Investigation of the Efficiency and Quality of Lightweight Gowns with Multi-Layered Nanoparticles Compositions of Bismuth, Tungsten, Barium, and Copper

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ABSTRACT

Background: Radiation protection plays a key role in medicine, due to the considerable usage of radiation in diagnosis and treatment. The protection against radiation exposure with inappropriate equipment is concerning.

Objective: The current study aimed to investigate the efficiency and quality of the radiation protection gowns with multi-layered nanoparticles compositions of Bismuth, Tungsten, Barium, and Copper, and light non-lead commercial gowns in angiography departments for approval of the manufacturers' declarations and improve the quality of gowns.

Material and Methods: In this case study, physicians, physician assistants, radiology technologists, and nurses were asked to wear two commercial and proposed gowns in the angiography departments. Dosimetry of personnel was conducted using a Thermoluminescent Dosimeter (TLD) (GR-200), and the radiation dose received by personnel was compared in both cases. The participants were asked to fill out a questionnaire about the quality and comfort of two radiation protection gowns.

Results: However, both gowns provide the necessary radiation protection; the multi-layer proposed gown has better radiation protection than the commercial sample (2 to 14 percent reduction in effective dose). The proposed gown has higher flexibility and efficiency than the commercial sample due to the use of nanoparticles and multi-layers (2.3 percent increase in personnel satisfaction according to the questionnaires).

Conclusion: However, the multi-layer gown containing nanoparticles of Bismuth, Tungsten, Barium, and Copper has no significant difference from the non-lead commercial sample in terms of radiation protection, it has higher flexibility and comfort with more satisfaction for the personnel.

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Keywords

Radiation Protection; Lead Gowns; Nanoparticles; Thermoluminescent Dosimeter; Angiography

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Introduction

X-rays are widely used in medical procedures, such as imaging, particularly in orthopedic and spine surgery, and X-ray-based imaging with high quality considerably affects precision surgery [1]. Ionizing rays are used for diagnosis and treatment in different departments, such as radiology, Computed Tomography (CT) scans, fluoroscopy, and nuclear medicine. However, radiotherapy and chemotherapy use radiation only for treatment, radiation can be also used for diagnosis and treatment in nuclear medicine and cardiac angiography. Ionizing-radiation diagnostic fields have had a 21% increase in employment since 2012, which is faster than the average for all occupations [2]. Non-invasive and semi-invasive techniques under fluoroscopic control are recently developed to minimize injuries due to invasive procedures [3]. However, exposure to ionizing radiation is considered a well-established occupational hazard, its damaging effects are also studied experimentally and epidemiologically. In addition, ionizing-radiation effects are classified as random or deterministic events. Therefore, the use of ionizing rays causes to consider protection seriously for the medical community and patients' health [1].

However, spine and cardiac angiography surgeons are not directly exposed to radiation, they are chronically exposed to scattered radiation due to the proximity to the patient and the radiation source. Additionally, the prevalence of minimally invasive techniques results in increasing the radiation dose in the operating room, leading to the harmful effects of radiation, such as eye tumors, thyroid disorders, solid malignant neoplasms, and leukemia for the surgical team [4, 5]. The radiation exposure of surgeons and surgical personnel decreases based on the following methods: 1) protective materials and 2) reducing X-ray exposure, by the As Low As Reasonably Achievable (ALARA) principle by decreasing the use of fluoroscopy, increasing the distance from the source, and the direction of radiation [6].

Lead aprons can protect medical and interventional imaging unit staff due to their high atomic number (Z), density, and photoelectric absorption [7]. A total of 0.5 mm lead can absorb scattered photons of diagnostic X-ray imaging. Further, the lead is easily molded into various shapes for use in protective clothing [8, 9]. For individuals at risk of X-ray, 4 kinds of lead shielding are available as follows: two-piece gowns, one-piece gowns, one-piece gowns with hip/waist belts, and one-way gowns only for the front of the body. High-risk individuals must always wear lead aprons since radiation exposure is intermittent and random during procedures. For example, staff with single-sided gowns must walk "crab-like" around the fluoroscopy machine to keep shields in the correct position, leading to receiving a dose. On the other hand, in two-piece suits, the distribution of the load between the shoulders and hips can reduce pressure on the neck, shoulder, back, and spinal structures [10, 11]. However, increasing the thickness of lead can increase protection due to decreasing beam transmission, the defects of the lead gowns also affect protection. Most of the lead gowns (68.2%) are defective in hospitals [12, 13].

The use of lead is recently reduced due to its toxicity, which is a concern in the world. Also, the toxicity of lead varies with the level of exposure; pure lead is absorbed and affects almost every part of the body, such as the cardiovascular, nervous, digestive, blood, endocrine, and kidney systems.

The European Union banned the use of lead in healthcare in Europe in July 2014 [2]. The heavy weight of lead gowns is considered a problem, resulting in physiological disorders, such as neck/shoulder and back pain. Moore et al. reported that back pain correlated to weight lead apron radiologists [10], which is consistent with those of Andersson et al. [14], showing excessive lead aprons can cause back pain in radiologists. Moreover, most personnel of interventional radiation departments suffer from back, neck, and shoulder pains when using lead gowns during examination and surgery [15].

Nowadays, gowns called "lightweight" are commercially available, with significantly less weight and more attenuation power than traditional gowns [16]. Furthermore, lightweight gowns are recently made from alternative sorbents (with lower atomic numbers) in combination with lead, and their manufacturers claim that attenuation characteristics are equivalent to lead. The “lead-equivalent” parameter is not clear since the properties of photon attenuation are significantly different during the energy spectrum for all materials, such as lead; the largest changes are in the diagnostic imaging range (70-120 kVp) [17, 18]. Most radiologists, who work with interventional methods, do not know that weight reduction for the protective gown can only be achieved in the range of kVp, and the photon energy and the duration of wearing is a potential trade-off between weight and radiation protection [9, 18].

A lead gown is mostly used to protect medical personnel from scattered radiation, which is produced by patients. The quality of the scattered radiation is hard to investigate due to its dependency on the quality of the initial X-ray radiation (kVp and filtration), varying from fluoroscopy to Digital Subtraction Angiography (DSA) considerably [18]. The personal dosimeters can investigate and validate the effectiveness of protective gowns using tracking of doses. Two personal dosimeters (based on the recommendation of the ICRP) can optimize the doses measured under the gown and compare them to those on the gown, resulting in radiological protection [19].

The current study aimed to compare two commercial and proposed gowns based on two methods: ICRP criteria, i.e., one dosimeter on the gown and another under the gown, and designing a questionnaire after using the gowns.

Material and Methods

In this case study, four internist specialists in the angiography department of Al-Zahra Shiraz Heart Hospital participated. All the nursing and radiology personnel were asked to participate in this study due to their rotational working shifts. The participants were completely explained how to use radiation-protection aprons and dosimetry requirements by the researcher. Also, all participants signed the informed consent.

Two gown models, approved with Iran’s radiation protection standards, were provided for the participants to use in turn during some specific angiography or angioplasty tests. The garments used in two investigated apron models is shown in Table 1. The gowns were numbered without the name of the manufacturing company and their materials.

All tests were performed by a digital system, C-arm single tube, and tube under the bed - flat plate (Philips AlluraClarity - Philips manufacturer in Eindhoven, the Netherlands). In the operating room, the monitor showed the angle of the tube towards the head or foot, the Right and Left Anterior Oblique (RAO/LAO), the rate of absorbed dose of the patient, and the dose depth at the moment of fluoroscopy or recording the image. In the control room, monitors showed time, the absorption dose rate of the patients, cumulative absorbed dose, and radiography technique for fluoroscopy and image recording, number of views, angles of view, time of each view, depth for recording each view, and technique used during record-

Table 1: Description of garments used in 2 investigated apron models, including composition of garment and lead equivalence values

Garment number	Material composition	Design	Condition	Lead equivalence: front panel (mm Pb)	Lead equivalence: back panel (mm Pb)
1	Bismuth, Antimony, Tungsten	Vest & Skirt	Light (6.35 kg)	0.5	0.25
2	Copper, Bismuth, Barium, Tungsten	Vest & Skirt	Light (6.4 kg)	0.55	0.3

ing, showing each view with the number of its frames.

For personnel dosimetry, TLD chips (model 200GR- (LiF: Mg, Cu, P) Made in the RadPro International GmbH company based in Germany), placed in plastic bags with disc shapes were used, and a Cesium-137 source was used for calibration. Also, heating (TLD Annealing Furnace model No 168-001 USA) was done in Shiraz University Radiation Research Center laboratory. The TLD reading device (RE 2000A - TLD reader model 1235-138 Sweden) was used to read TLDs in the laboratory of the Medical Physics Department of Shiraz University of Medical Sciences. The doses under and on the aprons of the physician assistants, nurses, and radiology technologists were calculated with certain TLDs for one working day in the cath lab, and the tests were planned on that day. Also, this process was repeated for each participant wearing once aprons 1 and 2 during on working days when the personnel could cooperate.

Computing TLD Correction and Calibration Coefficient

The GR-200 TLDs were firstly arranged on a steel tray, heated to empty in an oven at 240 °C for 10 min, irradiated with Cs^{137} at a rate of 5 mGry, and read with TLD reader to compute the correction factor of the TLD 110. Moreover, TLDs were heated again for calibration and dosimetry for 10 min at 240 to 250 °C, categorized, calibrated, and numbered to evaluate hand and foot dose (Hp (0.07)) and effective dose (Hp (10)); this procedure was conducted twice for each TLD to compute and average Element Correction Coefficient (ECC). Finally, the total average and correction coefficients were computed as follows [20]:

$$TV=SR/NTLD \qquad (1)$$

where TV, SR, and NTLD show the total average, the sum readings of all TLDs, and the number of TLDs, respectively [20].

$$CF=TN/TV \qquad (2)$$

where CF, TN, and TV describe the correction factor, total nanocoulomb for each TLD, and total average, respectively.

The TLDs should be calibrated based on energy after computing the correction factor for dosimetry. Two TLDs were also placed in the recovery room to measure the background dose, which was then subtracted from all TLDs.

The TLDs were irradiated based on the absorption dose proportional to the used techniques for cardiac angiography. The plastic badges were prepared; the plastic badges were installed on (in the chest area) and under (in the waist area) aprons of the physicians, and they were also installed just under (in the chest area) aprons for assistant circular, nurse, and radiology experts. TLDs were changed daily for each person.

In the present study, a personal dosimeter shows two values for every participant, including Hp (0.07) and Hp (10), showing the equivalent dose in soft tissue at a depth of 0.07 and 10 mm of the skin surface for the skin and depth dose, respectively. The Hp (0.07) is read from a dosimeter installed in the collar area on the apron or lead shield of the thyroid, showing the dose of the skin, hands, and feet without any protection. The Hp (10) is read from the dosimeter installed in the chest area under the lead apron, presenting the effective dose of the person.

The formula to calculate the effective dose (E), dependent on the dosimetry method is used in each department and the radiation protection organization of each country. According to the 85^{th} and the 122^{nd} reports of the International Commission on Radiation Protection and the American National Radiation Protection Assembly, respectively, the two-bag method is used for occupational dosimetry to accurately evaluate the dose of the personnel in the interventional radiology departments [20]. Therefore, two TLDs were used to calculate the effective dose of the senior physician so that they were installed under and on the aprons in the waist and the chest areas, respectively. The effective dose of the senior physician was computed based on NCRP Reports 122 as follows:

$$E=0.5\,H_u+0.025\,H_0 \qquad (3)\ [20].$$

H_u and H_0 are the doses read from the TLD under and on the apron (in the waist area) and the neck or chest area, respectively.

The average effective dose of participants was separately obtained, per time unit, per test, and angiography or angioplasty. All participants were asked to answer a questionnaire about their level of satisfaction with the quality and comfort of the gown after wearing the gown.

In order to achieve a high scientific standard, the badges and the gowns were coded in a double-blind manner. Therefore, the dose of aprons was measured by the experts without any information about apron types. Also, the participants answered the questions about the quality of the aprons without any information about the brand of aprons they were wearing.

Results

In the current study, the effective radiation dose was measured for 4 physicians, 6 nursing personnel, and 6 radiology technologists, working rotationally in angiography and angioplasty tests. A total of 146 and 130 patients with modes 1 and 2 were examined and operated on, respectively. Totally, 160 and 143 tests were performed in modes 1 and 2, including 108 and 52 angiography and angioplasty tests in modes 1, 97, and 46 angiography and angioplasty tests in mode 2, respectively. Furthermore, physicians were numbered from 1 to 4, and each physician treated and examined 35 patients diagnostically, therapeutically, or both.

The dosimetry was conducted in mode 1 during 5, 2, 3, and 3, and in mode 2 during, 2, 1, 2, and 4 days for the first, second, third, and fourth physicians, respectively.

Tables 2 and 3 show the average effective dose and the effective dose per test in two modes 1 and 2 for each physician.

Table 2: Average total effective dose and effective dose per test and time of fluoroscopy in mode 1 for each doctor in a comparative way

Physician	Mean ED (μSv)	Mean ED/case (μSv)	Mean ED/CA	Mean ED/PCI	Mean FT (min)	Mean ED/FT (μSv/min)
1	8.51	0.4255	0.3545	1.2157	62	0.1372
2	4.4	0.2	0.1466	0.3142	36.10	0.1218
3	21.88	0.8752	0.713	5.47	86.2	0.2538
4	15.42	1.542	0.37	3.084	89.35	0.1725

FT: Fluoroscopy Time, ED: Effective Dose, CA: Coronary Angiography, PCI: Percutaneous Coronary Intervention

Table 3: Average total effective dose and effective dose per test and time of fluoroscopy in mode 2 for each doctor in a comparative way

Physician	Mean ED (μSv)	Mean ED/case (μSv)	Mean ED/CA	Mean ED/PCI	Mean FT (min)	Mean ED/FT (μSv/min)
1	8.40	0.42	0.336	1.2	73	0.1150
2	4.23	0.1922	0.1458	0.3021	41.22	0.1026
3	18.61	0.8459	0.6892	4.6525	94.75	0.1964
4	14.81	1.3463	0.3702	2.962	92.11	0.1607

FT: Fluoroscopy Time, ED: Effective Dose, CA: Coronary Angiography, PCI: Percutaneous Coronary Intervention

A medical team, including a senior physician, a physician's assistant, and a nurse rotationally helps the physician and the patient to perform common tests in the angiography and angioplasty departments of hospitals. For example, a radiology expert in the operating room is responsible for the preparation of diagnostic or therapeutic instruments, contrast material, pressure control, and monitoring of an electrocardiogram (ECG) of the patient prepares medicine and surgical instruments. Also, a radiology expert in the control room controls monitors of the image recording, dose, and time. The physician assistant can be a cardiologist or another nurse depending on the type of operation and hospital (educational/non-educational).

In the present study, the occupational dose of the physician's assistant was obtained from the TLD dosimeter, placed under the apron in the middle region of the chest, However, the physician assistants were from the nursing staff of the department during the first series of dosimetry, they were generally from the inversion fellowship specialists in the second series. The dose of physician assistants, nurses, and radiology experts in the operating room was defined as a job position since the medical team of the cath lab department rotationally participated in all the exams in different job positions with almost the same experience.

Table 4 presents the average effective dose of physician assistants for both every test and all tests of all angiography and angioplasty in two modes 1 and 2.

The average effective dose of nurses and experts was obtained by the TLDs, placed under the apron in the middle region of the chest. Tables 5 and 6 show the effective dose of two modes 1 and 2 for the nurses and the radiology expert, respectively.

All personnel were asked to answer a questionnaire with scores, ranging from 0 to 10 in two modes 1 and 2. Table 7 shows the average points for each question in both modes.

Figure 1 shows the average total effective dose per case for each doctor in a comparative way in two modes 1 and 2.

Table 4: Average total effective dose and effective dose per test for the physician assistant in a comparative way

	mean ED (μSv)	ED/case (μSv)
mode 1	322.51	1.79
mode 2	312.44	1.47

ED: Effective Dose

Table 5: Average total effective dose and effective dose per test for rotating nurses in a comparative way

	mean ED (μSv)	ED/case (μSv)
mode 1	169.50	0.9
mode 2	146.83	0.83

ED: Effective Dose

Table 6: Average total effective dose and effective dose per for radiology technologists in a comparative way

	mean ED (μSv)	ED/case (μSv)
mode 1	173.52	0.73
mode 2	156.58	0.54

ED: Effective Dose

Discussion

The current study aimed to compare two commercial and proposed gowns based on two methods: ICRP criteria, i.e., one dosimeter on the gown and another under the gown, and designing a questionnaire after using the gowns. Tables 2 and 3 present that the effective dose considerably decreased for 4 physicians (From 2 to 14 percent reduction). In the operating room, the effective dose depends on various conditions, such as the type of fluoroscopy device and test, the patient's weight

Table 7: Questionnaire given to the personnel to check the level of satisfaction with the quality and comfort of the aprons

question number	question	Total points given in mode 1	Total points given in mode 2
1	How comfortable is it to wear a vest and skirt without the help of others?	80	79
2	What is the level of satisfaction of not putting pressure on the joints while wearing it? (joint rotation in a dangerous direction)	70	75
3	What is the satisfaction level of not taking time to wear a vest and skirt?	81	80
4	What is the satisfaction level of the weight of the vest and skirt?	83	80
5	What is the level of satisfaction with mobility and lack of restrictions in performing slow and fast movements? (back rotation and bending)	69	75
6	How satisfied is the distribution of weight between shoulders and waist?	85	83
7	How satisfied are you with the softness of the shoulder and no pressure on this part?	73	77
8	What is the level of satisfaction with the weight distribution of the back and front of the skirt vest and the lack of pressure on the back and waist?	70	71
9	What is the level of satisfaction with radiation reduction (covering different parts of the body) for different radiation angles of the radiation tube?	75	80
10	What is the level of overall comfort, improved concentration, and better performance during surgery?	76	80

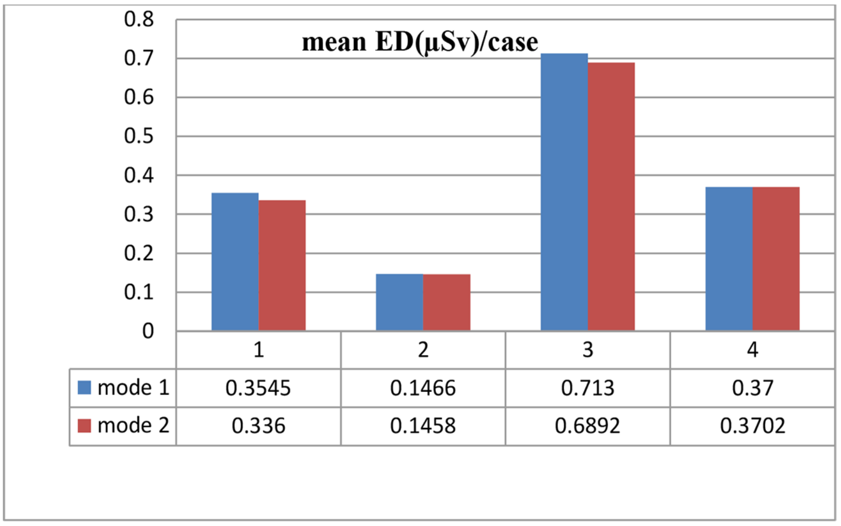

Figure 1: Average total effective dose per case for each doctor in a comparative way

index, collimation, fluoroscopy time, and the angle of the tube. Further, the physicians' experience is considered the factors, affecting primary radiation and the scattered beam (the main source of radiation in the C-arm room) during the test. The present limitations lead to a non-measured change of all these parameters. Therefore, the average effective dose for angiography and angioplasty tests and the average dose per minute for the other conditions show the effect of the difference on the use of aprons.

According to Tables 2 and 3, apron No. 2 had more attenuation than No.1 since apron No. 2 was layered so that Copper and Barium were used in the outer layers with K absorption edges 8.97 and 37.44 keV, respectively, with the highest amount of photoelectric absorption. Additionally, the third layer contains Tungsten, and the greatest attenuation occurs in the high energies of the imaging area (69 keV). However, nursing staff and physician assistants understood the superiority of gown No. 2, for individuals, who work in these departments [20]. Gown No. 1 is also acceptable without any concern due to the occupational dose limit of 20 mSv per year (Tables 4-6). However, nano-particle compounds were used in gown No. 2, and the attenuation would have an ignorable difference with No.1 (Figure 1). The nanoparticles in radiation shielding, compared to microparticles, increase surface atoms in a fixed volume, resulting in placing more particles in the path of the radiation and increasing the cross-section of the photoelectric interactions.

Changing microparticles to nanoparticles leads to breaking many bonds and increasing some electrons in these particles. However, free electrons are considered proportional targets for X-ray interactions, the probability of photons colliding with these electrons increases rays due to a higher cross-sectional area of collision than higher energies, leading to the dispersion of an irregular shape for the diagnostic energies [21]. Therefore, nanoparticles can not only absorb more scattered rays but also produce more scattered rays, with lower energy than that of primary rays.

The mentioned problem can be addressed based on two approaches as follows: 1) the personnel is not exposed to direct radiation due to the delivery of few high-energy rays in the Kempton area and 2) nanoparticles in the gowns cause suitable conditions: flexibility, weight, and comfort, directly affecting the health of personnel and decreasing the dose received indirectly. Table 7 shows the answers of personnel to the questions related to the quality of the gowns (the average total score of gowns No. 1 and 2 is 76.2 and 78 out of 100, respectively). Based on the results of asked questions, the use of a multi-layer style gown is more comfortable than a commercial style gown, leading to the health of the staff's spine and affordable medical expenses.

Conclusion

Based on the efficiency of non-lead gowns, which is done by measuring the radiation received by the personnel of the intervention departments with the help of TLDs, the commercial sample containing Bismuth, Antimony, and Tungsten has an acceptable radiation protection level.

The present study shows that the multilayer coating containing nanoparticles of Bismuth, Tungsten, Barium, and Copper metals has no significant difference from the commercial sample in terms of radiation protection. (Both are equally efficient in radiation protection.) The use of heavy nanoparticles in the energies related to diagnostic radiations does not lead to better radiation protection compared to the microparticles of these metals. However, the use of nanoparticles and the combination of layers containing metal nanoparticles provides greater flexibility, comfort, and satisfaction for the personnel, which is in accordance with the objectives of this research.

Authors' Contribution

A. Jafari conceived the idea. The paper was written and designed by A. Jafari and SH. Mousavi. A. Jafari and M. Khoshfetrat gathered data and the related literature. SA. Mohsenizadeh and SH. Mousavi. helped with writing-related works. The method implementation was conducted by A. Jafari. Analysis was conducted by A. Jafari and R. Arefizadeh. The research work was proofread and supervised by SA. Mohsenizadeh, SH. Mousavi. And R. Arefizadeh. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

All procedures performed in the study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study was approved by the ethics committee of AJA University of Medical Sciences, Tehran, Iran (Ethic code: IR.AJAUMS.REC.1401.002).

Informed Consent

Informed consent was obtained from all individual participants involved in the study.

Conflict of Interest

None

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