Evaluation of the occupational X-rays doses of the medical staff in a cardiac catheterization laboratory using an acrylic phantom and semiconductor dosimeter

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Abstract

Objective: The occupational X-rays doses of medical staff in a cardiac catheterization laboratory were evaluated. **Methods:** Four customized acrylic phantoms were used to simulate a patient, medical doctor, assistant, and radiologist to evaluate the in-situ X-rays exposure dose using semiconductor dosimeters. The exposure dose was measured under three scenarios that were preset to imply: no shielding, moderate shielding and complete shielding for the medical staff in the laboratory. The doses were applied by changing the dose area product (DAP) from 11,000 to 500,000mGy·cm^2 in 14 increments. **Results:** The estimated annual occupational doses for doctors, assistants and radiologists in scenarios I, II, and III were: I) 35.03, 7.78, 1.95; II) 1.95, 0.78, 0.06; and III) 0.19, 0.10, 0.05cSv, respectively. The derived linear regression line of the exposure dose with respect to the DAP were extrapolated to obtain the minimum detectable level (MDL) of DAP for triggering the staff dosimeters. Accordingly, the minimum annual dose was estimated as 0.05cSv. Additional shielding provided measurable protection to the staff. The protective clothing used in scenarios II and III can reduce the original dose from scenario I to ~3% (scenario II) and ~0.5% (scenario III). The annual occupational dose also changed with the various X-rays energy settings. The annual dose increased to 126% when the preset X-rays energy was changed from 70 to 100kVp. **Conclusion:** The semiconductor dosimeter proved to be an adequate tool for measuring low doses and low dose rates under these circumstances. The dose can be reduced of I) 35.03, 7.78, 1.95; to II) 1.95, 0.78, 0.06 (~3%); or III) 0.19, 0.10, 0.05 (~0.5%)cSv, respectively according to different protective scenarios.

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Introduction

Occupational radiation exposure has been a continuous concern for medical staff in cardiac catheterization labs. Unlike in routine diagnostic X-rays radiography, the patient is isolated in an exposure chamber with a lead-covered wall, whereas the cardiologist and angiologist stand beside the patient during the lengthy medical procedure. Although the instant dose is negligible, staffs are directly exposed to low doses of scattered X-rays for long durations, which causes may cause radiation damage [1]. The annual occupational dose creates a measurable increase in cancer risk or could lead to malignant disease [2]. Furthermore, staff exposure in catheterization labs has become higher than ever since more and more patients are undergoing cardiac angiography diagnosis due to the advantages of this minimally invasive technique. Numerous interventional cardiology procedures have been observed in the last 15 years in Taiwan, and the cumulative dose for medical staff has been increasing. Thus, determining the cumulative dose for medical staff is essential. Kuon et al. (2002) [3] suggested adding lead shielding to reduce exposure. Best et al. (2011) [4] claimed that cumulative doses become more malignant for pregnant cardiologists and technical personnel and that additional monitoring is still warranted. Other researchers suggested reducing the radiation dose in cardiac catheterization labs by changing the design and by better educating the staff [5, 6]. Chida et al. (2013) [7] compared the annual occupational dose among interventional radiology staff and found by monitored film badges that physicians had the largest compared to nurses or radiological technologists. In the present work, X-rays exposure dose was evaluated using a silicon semiconductor dosimeter, which features sensitivity and precision. The dosimeter was attached to the front of customized acrylic phantoms to simulate medical staff in a cardiac catheterization lab and to record the in-situ dose. The derived data were interpreted to develop a well-organized database for evaluating the annual dose of medical staff in a cardiac catheterization lab. The database was built according to the latest medical procedures in Taichung Armed Forces General Hospital, Taiwan.

Methods

Figure 1 shows the cardiac catheterization laboratory at Taichung Armed Forces General Hospital. The medical doctor, assistant and radiologist were replaced with three acrylic phantoms. The customized trunk phantoms were made to simulate a 70kg male adult according to the International Commission on Radiation Units (ICRU) 48 reports [8]. An acrylic trunk phantom with the same size was also placed on a couch to simulate X-rays exposure. This was done to minimize the uncertainty from unpredicted factors and to reduce the intrinsic variation in dose measurement. A silicon semiconductor dosimeter (PDM-122) [9] was used to evaluate the X-rays exposure doses for personnel. The semiconductor dosimeter is known for precise and sensitive measurements of low doses. The minimum detectable dose and dose rate were 1μSv and 1μSv/h, respectively.

Figure 1. The cardiac catheterization laboratory at Taichung Armed Forces General Hospital, Taiwan. The three staff members (from left to right: medical doctor, assistant and radiologist) were replaced by three acrylic trunk phantoms.

The Philips Allura Xper FD10/10 can provide bi-planar features in clinical diagnosis, but only a single shot from the frontal head was used in this work. The preset protocol for X-rays exposure involves a 0.1mm-Cu+1.00mm-Al filter, a $25\times25cm^2$ field of view (FOV), a 102cm source to image-receptor distance (SID), a frontal alignment of zero degrees with no cranial or caudal alignment, and a maximum 70kVp. The current (mA) was manually adjusted to provide the desired dose area products (DAP).

The effective X-rays energy was defined as the actual X-rays energy needed to produce a particular personnel dose. This was done by placing multiple solid water plates in front of the semiconductor dosimeter during the X-rays exposure. The plates had a dimension of $20\times20\times1cm^3$ and were placed one by one between the dosimeter and the X-rays probe to derive the energy-dependent attenuation coefficient of the solid water material using the following equation:

$$D = D_0 \times e^{-\mu t} \rightarrow Ln\left(\frac{D}{D_0}\right)/t = -\mu \qquad (1)$$

where D_0 and D are the initial and attenuated doses from the semiconductor dosimeter, respectively. μ is the energy-dependent attenuation coefficient, and t is the thickness of the solid water plate. The effective X-rays energy can be easily obtained from the derived energy-dependent attenuation coefficient of the solid water plates.

The personnel exposure dose was evaluated under three different scenarios to simulate: I) staff without any additional protection; II) staff with a 0.5mm-Pb-equivalent thyroid collar, vest, and apron and 0.07mm-Pb-equivalent glasses, as depicted in Figure 2; and III) additional protection from a 0.5mm-Pb-equivalent transparent shield. The well-calibrated dosimeter was attached to the center of the trunk phantom (120cm from the ground) to imply the chest position. Figure 3 illustrates the simulated situation for fully shielded staff. The three acrylic phantoms were covered with a 0.5mm-Pb-equivalent vest and placed behind the transparent shield to provide the maximum protection during the cardiac angiography process. Experiments were repeated three times for each DAP of X-rays exposure. The DAP range was from 11,000 to 500,000mGy·cm² to ensure reproducibility and linearity of the dosimeter.

Figure 2. Protective clothing for medical staff in the cardiac catheterization laboratory. 0.07mm-Pb-equivalent glasses and 0.5mm-Pb-equivalent thyroid collar, vest, apron.

Figure 3. Simulation of fully shielded staff. The three acrylic phantoms were covered with 0.5mm-Pb-equivalent vests and placed behind a transparent shield to provide the maximum protection during the cardiac angiography process.

Results

Figure 4 shows the relative dose derived from the dosimeter for various thicknesses of solid water plates. The dose clearly degraded with increased thickness. The energy-dependent attenuation coefficient μ obtaining using Equation 1 was -0.1 23cm^{-1} (r^2=0.98) for the solid water material. Thus, the derived effective X-rays energy was 38.0kVp [10], which is less than the preset maximum X-rays energy of 70kVp. The effective X-rays energy was essential for staff dose prediction and developing a database of annual occupational doses from a health physics perspective.

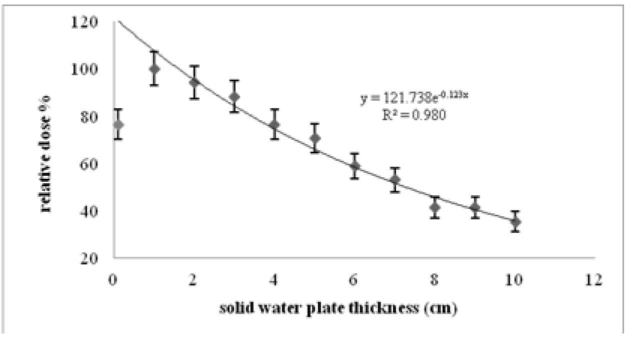

Figure 4. Relative dose derived from the dosimeter for various thicknesses of solid water plates. The dose degraded with increased thickness, and the obtained linear attenuation coefficient μ (Equation 1) was -0.123 [cm^{-1}] (r^2=0.98) for solid water material.

Table 1 shows the doses obtained from the semiconductor dosimeter. Each reported dose was averaged from three independent measurements, and all of them deviated from 0.7% to 1.1%. The deviations of DAP were below 0.4%. As clearly shown, the protective clothing can reduce the original dose from scenario I to ~3% (scenario II), and the additional transparent lead shield can suppress it to ~0.5% (scenario III). The high cumulative radiation intensity in the cardiac cathe-terization laboratory can easily reach dangerous levels for the staff. A corresponding high cancer risk is also measurable for staff in such a highly radioactive environment. Well-equip-ped protective clothing is strongly recommended for the laboratory staff. The distances from the frontal X-rays to the doctor, assistant and radiologist were 80, 100, and 180cm, respectively (Figure 1 and 2). The doctor received the highest dose in all three scenarios, while the radiologist received barely any dose, regardless of the additional shield (Table 1, scenarios II and III).

Table 2 shows the linear regression lines of the predicted dose of the staff with respect to the DAP in various scenarios. As shown, every regressed line had a high coefficient of determination (r^2), indicating high consistency for the predicted doses for a particular DAP. The minimum DAP in the last column of Table 2 implies the minimum DAP setting to trigger the semiconductor dosimeter. In other words, the dosimeter produces no readings if the instant DAP for a single X-rays shot is below the minimum level of 1μSv [9].

Discussion

Table 1. *Obtained doses from a semiconductor dosimeter. Every reported dose was averaged from three independent measurements, and all deviated by 0.7%-1.1%. The deviations of DAP were below 0.4%.*

DAP [mGy·cm^2]	Scenario I No vest, No Pb plate [μSv]			Scenario II Vest, No Pb plate [μSv]			Scenario III Vest, Pb plate [μSv]		
	Dr.	Ass.	Radio.	Dr.	Ass.	Radio.	Dr.	Ass.	Radio.
0	0	0	0	0	0	0	0	0	0
11001±25	43	8	3	0	0	0	0	0	0
20345±51	90	17	5	2	0	0	0	0	0
30320±73	129	25	7	4	1	0	0	0	0
42142±99	174	34	10	5	1	0	0	0	0
51215±116	205	42	12	7	2	0	0	0	0
60740±139	145	51	14	9	2	0	1	0	0
71472±163	288	60	16	11	3	0	1	0	0

(continued)

80497±183	324	68	18	12	4	0	2	1	0
90657±205	363	76	21	13	5	0	3	1	0
100742±282	402	85	23	14	7	0	3	1	0
203344±525	748	161	45	24	17	0	5	2	0
305452±794	1130	248	66	33	22	1	7	4	0
401787±1027	1460	322	84	47	29	1	8	5	1
502994±1309	1861	416	106	58	36	1	10	7	2

Table 2. *Regressed lines of the predicted dose to staff for various DAP in different scenarios. Every regressed line had a high coefficient of determination (r^2), indicating high consistency for the predicted dose with the actual DAP.*

Scenario	Staff	Dose [μSv]= a·x[DAP]+b	r^2, coeff. of determination	Minimum DAP [Dose=1.0μSv]
	Doctor	0.0036x+19.421	0.9996	<0
I	Assistant	0.0008x+0.5281	0.9995	<0
	Radiologist	0.0002x+1.174	0.9995	<0
	Doctor	0.0002x-0.9462	0.9862	9731
II	Assistant	0.00008x-1.3602	0.9914	29502
	Radiologist		N/A	
	Doctor	0.00002x-0.1383	0.9594	56915
III	Assistant	0.00001x-0.4693	0.9791	146930
	Radiologist		N/A	

N/A: not available

A thorough statistical survey of the patients who underwent the cardiac procedure was conducted from 2000 to 2014 at the Taichung Armed Forces General Hospital. The statistical data indicated that an average of 315±73 patients (min. 243, max. 394) had undergone cardiac diagnosis and 221±51 (min. 166, max. 267) had undergone therapeutic procedures. The uncertainty is related to the various patient numbers from all databases with a 95% confidence level. The average DAP exposures for patients who have undergone diagnosis and therapy are 63881±24541 (min. 22590, max. 89801) and 349414±227802 (min. 129889, max. 7560 69)mGy·cm^2, respectively. The average DAP were derived from sequential surveys of the cardiac catheterization lab from January 2013 to October 2014 [11]. The cumulative DAP can be obtained as 97.3±53.4×10^6mGy·cm^2 [(315±73)×(63881±24541)+(221±51)×(349414±227802)=97.3±53.4×10^6]. Therefore, the estimated annual occupational doses for doctors, assistants and radiologists in scenarios I, II, and III were (I) 35.03±19.23, 7.78±4.27, 1.95±1.07; (II) 1.95± 1.07, 0.78±0.43, ~0.06; and (III) 0.19±0.10, 0.10±0.05, ~0.05cSv, respectively.

The doctor has the highest dose among all staffs, although the dose degrades rapidly from 35.03 to 1.95 and eventually only 0.19cSv with protective clothing and an additional shield. According to the radiation protection regulations in Taiwan, the occupational dose limit for radiation workers is 5cSv/year or 10cSv/5 years [12]. Thus, protective clothing can provide effective protection with or without the transparent shield. However, the additional shield is strongly recommended to satisfy the principle of ALARA ("as low as reasonable approach").

To reach the detection limits (minimum DAP to obtain 1μSv) of the dosimeter in all cases, the minimum detectable level (MDL) of DAP was calculated from extrapolation of the linear regression lines (Table 2) using the following equation:

$$MDL = \Delta_0 + \sqrt{\Delta_0}\left[K_\alpha + \frac{K_\beta^2}{2\sqrt{\Delta_0}} + K_\beta\sqrt{1 + \frac{K_\alpha}{\sqrt{\Delta_0}} + \frac{K_\beta^2}{4\Delta_0}}\right] \quad (2)$$

where Δ_0 is the minimum DAP to trigger the dosimeter detection in this work, which was obtained by setting y=1 to derive the minimum DAP of the four linearly regressed equations for scenarios II and III in Table 2. K_α and K_β were each set to 1.645 to maintain a 95% confidence level and to avoid Type 1 (false alarm) or Type 2 (missed alarm) errors [13].

The derived minimum DAP to trigger the dosimeter for doctors and assistants are 10058 and 30070mGy·cm^2 for scenario II and 57703 and 148149mGy·cm2 for scenario III, respectively. Thus, the corresponding doses for doctor and assistant are 1.0654 and 1.0454μSv for scenario II and 1.0157 and 1.01263μSv for scenario III, respectively. In other words, the dosimeter would have no reading if the DAP does not exceed the MDL in a single X-rays shot, but the staff may still receive a measurable dose in actuality. Unlike thermoluminescent dosimeters (TLD), which accumulates discrete exposure doses in long-term X-rays exposure, a semiconductor dosimeter receives a dose from a single X-rays shot only. Thus, reasonable assumptions for the minimum annual dose for radiologists in scenarios II and III are 0.056±0.009 and 0.053±0.009cSv, respectively [1.04×(535±89)=556±93, 1.01×(535±89)=540±90μSv]. This estimation might heavily underestimate the exposure dose of radiologists but the calculation is done with the assumption that no dose is detected by the dosimeter for the radiologist for every medical procedure in the cardiac catheterization laboratory.

The derived exposure doses were calculated according to the surveyed cases from Taichung Armed Forces General Hospital and the X-rays preset energy was 70kVp. The estimated occupational dose for staff increased when X-rays were applied with high energy settings. The high X-rays energy creates high effective energy and X-rays are scattered around the laboratory. The exposure dose can be calculated by a simplified version of Equation 3 [10]:

$$Dose = \Phi e^{-\mu r} E\left(\frac{\mu}{\rho}\right)_{en} \left[\frac{J}{kg}\right] \quad (3)$$

where Φ is the beam flux and E is the effective X-rays energy. The term $(\mu/\rho)_{en}$ is the real mass absorption coefficient of tissue and μ is the linear attenuation coefficient of air at a particular X-rays energy.

Table 3 shows the correlating information for calculating the exposure dose and the changes in air attenuation is negligible (Equation 3). The effective X-rays energies of various preset energies were either extrapolated from the measurements in this work or obtained from previous surveys [11]. As clearly depicted, the dose changes are sensitive to changes in the preset X-rays energy, which is 70kVp in this work. For example, the preset X-rays energy changes to 100kVp for patients with high body mass index (BMI) and the effective X-rays energy and dose increase to 54kVp and 126%, respectively. Therefore, the annual occupational doses for scenario III become 0.24±0.13, 0.13±0.06 and ~0.06cSv [0.19±0.10×126%=0.24±0.13, 0.10±0.05×126%=0.13±0.06, 0.05×126%=0.06] for the doctor, assistant and radiologist, respectively (Table 3). Notably, the maximum preset X-rays

Table 3. *Correlated information for calculating exposure dose (Equation 3). The effective X-rays energies of other preset energies are either extrapolated from the measurements in this work or obtained from previous surveys.*

Preset X-rays energy [kVp]	Effective X-rays energy [kVp] [AA]	$(\mu/\rho)_{en}$ [cm^{2}mg^{-1}] [BB]	[AA]X[BB]	Relation to 70kVp X-rays [%]
60	33	0.0320	1.042	95
70	**38**	**0.0290**	**1.102**	**100**
80	43	0.0262	1.138	103
90	49	0.0259	1.265	115
100	54	0.0256	1.390	126
110	60	0.0261	1.559	141
120	65	0.0264	1.720	156

[AA], [BB]: Implying the specific included item

Table 4. *Annual occupational dose of medical staff in the cardiac catheterization laboratory from other research.*

Reference No.	Medical staff	Annual dose [cSv]	Method	Description
[7]	Physician	0.30±0.15	Film badges	All under apron
	Nurse	0.13±0.06		
	Radiologist	0.06±0.05		
[14]	Doctor	120-360	N/A	No apron
		1.02		Under apron
		0.12		Under optimized medical procedure
[15]	Doctor	24.2	Personal dosimeter	No apron
		4.56		Under apron
[16]	Doctor 1	4.72	TLD	Under apron
	Doctor 2	1.83		
[17]	Doctor	10.9	TLD	No apron
		<2.0		Under apron

N/A: not available

energy is 125kVp for the Philips Allura Xper FD10/10. A high preset X-rays energy rapidly increases the actual exposure dose for staff. Thus, an additional shield is always recommended for the cardiac catheterization laboratory.

Table 4 shows the annual occupational dose of medical staff in a cardiac catheterization laboratory from other research. As illustrated, the data are rather controversial, because the calculation methods may differ, which is also the case for the work loading of every subject. However, a reasonable estimation of the annual dose for doctors falls within 1.0 to 4.7cSv, which is slightly higher than the value derived in this work. The data from other studies indicate that the additional shield protects staff and reduces the dose to only one tenth of the original value (1.95 to 0.19cSv for doctors in scenarios II and III). In addition, TLD is a popular and convincing tool for quantifying personnel doses for either X-rays or gamma rays. However, any inadequate settings during the pre-or post-processing in the TLD readout systems might affect the dose calculations, whereas the silicon semiconductor dosimeter adopted in this work can provide stable readings, even with low exposure rates.

In conclusion, the occupational doses of medical staff in a cardiac catheterization laboratory were evaluated in this work. The medical doctor has the highest dose among all staff, because the standing position is close to the patient during the interventional cardiology procedures. An additional shield can provide effective protection and reduce the actual measurable dose to medical staff. By using the highest level of shielding in this work (scenario III), the annual doses can be reduced from 35, 7.7, and 1.95 to only 0.19, 0.10 and ~0.05cSv for the doctor, the assistant, and the radiologist, respectively.

The semiconductor dosimeter proved to be an adequate tool for measuring low doses and low dose rates under these circumstances. The minimum detectable limit of 1μSv also helped to quantify the X-rays exposure dose. The estimated annual dose for the medical staff can be revised to accommodate various X-rays preset energies, since the exposure dose to personnel changes with different X-rays energies.

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The upper part of a marble statue of a professional boxer. First century B.C. Notice the broken nose, injuries in the checks and the very hypertrophic strong muscles. Antichita, Rome