Assessment of radiation doses to cardiologists during interventional examinations

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The accuracy of two on line dosimetric techniques was investigated for the estimation of cardiologist doses. The first technique involves the establishment of a database relating the cardiologist extremity doses to patient DAP values. Doses of nine cardiologists were measured together with patient doses during the interventional cardiac examinations of 166 patients for this purpose. Data were collected from five cardiology departments. The mean of the eye, thyroid, waist, right-left wrist, and right-left leg doses per procedure were measured as 72.4 (31.6–107.1), 68.5 (13.3–174.6), 11.2 (0.9–28.4), 67.8 (21.9–120.3) to 216 (52.7–425.4), and 137 (51.4–386.2) to 384 (135–1168.3) μGy/procedure. The effective doses were calculated according to the use of protection tools and a mean value of 12.14 (1.2–30.2) μSv/procedure was found. The ratios of staff dose to patient DAP were found to be within the range of 0.14–3.75 for each procedure. In the second method, cardiologist doses were calculated and compared with the measured values. Scatter doses were measured at the positions of cardiologists from Rando phantom exposures using similar conditions with patient procedures for this purpose. The parameters obtained from these exposures and patient examinations were used to calculate the doses to cardiologists. [DOI: 10.1118/1.3168971]

Key words: staff dose, effective dose, dose-area product, interventional cardiology

I. INTRODUCTION

Interventional cardiological examinations are associated with the highest radiation exposures both to patient and cardiologist compared to other radiological examinations.[1,2] In order to reduce the risks of occupational exposures, cardiologists should follow all the radiation protection rules during their patient studies. Several aspects of radiation safety in the practice of cardiology have been addressed by the American College of Cardiology in a document.[3]

The complexity of the procedure, improper use of exposure parameters of the x-ray system, and large numbers of patients may cause excessive occupational exposures. High level multidirectional exposures require measurements of extremity doses as well as effective dose assessments for personal dosimetry of cardiologists. The use of film badges or thermoluminescent dosimeters (TLDs) are the common methods for monitoring personal exposures. However, neither of these techniques provides on line information, and results are obtained retrospectively. On the other hand, measurement of dose-area product (DAP) is a reliable technique for the assessment of patient doses received in fluoroscopic procedures and in use for the majority of the angiographic systems as a dose monitoring device.[4,5] Trigger values for DAP are also suggested for the patient skin doses approaching deterministic levels.[6,7] The DAP readings during the cardiac examinations may also be used for the brief estimation of cardiologist doses.

The aim of this work was to investigate the accuracy of the methods that provide on line dosimetric information for the estimation of cardiologist doses. Patient DAP values and cardiologist extremity doses were measured simultaneously to establish a database for "cardiologist dose/patient DAP" per procedure of interventional examinations. As an alternative technique, cardiologist doses were tried to be estimated from the scatter data. Simulation of a clinical examination was carried out by exposing the Rando phantom. Scatter radiations for fluoroscopic and radiographic exposures at specific points around the patient bed were measured for each projection of cardiac examinations. Extremity doses were calculated for each cardiologist by using these scatter data and also some of the patient exposure parameters such as fluoroscopy time and radiographic frame numbers used in their patient examination. Patient and phantom doses were separately measured for each projection of the cardiac examinations in order to improve the accuracy of experimental results and dose calculations.

Variations among the measured extremity doses of cardiologists have also been discussed with regard to their experience and involvement with the complex procedures, positions during the procedures, handling of exposure parameters, use of protection tools, and also effect of different systems.

II. MATERIAL AND METHODS

Staff doses were measured during the interventional cardiology examinations of 166 patients at the cardiology departments of five university hospitals. Data from five angiographic units (SYS1, ... , SYS5) have been collected by the involvement of five groups of nine cardiologists (CARD1, CARD2, ... , CARD9). Two Philips Integris H

3000 (Philips Medical Systems, The Netherlands), two GE Advantx LC+DLX (GE Medical Systems Milwaukee, WI), and one Siemens Bicor Plus (Siemens, Erlangen, Germany) were the x-ray angiographic systems. Performance tests of all these equipments were carried out according to the protocols given by IPEM.[8] Patient DAP data together with staff doses were measured for coronary angiography (CA), complex examinations (CA and/or PTCA and/or stent procedures), and ablation examinations. Patient dose measurements were carried out separately for each of ten projections. All the fluoroscopic and radiographic exposure parameters were recorded continuously during the course of the examination. Details of these acquisition procedures can be found elsewhere.[7] The DAP meter (Diamentor M4KDK, Freiburg, Germany) used in these measurements was calibrated for each x-ray system according to manufacturer recommendations.

II.A. Cardiologist doses: Direct measurements

In order to determine the extremity and effective doses for the cardiologists, lithium fluoride TLD pockets (containing two chips for each) were attached to the following points: One pocket to the collar level over the apron, one pocket at the waist level under the apron, two pockets hang to the tail of the apron at the knee level (one for each leg), one pocket on the forehead, and one chip for one finger (or wrist) of each hand. A model 3500 Reader (Harshaw Chemical, Solon, OH) was used for the TLD readout. In order to minimize batch to batch variability, TLDs were calibrated initially and variation of sensitivities was kept within ±5%. Background subtraction was also carried out for all the readings.

Extreme care was taken to measure the staff and patient doses simultaneously, i.e., staff wore these dosimeters only during the measurements of patient doses, since they were also carrying their regular personal dosimeters. The active involvement of each cardiologist to each patient examination was carefully observed and records were prepared for each cardiologist indicating related dosimetric data of their patient examinations (total fluoroscopy time, number of radiographic frames, exposure factors, and patient DAP for each projection). In case of leave of the cardiologist from the procedure, the dosimetric information for this part of the examination was excluded from the records. The lead equivalent of protective aprons and wearing style by the cardiologist as well as use of additional shielding were also noted for each cardiologist and tried to be made similar in use during each exam.

Effective doses of staff can be calculated from the readings of personal dosimeters. Different formulas have been suggested for these calculations depending upon the number and position of dosimeters, as well as the use of thyroid shields by the staff. Seven of the nine cardiologists wore the dosimeters, one above and another under the apron, and used thyroid shields. Effective doses for these cardiologists were calculated from the TLD readings positioned at the collar and waist levels using the following formula:[9]

$$E = 0.02(H_{os} - H_u) + H_u, \quad \text{two dosimeters with a thyroid shield,}$$

$$E = 0.03H_{os}, \quad \text{single dosimeter worn at the collar level with a thyroid shield,}$$

where H_u is the under apron dose at the waist level and H_{os} is the measured dose at the thyroid level over the apron. One cardiologist used two dosimeters without thyroid shield, and the other one used only one dosimeter at the collar level without a thyroid shield. Effective doses for the seven cardiologists were also calculated from TLD readings obtained only from the TL dosimeters carried on the collar level. The following formulas were used for the effective dose calculations of these cardiologists:[10]

$$E = 0.06(H_{os} - H_u) + H_u, \quad \text{two dosimeters without a thyroid shield,}$$

$$E = 0.07H_{os}, \quad \text{single dosemeter worn at the collar level without a thyroid shield.}$$

II.B. Scatter radiation measurements

Left anterior oblique 45° (LAO45), anterior-posterior (AP), right anterior oblique 30° (RAO30), left anterior oblique 45°-caudial 30° (LAO45-CAUD30), and left lateral (LLAT) views were selected as dominant projections from the evaluation of patient examinations.[5] A Rando phantom was irradiated at each system at these projections. A complex cardiac examination was simulated using fluoroscopic and radiographic exposure modes similar to patient studies. Scatter radiations from the phantom (and also some fraction of tube-housing leakage radiation) were measured with a suitable detector (model 9010 radiation monitor controller, 90 ×6-180 ionization chamber, MDH Radcal Monrovia, CA) at three different points where the cardiologist and assisting staff most likely stand during the examination. These measurements were made at 20 cm distant from the patient bed at 50, 100, and 150 cm above the floor level and also repeated for the points 70 cm far from the patient bed. Scatter radiation values at these three distances from the floor were subsequently used for the estimation of the leg, wrist, and thyroid (or eye) doses. The total number of measurements for each system was 90 for each exposure mode. These results were also used to derive scatter radiation maps for each system.

II.C. Calculation of cardiologist doses

The mean values of total fluoroscopy time (T_{fl}) and number of radiographic frames (N_{rf}) for each projection of a specific examination were derived from patient records and then used together with the measured values of scatter data to calculate the extremity doses (D_x) for each cardiologist using the following formula:

TABLE I. Distributions of the numbers of coronary angiography, complex, and ablation patients examined by each cardiologist. The levels of protection, experience, and position during examinations are also given for each cardiologist.

	SYS 1			SYS 2		S YS 3	S YS 4		S YS 5
	Card 1	Card 2	Card 3	Card 4	Card 5	Card 6	Card 7[a]	Card 8	Card 9
Protection at the waist level	1 mm Pb	0.5 mm Pb	0.5 mm Pb	1 mm Pb	1 mm Pb	1 mm Pb	1 mm Pb	0.5 mm Pb	0.5 mm Pb
Experience	6 months	3 years	3 years	13 years	6 months	6 months	6 years	6 months	5 years
Thyroid shield	+	+	+	−	+	+	+	+	−
Position during the examination[b]	2	2	2	1	2	2	1	2	1
Coronary angiography	14	6	19	15	21	15	12	26	
Complex procedure	7	12	15	8	14	11	4	2	
Ablation									9

[a]Used ceiling suspended barrier.
[b]1: Closer position to the x-ray tube. 2: Assisting position.

$$D_x = \sum_n \mathrm{DFL}_{x,n} T_{\mathrm{fl}} + \sum_n \mathrm{DRN}_{x,n} N_{\mathrm{rf}}.$$

n gives the projection and x is the distance from the floor level. $\mathrm{DFL}_{x,n}$ is the 1 min fluoroscopic exposure and $\mathrm{DRN}_{x,n}$ is the one frame radiographic exposure. Both of these values were derived for each projection from Rando phantom exposures. The known positions of the cardiologists during the examinations were taken into account in these calculations. Since the scatter radiations were only measured for five projections and the possibility of using other projections in the patient examinations, the missed scatter data were tried to be predicted from the measured ones that might give similar scattering. Accuracy of these calculated doses were tested by comparing them with measured data.

III. RESULTS

The distributions of numbers of CA, complex, and ablation patients examined by each cardiologist are presented in Table I. The wearing style and level of protection used by each cardiologist as well as their experience and position during the examinations are also given in this table. Thyroid, eye, left-right leg, and wrist doses and effective doses per examination for each cardiologist are given in Table II. Effective doses are calculated according to the use of protection tools. Total DAP values of patients examined by each cardiologist are also indicated in this table together with the dose to DAP ratios per procedure.

The points where the scatter radiations were measured are shown in Fig. 1. Calculated doses at 50, 100, and 150 cm corresponding to the legs, wrist, and thyroid are presented in Figs. 2(a)–2(c) together with the measured doses. The calculated results at the leg and wrist levels are generally found to be within the range of the measured left-right leg and wrist doses. Similar distributions of scatter radiations around the patient bed were found among the angiographic systems that were used in this study. Doses at the operator position were lower for AP and RAO30 projections and increased toward LAO45 and LAO45-CAUD30 projections and reached maximum doses for LLAT view. These findings were in good agreement with the reported values.[11–15]

The accuracy of dose estimation degrades if the patient data from all projections are assigned to a single projection and only the scatter measurements of this projection are considered. As it is shown in Figs. 3(a)–3(c), accuracy of the calculations starts to degrade if this assignment is made for a dominant LAO45 projection and highly degraded if a less used projection LAO45-CAUD30 is selected.

IV. DISCUSSION

A wide variation in extremity and effective doses has been noticed among cardiologists due to the effect of many variables. For cardiologists using the same system, the complexity of the procedure and experience of cardiologist are the important factors. Use of different protection tools (variation of thickness of shielding material, wearing style of lead aprons, presence of additional barriers) and handling of exposure parameters and irradiation geometry (exposure mode, fluoroscopy time, number of radiographic frames, FOV selection) are also the parameters that have a strong influence on the doses. If the staff dose comparisons are tried to be made between the cardiologists working at different systems then additional factors related to the design and output of the system should be considered.

The doses of three assisting cardiologists working in SYS1 can be evaluated by comparing their involvement with complex cases and also the handling of exposure modes. The patient input exposure rate at the high fluoroscopic exposure mode of SYS1 was two times higher than in normal normal fluoroscopy mode and percentage use of these modes by the cardiologists of this system was different. The selection of the high mode by CARD3 was higher (76%) than CARD1 (50%) and CARD2 (28%); however, CARD2 received higher doses than CARD3 most probably due to his involvement with a higher number of complex examinations (66% versus 45%). The effective dose for CARD1 is lower since the thickness of his apron was two times more than the aprons of CARD2 and CARD3 at the waist level. Although he had less complex examinations, his extremity doses were measured to be higher than those of CARD3; the experience of CARD3 probably caused these differences.

TABLE II. Result of direct measurements (Card: Cardiologist. *N*: Patient numbers. Proc.: Procedure).

	SYS 1						S YS 2				S YS 3		S YS 4				S YS 5			
	Card 1		Card 2		Card 3		Card 4		Card 5		Card 6		Card 7		Card 8		Card 9			
	$N=21$, 1622.6 Gycm^2		$N=18$, 1537.0 Gycm^2		$N=35$, 1976.7 Gycm^2		$N=22$, 1597.3 Gycm^2		$N=35$, 2875.6 Gycm^2		$N=26$, 3764.2 Gycm^2		$N=16$, 813.6 Gycm^2		$N=28$, 1994.5 Gycm^2		$N=9$, 1707.1 Gycm^2		Mean	
	μGy/proc.	μGy/DAP	μGy/proc.	μGy/DAP	μGy/proc.	μGy/DAP	μGy/proc.	μGy/DAP	μGy/proc.	μGy/DAP	μGy/proc.	μGy/DAP	μGy/proc.	μGy/DAP	μGy/proc.	μGy/DAP	μGy/proc.	μGy/DAP	μGy/proc.	μGy/DAP
Thyroid	71.5	0.93	61.8	0.72	33.4	0.59	27.3	0.38	50.4	0.61	68.4	0.47	13.3	0.26	116.0	1.63	174.6	0.92	68.52 (13.3–174.6)	0.72 (0.26–1.63)
Waist[a]	2.7	0.04	13.8	0.16	5.7	0.10	20.0	0.28	2.9	0.03	14.9	0.10	0.9	0.02	28.4	0.40	…	…	11.16 (0.9–28.4)	0.14 (0.02–0.40)
Right leg	51.4	0.67	100.7	1.18	67.6	1.20	136.7	1.88	176.5	2.15	116.7	0.81	105.8	2.08	92.1	1.29	386.2	2.04	137.08 (51.4–386.2)	1.48 (0.67–2.15)
Left leg	219.4	2.84	282.7	3.31	134.9	2.39	420.0	5.78	270.6	3.29	257.1	1.78	…	…	318.8	4.48	1168.3	6.16	383.98 (134.9–1168.3)	3.75 (6.16–1.78)
Right wrist	…	…	84.8[b]	0.10[b]	42.5	0.75	21.9	0.30	50.3	0.61	61.2	0.42	102.4	2.01	59.0	0.83	120.3	0.63	67.82 (21.9–120.3)	0.71 (0.10–2.01)
Left wrist	…	…	408.8[b]	0.48[b]	96.9	1.71	238.4	3.28	88.9	1.08	105.7	0.73	52.7	1.04	311.4	4.37	425.4	2.24	216.02 (52.7–425.4)	1.87 (0.48–4.37)
Eye	85.8	1.11	107.1	1.25	53.3	0.94	75.2	1.04	63.6	0.77	70.3	0.49	31.6	0.62	77.6	1.09	87.3	0.46	72.44 (31.6–107.1)	0.86 (0.46–1.25)
Effective dose/procedure	4.1[c]	0.05[c]	14.7[c]	0.17[c]	6.3[c]	0.11[c]	20.5[d]	0.28[d]	3.8[c]	0.05[c]	16.0[c]	0.11[c]	1.2[c]	0.02[c]	30.2[c]	0.42[c]	12.2[e]	0.06[e]	12.14 (1.2–30.2)	0.14 (0.02–0.42)
	2.15[f]	0.03[f]	1.85[f]	0.02[f]	1.0[f]	0.02[f]	1.9[e]	0.03[e]	1.5[f]	0.02[f]	2.1[f]	0.01[f]	0.4[f]	0.01[f]	…	…	…	…	1.5 (0.4–2.2)	0.02 (0.01–0.03)

[a]Under the apron.
[b]$N=13$, DAP=1039 Gy cm^2.
[c]Effective dose $E=0.02*(H_{os}-H_u)+H_u$.
[d]$E=0.06*(H_{os}-H_u)+H_u$.
[e]$E=0.07\times H_{os}$.
[f]$E=0.03\times H_{os}$ in μSv.

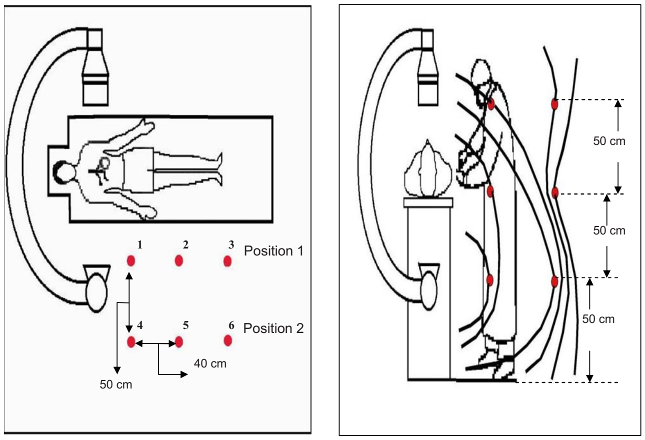

FIG. 1. Measurement points for scatter radiation.

The doses of CARD4 and CARD5 working in SYS2 can be similarly compared; the senior cardiologist CARD4 always remained close to the x-ray tube (location 1) and was assisted by CARD5. Both cardiologists were using the same protection aprons; however, CARD5 did not find himself comfortable with the thyroid shield and ignored its use. Although CARD5 examined more complex patients, doses at his waist level were lower since he remained under the protection of CARD4 during the patient exposures. The higher doses of the right wrist and leg of CARD5 confirm this protection. The benefit of use of shielding and cardiologist experience can be seen from the lower doses of CARD7 in comparison to CARD8, even though he always remained close to the x-ray tube. Use of ceiling suspended mobile barrier and wearing a thicker lead apron considerably reduced his extremity and effective doses.

Ablation patients were examined in SYS5 using only LAO45 and PA projections. Some of the extremity doses of CARD9 were found to be considerably higher than the others especially from those who worked with SYS1 which was the same model as with SYS5. Detailed investigation revealed that 115 cm^2 collimator opening of this system at the patient bed in comparison to the 64 cm^2 of SYS1 was the main reason for the high doses. This is also confirmed by the results of scatter measurements. The mean scatter values for SYS5 for PA and LAO45 projections were found to be considerably higher (32 and 82 μGy/min) than the mean of the remaining four systems (7.5 and 20.1 μGy/min). The complexity of the ablation procedures and higher patient input exposure rate of SYS5 (22.6 mGy/min versus 14.6 mGy/min) may also have contributed to the high extremity doses of CARD9.

CARD8 was mainly involved with the less complex CA and PTCA examinations in comparison to other assisting cardiologists (CARD1, CARD5, and CARD6); however, his effective dose was found to be much higher than the others due to use of a thinner lead apron.

The calculated doses at 50 and 100 cm were compared with the measured leg and wrist doses. In general, calculated doses for each cardiologist were remained between the results of the left and right extremity measurements. This in-

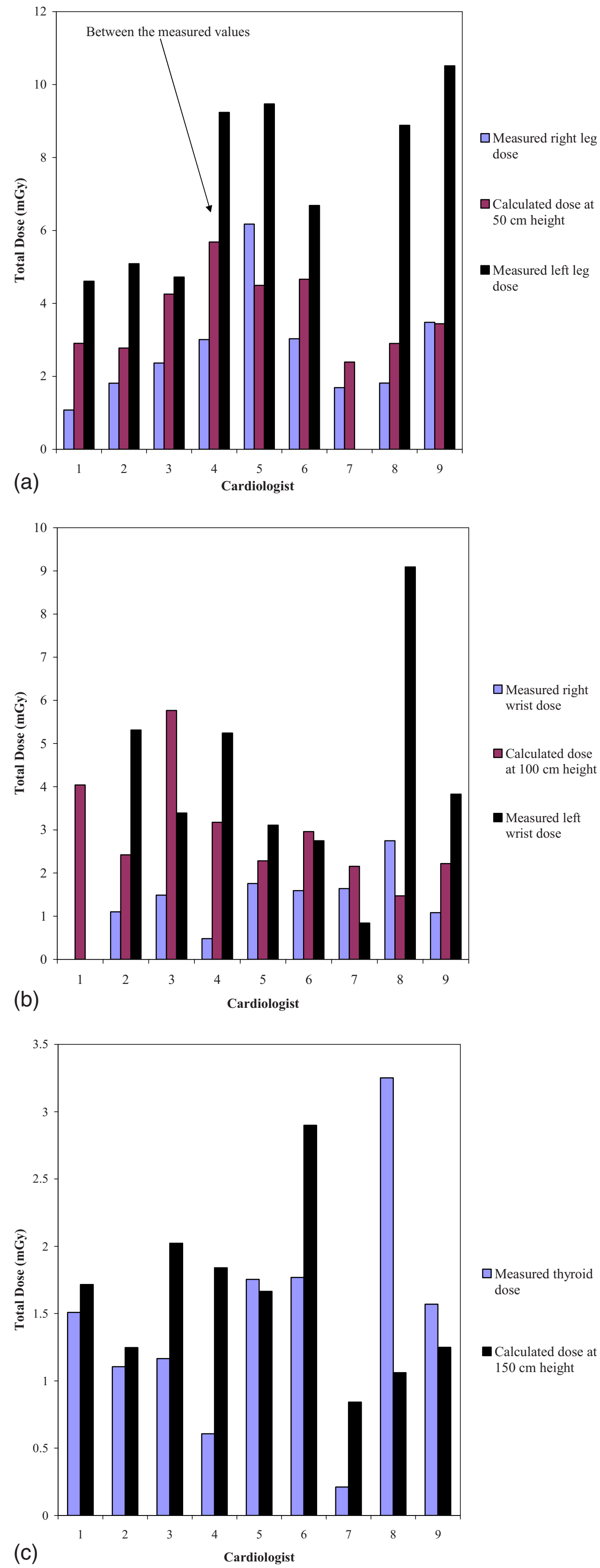

FIG. 2. (a) Comparison of measured leg and calculated doses at 50 cm for each cardiologist according to contribution of all projections. (b) Comparison of measured wrist and calculated doses at 100 cm for each cardiologist according to contribution of all projections. (c) Comparison of measured thyroid and calculated doses at 150 cm for each cardiologist according to contribution of all projections.

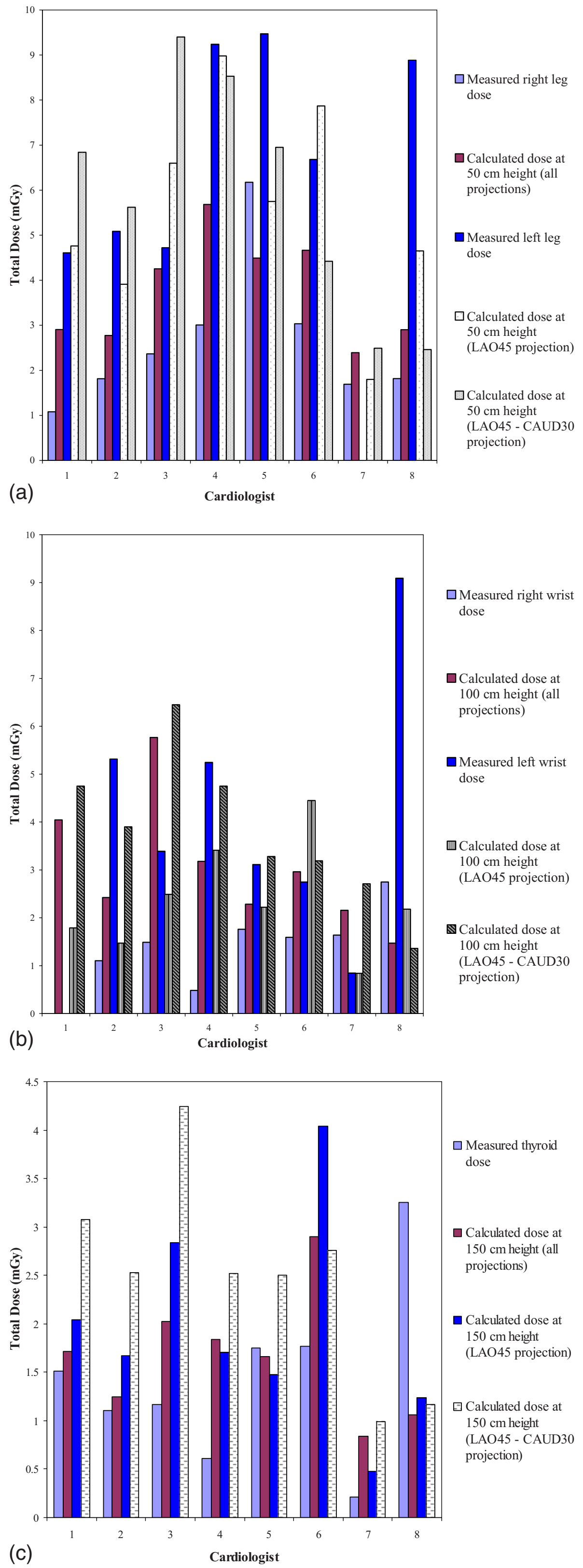

FIG. 3. (a) Comparison of measured leg and calculated doses at 50 cm for each cardiologist according to contribution of all projections and only LAO45 and only LAO45-CAUD30 projections. (b) Comparison of measured wrist and calculated doses at 100 cm for each cardiologist according to contribution of all projections and only LAO45 and only LAO45-CAUD30 projections. (c) Comparison of measured thyroid and calculated doses at 150 cm for each cardiologist according to contribution of all projections and only LAO45 and only LAO45-CAUD30 projections.

dicates an acceptable correlation of measurements with the calculated results. A similar correlation can also be seen for the doses measured over the thyroid and calculated for 150 cm height. The movement of the cardiologists from their position during the examination is one important reason for the discrepancy of results. Variations at the irradiation geometry and exposure technique among the patient examinations and Rando phantom study also contribute to this discrepancy.

In order to improve the accuracy of the dose calculations, Rando phantom irradiations were made for projections similar to those used in patient studies. As it is shown in Figs. 3(a)–3(c), instead of using the data specific to each projection, the use of one dominant projection (LAO45) data for all the projections degrades the correlation. This is even more pronounced if the second heavily used projection, LAO45-CAUD30, view is selected.

Calculation of extremity doses can be generalized; this requires the measurement of scatter radiation at the point of interest (for a certain fluoroscopy time and number of radiography frames) as well as information regarding the average fluoroscopy time and frame numbers used for a specific examination. However, the uncertainty in these dose estimation increases with these generalizations.

Review of the literature indicates large variations of staff doses in interventional cardiological examinations. The means (and the ranges) of the reported results of 168 (6–500) μGy/procedure for the eye lens, 94 (3.8–370) μGy/procedure for the thyroid, 408 (12–1100) μGy/procedure for the hands, and 75 (15–201) μGy/procedure for the legs are higher than our results with the exception of the effective dose of 6.1 (0.5–50) μGy/procedure which is of literature average.[16–36] The reported results for effective dose–DAP ratio also indicates a wide range (0.006–0.41 $\mu\text{Gy/Gy cm}^2$ per procedure) due to the effect of many factors for the effective dose calculation.[10] Including extremity dose–DAP ratio data to dosimetric information may help users to better compare the results reported by different centers.

Effective dose ratios calculated from double and single dosimeter readings exhibit a wide variation among the cardiologists (1.9–11). The higher effective doses obtained from double dosimeter readings were probably due to the use of thinner lead aprons at the waist level by the cardiologists

Personal dosimetry carried out with TLDs or film badges gives only retrospective dosimetric information. Therefore on line dose data may be needed following the high dose examinations. Furthermore, this information can also be used for the improvement of cardiologist work practice. In order to find a reliable ratio of cardiologists dose/patient DAP, a database including these measurements should be created for a specific x-ray system. The main difficulty of this technique is to measure the patient DAP and cardiologist doses simultaneously for a number of patients. Assessment of immediate dosimetric information from the scatter data is another solution; it eliminates patient dose information but requires the simulation of a clinical examination for a specific x-ray system. Establishment of an initial database is also required for this technique including scatter dose data at various points around the patient bed for fluoroscopic and radiographic exposure modes. The main practical difficulties of this method are in carrying out an exact simulation of a patient examination which requires preknowledge about the percentage use of projections for the examinations and also the selected exposure parameters. Once the scatter information for the dominant projections becomes available, cardiologists need to know only the total fluoroscopy time and number of radiographic frames of their patient studies for the estimation of their extremity doses. Quite accurate dose estimation can be done if this knowledge is possible on the projection base.

V. CONCLUSION

Cardiologists should carry both under and over apron (at the thyroid level) dosimeters during the interventional examinations, since they are exposed to radiation from many directions. Establishment of database relating staff doses to patient DAP could be very useful for the cardiologists to estimate their doses during or immediately after the patient examination. In case of prediction of personal doses from the scatter data, collection of dosimetric information separately for each projection improves the accuracy of these estimations.

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