emitted photons from 120 mCi using* ^{131}I *source has been calculated. Also, a comparison between the suggested apron and the commonly used lead apron on the effective dose reduction, mass attenuation coefficient and heaviness % are calculated.*

Results: *Two of the prepared compositions have a better attenuation ratio compared to the lead shield with similar thicknesses. The effective dose values for workers using light materials shields were nearest to the values of the lead shield.*

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Conclusion: *The last results are encouraging the recommendation of two suggested composites to be used as shielding aprons.*

Keywords: Light materials, Shielding apron, Monte Carlo Simulation, Effective dose reduction, Medical staff.

INTRODUCTION

Due to the use of radiation in many fields such as industrial, medical and agricultural, etc. So, the γ- radiation penetration through matter depends on the photon energy and the nature of absorbing material (1). Gamma radiation can change biological particles through direct or indirect mechanisms (2). The parameter of attenuation coefficient is very important to study the interaction of radiation with matter that gives us the portion of energy scattered or absorbed (3). So that it is necessary to study different parameters related to the interaction of γ-ray with shielding material, and experimentally obtained the gamma-ray shielding parameters such as linear and mass attenuation coefficients to know the effectiveness of the materials as the gamma-ray shielding.

Ionizing radiation and its impact on health are one of the great concerns to the health concern people nowadays (4). While working with the ionizing radiation, the protection of living organisms and sensitive equipment against the hazard of radiation is crucially needed. This protection can be done in terms of the dosimetry and/or shielding against ionizing radiation. Shielding an experimental setup containing radioactive sources, with a suitable transparent shielding material will protect the experimenter personnel from the hazard as well as preventing the experiment results from environmental interference, without losing the visual contact. Photon-matter interaction parameters such as linear and mass attenuation coefficients can provide some information to evaluate the performance of the radiation shielding materials (5,6). Also, the use of X-ray and different forms of ionizing radiation has increasingly increased over the years for radiological investigation (7)

The aprons are usually used for the protection of workers against primary and scattered radiation throughout diagnostic imaging and treatment (8). Lead is that the most typically used material in coming up with protecting aprons for medical staff. It has been used at some of the nuclear medicine centers, and excellent results have been obtained, however, the 0.5 mm thickness of the lead apron is about the weight of 9 kg, therefore this loading on the spine and standing could result in back pains (9). Besides, lead could be a toxic substance and it is suggested to be substituted if it is possible. In nuclear medicine procedures, it is nearly impossible to measure the organ radiation dose directly using any kind of radiation detector. Instead, this needs to be calculated by using a variety of physical and biological data and mathematical equations specially developed for this purpose (10). An applied technique of accurate organ dose valuation is to use Monte Carlo (Mird) methods to calculate the organ doses (11-13). Heavyweight metal elements (high Z materials) such as tungsten and composites of this material are traditionally used for protection against x-rays or γ rays as a result of their higher mass density. Low poisonous character makes tungsten a convenient candidate for the materials of lead-free shielding (14). Shielding helps to lower the dosage of vital organs (15). Without using the apron shields, direct and secondary exposure to radiation would possibly result in biological damages in healthy tissues.

The purpose of this study is to present some lead-free based materials for the medical apron as radiation attenuators that have less weight and toxicity as compared with lead and valuation of their attenuation characteristics within the diagnostic radiology. During this study, five different types of apron contain completely different elements Bismuth (Bi), Tin (Sn), Samarium (Sm), Antimony (Sb), and Tungsten (W) in certain proportions that have less density and toxicity as compared with lead (Pb) have been studied. The MIRD-5 type human phantom has simulated using MCNP-5 Mont Carlo Code that represents the human body with geometrically approximated organs and tissues and information of their chemical compositions have been used to assess the absorbed dose organs of the body.

MATERIALS AND METHODS

- *Theoretical methodology*

Absorbed dose is the concentration of energy deposited in tissue as a result of exposure to ionizing radiation. While Equivalent dose is the absorbed dose to an organ, adjusted to account for the effectiveness of the type of radiation, it can be considered as shown in equation 1(16):

$$H_T = \sum_{\gamma} \omega_{\gamma} \times D_{\mathrm{T},\gamma} \qquad (1)$$

Where ω_{γ} isthe radiation weighting factor (for X-ray and gamma- ray = 1) and $D_{\mathrm{T},\gamma}$ is the mean dose of incident radiation of type γ absorbed by the organ or tissue T(16). Also, Effective Dose is the equivalent dose to the organ times the appropriate tissue weighting factor, it can be considered as shown in equation 2(17):

$$E = \sum_{T} \omega_T \times H_T \qquad (2)$$

Tissue weighting factors (ω_T) in ICRP 2007 were listed in Table 1.

Table1. Tissue weighting factors (ω_T) according to ICRP 103 (ICRP 2007) (18).

Organ	**Tissue weighting factor ω_T**	**Σ ω_T**
Redbone marrow, Colon, Lung,	0.12	0.72
Stomach, Breasts, Remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, Esophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04
Total	1.00	

* Remainder tissues: Adrenals, Extra thoracic region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate, Small intestine. Spleen. Thymus. Uterus cervix.

- *MIRD phantom models*

The Medical Internal Radiation Dose (MIRD) Committee phantom (the original model) is a heterogeneous mathematical representation of the human body that was first designed to calculate absorbed doses from radiation. The MIRD phantom is analytically defined in sections: an elliptical cylinder represents the arms, torso, and hips; truncated elliptical cones represent the legs; and an elliptical cylinder represents the head and neck. The arms are not separated from the torso. No models have been adopted for small organs (e.g., nose, ears, feet, and fingers) (19). Computational human phantoms, which can be compiled by the Monte Carlo code, have been used to evaluate the absorbed dose to tissue and organs of the body. The phantom is adjusted to include all major organs as shown in Figure 1.

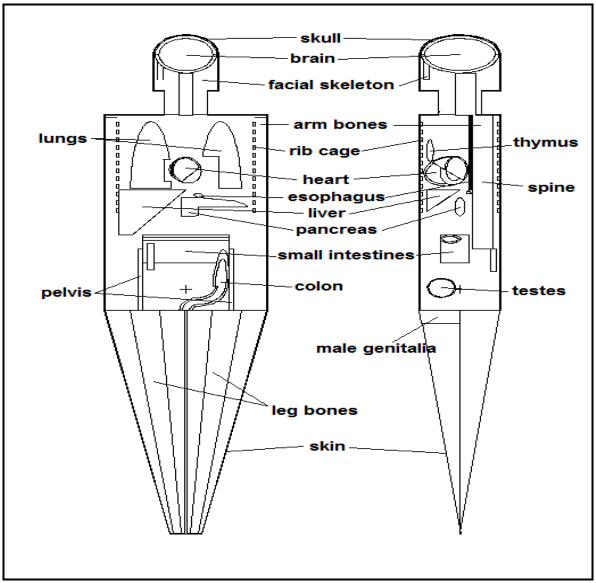

Figure 1: Diagram of the MIRD phantom

- *MCNP-5 modeling and simulation*

In this study, the MCNP-5 model was used to assess the attenuation effect of shielding materials of aprons. Geometry in the model is constructed with cells, surfaces, materials data, and tallies card. To simulate the problem with MCNP-5, an input file must be prepared which includes information about the materials specification, the characteristic of geometry and choice of cross-section assessments, the location and features of the source, the kind of answers or tallies desired, and any variance reduction methods used to increase efficiency (20). Absorbed dose in each organ is quantified individually using F4 tallies. The F4 tallies, which give results in (μGy) were later converted to (μSv/hr) with the tally multiplier card (FM card). The simulation was done for 10^6 particles and relative error was decreased to <0.001 for each organ. The absorbed doses are then converted to an effective dose rate (μSv/hr).

- *Samples preparation*

Monte Carlo simulations in the MCNP-5 code have carried out to compare the lead apron with five new aprons which contain new composition materials as shown in Table 2, for simulating of each apron the mass attenuation coefficients, heaviness%, transmission doses%, the effective human organ doses and the effective dose reduction% against gamma radiation have been calculated.

Table 2. The elementals composition and weight fraction percentage of each element for five aprons

Apron name	Weight fraction %				
	Bi	W	Sm	Sn	Sb
S1	90	10			
S2	91	4	3	1	1
S3	90	5	5		
S4	90		10		
S5	90		5	5	

Our simulation code has used I-131 radioactive source with activity 120 mCi (energy 364 KeV) at 90 cm distance from MIRD phantom with the apron, for 0.5 and 0.8 cm thickness of apron as shown in Fig.2.

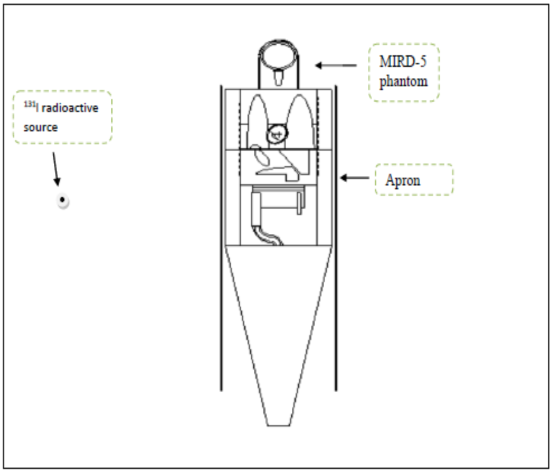

Fig. 2 The schematic diagram of the simulated MCNP5 code with MIRD-5 phantom wears an apron.

RESULTS

- *Heaviness%*

Because it is important in our study to focus on the heaviness of the apron, to reduce physical stress caused by wearing lead aprons, lead was assumed as standard and normalized to 100%. With reference to lead, the % of the heaviness of the other aprons shielding materials have been evaluated using equation 3(21), and plotted in Fig. 3.

$$\% \text{ of heaviness} = \frac{Densityofnewapronshield}{Densityoflead} X100\% \qquad (3)$$

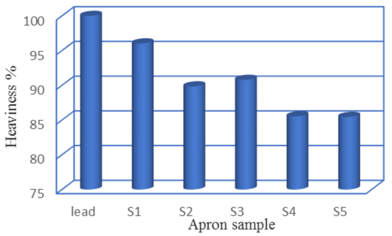

Fig. 3 The heaviness % of the new apron composition comparing with lead apron

- *Mass Attenuation Coefficient*

Although the new apron compositions are lighter, but this is not enough to consider them to be better than the lead apron. It is very important to compare between their efficiency to absorb gamma energy represented by mass attenuation coefficients (μ_m). MCNP-5code has been used at energies ranging from 0.03 to 0.7 MeV to calculate μ_m as shown in Fig. 4. To more accurate test for these new aprons, we need to compute the dose transmission% for all five aprons with 0.5 cm and 0.8 cm thickness at energy 364 KeV by using equation 4 and plot it in Fig. 5:

$$\text{Dose transmission } \% = \frac{Dosewith\ apron}{Dosewithoutapron} \text{ x } 100\% \qquad (4)$$

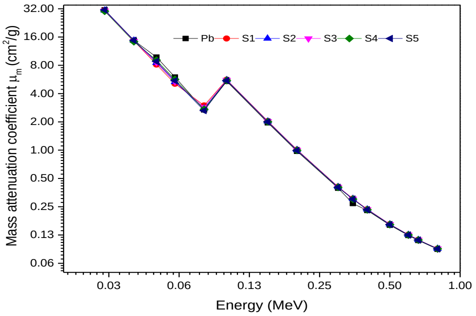

Fig.4 The mass attenuation coefficients of lead and the new composition of an apron

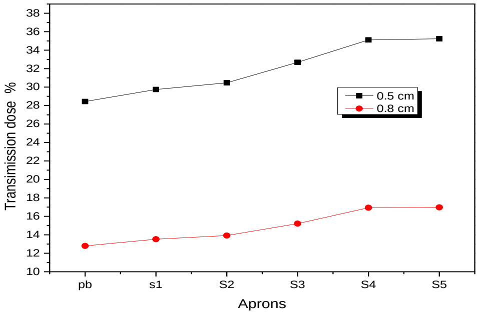

Fig. 5 The transmission dose % for all studied aprons composition at 0.5 and 0.8 cm thickness

- *Effective Gamma Dose*

The results of absorbed radiation doses for some organs of the worker are obtained by using the MCNP-5 model with F4 and Fm4 commands tallies for lead and the new apron materials with 0.5 cm and 0.8 cm thickness at 364KeV. These values are multiplied by a gamma weighting factor (=1) to signify the equivalent dose. The effective organ dose, which is the individual equivalent organ dose multiplied by the respective tissue weighting factor, are listed in Table 3 and 4 using 0.5 cm and 0.8 cm thickness respectively.

Table 3. The simulation effective gamma doses from MCNP-5 for some human organs by using lead and new aprons with thickness 0.5 cm at 364 KeV

Organs	Effective does (μSv/h)							
	ω_T (ICRP2007)	Without an apron	With an apron of 0.5 cm thickness					
			Lead	S1	S2	S3	S4	S5
Liver	0.05	3.84	1.07	1.10	1.13	1.19	1.28	1.29
Stomach	0.12	16.35	4.31	4.44	4.56	4.80	5.22	5.23
Lung	0.12	16.97	4.62	4.75	4.88	5.16	5.59	5.60
Spleen	0.05	13.27	3.53	3.65	3.76	3.97	4.30	4.31
Pancreas	0.05	5.16	1.40	1.43	1.45	1.58	1.65	1.67
Kidney	0.05	4.79	1.25	1.29	1.31	1.37	1.48	1.48
Bladder	0.05	0.87	0.20	0.21	0.21	0.22	0.24	0.25
Testes	0.12	10.34	2.38	2.47	2.57	2.77	3.12	3.18

Table 4. The effective gamma doses from MCNP-5 for some human organs by using lead and new aprons with thickness 0.8 cm at 364 KeV

Organs	Effective does (μSv/h)							
	ω_T (ICRP2007)	Without apron	With an apron of 0.8 cm thickness					
			Lead	S1	S2	S3	S4	S5
Liver	0.05	3.84	0.47	0.49	0.50	0.56	0.62	0.63
Stomach	0.12	16.35	1.82	1.93	2.00	2.22	2.53	2.54
Lung	0.12	16.97	2.06	2.16	2.24	2.44	2.77	2.78
Spleen	0.05	13.27	1.52	1.60	1.68	1.84	2.06	2.08
Pancreas	0.05	5.16	0.55	0.58	0.61	0.71	0.81	0.82
Kidney	0.05	4.79	0.54	0.59	0.60	0.67	0.76	0.76
Bladder	0.05	0.87	0.09	0.09	0.09	0.10	0.12	0.12
Testes	0.12	10.34	0.76	0.79	0.82	0.90	1.06	1.10

To additional validate the efficiency of the aprons compared to the lead apron, the effective dose reduction % have been calculated for each studied organ at different apron shield with 0.5 cm and0.8 cm thickness as represented in Fig. 6 and 7, by using the equation 5:

$$\text{Effective dose reduction\%} = \frac{(effective\ dose\ without\ apron - effective\ dose\ withapron)}{effective\ dose\ without\ apron} X100 \quad (5)$$

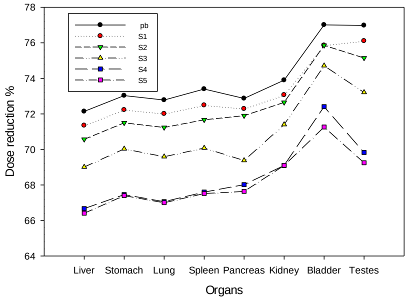

Fig.6 The reduction doses % for different organs due to the uses of different our studied apron at thickness 0.5 cm

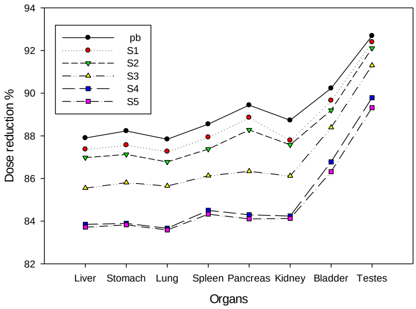

Fig. 7 The reduction doses % for different organs due to the uses of different our studied apron at thickness 0.8 cm

DISCUSSION

As shown in Fig. 3, all new aprons are lighter than the lead apron. S1 is the heaviest one from new aprons and close to lead sample, while S5 is the lightest one and the best materials that can be used for the apron relative to the %heaviness.

From Fig.4, the value of μ_m for all five aprons with gamma energy ranges from 0.03 to 0.7 MeV, which is near to the values of the lead apron. All new composition materials of the apron are suitable to be used. The standard deviation of μ_m for each apron tends to decrease with increasing gamma-ray energy. A low-energy, gamma-rays are typically attenuated by photoelectric absorption in the medium of the interaction. In different words, considering photoelectric absorption is proportional to $Z^{4\sim5}$(22). The μ_m for low energy can differ significantly if the effective atomic numbers vary from one element to another, even if they are of the identical type. It can be noted that the resonance absorption peaks are present in all μ_m, which are called photoelectric absorption edges at around 100 KeV. Therefore, in the low-energy area where photoelectric absorption dominates, materials have the maximum mass attenuation coefficients, while mass attenuation coefficients decrease as the energy enlarged.

We can be noticed from Fig.5 that, the dose transmission% for all aprons at 0.5 cm thicknesses is higher than values at 0.8 cm thicknesses. The values of transmission dose% for all aprons are ranged from 28.5% to 35.5% at 0.5 cm thickness and from 12.7% to 17% at 0.8 cm thickness. So, the variation in thickness from 0.5 to 0.8 cm decreases the dose transmission% by about 15.8% to 18.5%.

It's clear that, by knowing the transmission dose % values, the aprons S1 and S2 are found to be the best radiation shielding material. Heaviness % values explained that apron S1 and S2 are lighter than the lead apron by 4% and 10% respectively.

To verify the results of the MCNP-5 simulation, its results and practical measurements of equivalent radiation doses at the same distances from the radioactive source I-131 with activity 120 mCi have been compared, first without the presence of the apron and second directly behind the apron with a thickness of 0.5 and 0.8 cm as shown in Table 5. The practical measurements have done by using RadEye G-10 with red label personal dose rate meters.

Table 5. The comparison between simulated and experimental equivalent gamma doses.

Dose (μSv/h)	Simulate data	Experimental data	Deviation %
Without apron	122.4	119.1	2.696078
Behind lead apron of 0.5 cm thickness	34.2	32.5	4.970760
Behind lead apron of 0.8 cm thickness	15.7	14.7	6.369427

The deviation% values validate that the results of the simulation MCNP code are near to the experimental values. To have more accurate knowledge about the effectiveness of these aprons in shielding the effective radiation dose for different human argons have been calculated. The results reported in table 3 and 4, showed that the effective doses for aprons with thickness 0.8 cm are less than 0.5 cm thickness; we observed that the value of effective doses for aprons nameS1, S2, and S3 are nearest to the value of lead apron. The effective dose of the lung was the highest followed by the Stomach, the Spleen, and the minimum value at the Bladder. The difference of effective dose values for different human organs is due to the difference between them in size and materials contain used in MCNP-5 and the main reason is a difference in their tissue weighting factors.

From Fig.6, which represented dose reduction% with aprons at 0.5 cm thickness, we noticed that dose reduction% values are approximately from 72.14 % to 77.01% for the lead apron, while apronsS1 and S2 are closed to the value of lead apron and values of dose reduction % for other are approximately from70.57% to 76.11%. While in Fig.7, the dose reduction % values with aprons at 0.8 cm thickness are approximately from 88% to 93% for the lead apron and apron name S1 and S2 are closed to the value of lead apron, and values of dose reduction% for all other aprons are approximately from 84% to 89%.

CONCLUSIONS

The importance of our study is based on the importance of wearing a protective apron and providing new lighter types of aprons to reduce the risk of exposure to gamma- rays and their possibility of developing cancer. Also, some medical staff stays for long time near the injected patient for helping him to be on the bed of the gamma camera room or in other medical examinations. This increase in the danger of absorbing more radiation doses. A comparison between organs' effective gamma doses for medical staff using MCNP-5 simulation code without wearing an apron and with different aprons compositions. Also, the attenuation coefficients for all aprons comparing these with a lead apron and the heaviness% have been determined.

The heaviness% of S1 and S2 are 96% and 90% respectively, while the other aprons are lighter than lead, but the other parameters showed that the apron S1 and S2 are better than the others. They can reduce the dose transmission% and the effective doses to the human organs. While the mass attenuation coefficients are not enough in this comparison. But the other aprons S3, S4, and S5 are suitable for low-energy X-rays. Therefore, with increasing aprons thickness, the dose received by each organ is reduced, but the choice of a suitable apron depends on the x-ray or gamma energy.

From the results, it can be concluded that materials with lighter weight than lead can be suitable as alternatives for lead apron shields.

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