ASSESSMENT OF THE OCCUPATIONAL EXPOSURE IN REAL TIME DURING INTERVENTIONAL CARDIOLOGY PROCEDURES

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Short Title: STAFF DOSES IN REAL TIME

Interventional cardiology (IC) procedures can be complex, requiring the operators to work near the patient, during long exposure times. Due to scattered radiation in the patient and the fluoroscopic equipment, the medical staff is exposed to a non-uniform radiation field and can receive high radiation doses. In this study, we propose to analyze staff doses obtained in real-time, during IC procedures. A system for occupational dosimetry in real-time was used. In order to identify some parameters that may affect the staff doses, Monte Carlo (MC) calculations, using MCNPX v.2.7.0 code and voxel phantoms, were performed. The data obtained from measurements, together with MC simulations, allowed us to identify actions and behaviors of the medical staff that could be considered a risk under routine working conditions. The implementation of this monitoring system for personnel exposure may have a positive effect on optimization of the radiological protection in fluoroscopically guided cardiac procedures.

INTRODUCTION

Cardiac interventional practices can be complex, requiring the operators to work at short distances from the patient, during long exposure times [1], [2]. Due to the scattered radiation in the patient and the fluoroscopic equipment, the staff is exposed to a non-uniform radiation field characterized by dose-rate values which rapidly vary from point to point inside the room [3], [4]. Consequently, the medical staff can receive high radiation doses during these interventional examinations.

A requirement for optimization of radiological protection is to know occupational dose levels and how different behaviors affect these levels [5]. This knowledge can be improved by providing the medical staff with instant feedback of their personal exposure, through a system for real-time visualization of occupational dose and dose rate [5], [6], [7]. This system is composed by individual electronic dosimeters that detect radiation dose rate with 1 s of interval. The dosimeters are calibrated to measure personal dose equivalent in soft tissue, at a depth of 10 mm ($H_p(10)$), and have wireless connection that sends the data to the equipment's display (base station). The radiation dose data can be managed by dedicated software to show the evolution of the cumulative dose and dose rate during a procedure for the different professionals. Moreover, the data can be stored to enable retrospective analysis [6], [7].

The aim of the present study is to analyze radiation doses in real time, during IC procedures. Moreover, we propose to assess the potentially high doses and simulate complex clinical scenarios using Monte Carlo (MC) simulations.

MATERIALS AND METHODS

Dosimetry in Real Time

In this work, staff radiation doses were measured by a real-time dosimetry system for whole-body exposure (RaySafe® i2 System), during 41 IC procedures. The measurements cover a period of 10 days and were performed at a cardiac cath lab of a Portuguese Hospital, equipped with a Siemens Artis zee biplane system (Siemens®), whose floor stand C-arm was used.

As can be observed in Figure 1, a cardiologist and a cardiovascular technologist are the professionals who perform the cardiac examinations and are considered the first and the second operators, respectively. They operate directly on the patient, closer to the x-ray tube than the rest of the staff. A second cardiovascular technologist stays farther from the patient table and may move around, inside the procedure's room, in order to provide the medical devices to the operators. The nurse monitors the vital signs of the patient, farthest from the x-ray tube. However, if it is necessary to assist the patient, the nurse may also move around the room and may be closer to the radiation source. Each professional was equipped with one personal dosimeter, placed above the lead apron at chest level. The radiation exposure was detected every second and wirelessly sent to a base station, positioned outside the cardiac cath lab. Accumulated radiation doses and dose rates of each professional were recorded. The dose data were analysed collectively, due to the limited number of procedures per professional, therefore the radiation dose data were associated with the working role.

All medical staff used lead aprons (0.5 mm Pb equivalent), and the operators also used thyroid collars (0.35 mm Pb equivalent) and lead glasses (0.5 mm Pb equivalent). A ceiling suspended lead screen and a lead curtain, suspended from the side of the patient table, both with 0.5 mm lead equivalence, were used during all procedures.

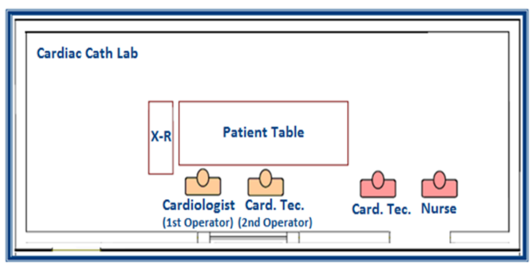

Figure 1 – Scheme of the position of the different personnel inside the cardiac cath lab.

Monte Carlo simulations

For MC simulations, the state-of-the-art computer program Monte Carlo N-Particle eXtended (MCNPX) code, version 2.7.0 [8] was used, and to simulate the medical staff, the voxel phantom named "Golem" was selected [9], due to its external dimensions being close to those of the ICRP Reference Man. This model represents an adult male at the age of 38 years, with 1.76 m height and 68.9 kg weight, having a spatial

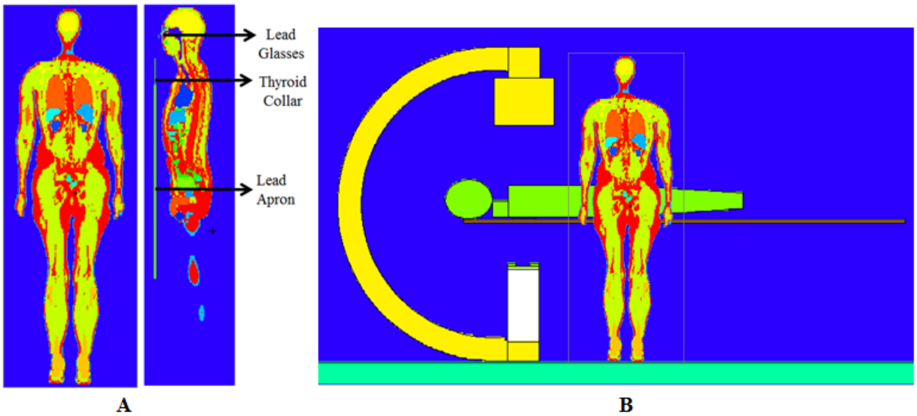

Figure 2 - Geometry implemented with MCNPX: A- Representation of the Golem voxel phantom and personal protective devices. B – Scheme of the C-arm equipment, patient and operation table, with Golem in the cardiologist's position.

resolution of 2.08x2.08x8 mm^3 [9]. The personal protective devices ere simulated (Figure 2-A), taking into account the professional groups studied: cardiologist and cardiovascular technologist. The nurse was not simulated explicitly, since his or her position inside the procedure's room is similar to the one assumed by the second cardiovascular technologist. The equipment mounted shield was also implemented in the simulations.

Considering the default conditions, F6 tallies, for energy deposition over a cell, were used to perform dose calculations in the following organs: eye lens, thyroid, right leg (adipose tissue) and left leg (adipose tissue). The energy range used in this work is relatively low, therefore the condition of charged particle equilibrium (CPE) is satisfied [4], [10]. Thus, the absorbed dose is equal to the collision kerma and the energy locally transferred to the electrons is also absorbed at the interaction site. Therefore, only the photon physics mode of the MCNPX was used.

The organ doses were normalized per KAP (Kerma-Area Product), and considering the radiation weighting factor for photons (W_R=1), the results were obtained in equivalent doses per KAP (μSv/Gy.cm^2). To calculate the KAP value, an air cell with 1 cm of thickness and an area of 15x15 cm^2 was placed between the patient and the operation table. The calculated entrance dose in this cell was then multiplied by the area of the beam at that point to obtain KAP.

In Figure 2-B is represented the geometry implemented with MCNPX of the cardiac cath lab, whose model was validated in previous works [11]. The focal spot of the x-ray tube was approximated by a point source, emitting a conical beam of primary photons in the direction of the imaging detector. The energy spectra (60 kVp, 80 kVp and 100 kVp) were generated by a program based on the x-ray data, of the Institute of Physics and Engineering in Medicine (IPEM) [12], taking into account the following parameters: tungsten target, 12º anode angle and 1.5mm of thickness for the aluminum flat filter [11]. Additionally to the C-arm equipment, the patient was simulated with simple geometric forms and composed by water. Three specific C-arm angulations typically used for CA examinations were studied: Posterior-Anterior (PA), Left Lateral (LLAT) and Right Anterior Oblique 30° without cranio-caudal angulation (RAO 30º) [13]. For these projections, scatter dose rate distribution plots around the C-arm were obtained using a mesh tally card of the MCNPX. Track-averaged mesh tally was selected to score the average flux, which was modified by an energy dependent function to obtain the dose rate [8]. A number between $1x10^9$ and $1.5x10^9$ of particle histories were run, which gives a statistical uncertainty up to 10% for the results of the smaller organs.

RESULTS AND DISCUSSION

Dosimetry in Real-Time

Figure 3 presents the accumulated personal doses for the 1st and 2nd operators, over the period of the study, obtained using the system for real time dosimetry. Similar plots were obtained for the second cardiovascular technologist and for the nurse, but only the dose data for the operators will be shown. Considering the 41 IC procedures, the accumulated occupational dose for the cardiologist was 0.458 mSv while the dosimeter used by the second operator registered an accumulated dose of 0.185 mSv. The physician registered a higher dose value due to his/her work position, near the x-ray tube. Moreover, in this cardiac cath lab, the arterial access commonly chosen to perform the examinations is the radial access, which also influences the proximity of the cardiologist to the patient and to the radiation source, leading to an increase of the occupational dose. Furthermore, the dose values measured by the electronic personal dosimeters are dependent on the angulations used on the C-arm during the procedures. If steeper angulations are used and if there is a poor practise of personal radiological protection (e.g. incorrect positioning of the lead screen), the cardiologist may receive higher radiation doses than the rest of the staff members.

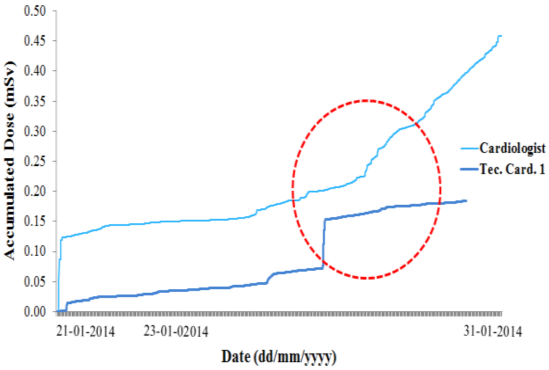

Figure 3 - Results of the accumulated occupational doses, over the period of the study, for the 1st operator and 2nd operator. The region where there is a steep increase of the accumulated dose is pointed out on the plot.

The collected dose data can be assessed with more detail and, for instance, it can be identified what caused the increase of the accumulated dose that is pointed out on the plot for both operators. Additionally, the patients' examination protocols related with the examinations performed during the period of the study were analysed.

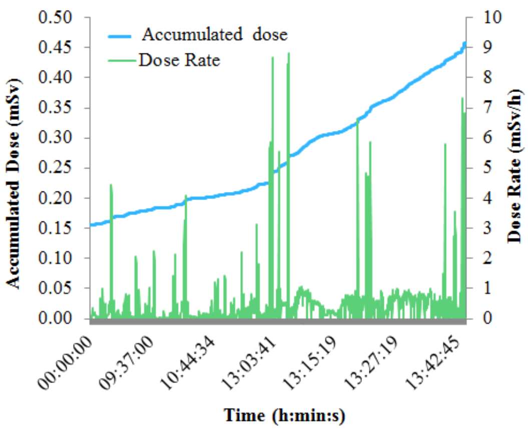

Figure 4 – Plot of the accumulated dose and dose rate for the 1st operator, considering the region pointed out on the plot of Figure 3.

In Figure 4, the occupational dose rate measured for the cardiologist is plotted along with the accumulated dose. The highest dose rate registered for the physician was 8.8 mSv/h. During the IC examination in which this dose rate was registered, a total KAP of 88.44 Gy.cm^2 was delivered to the patient with 18.35 min of fluoroscopy. Sixteen cine series were acquired at a frame rate of 15 f/s, which represents 52.13 % of the total KAP of the procedure. Consequently, the main contribution to the personal dose may be due to the cine acquisition mode, whose associated dose rate is higher than that used in fluoroscopy.

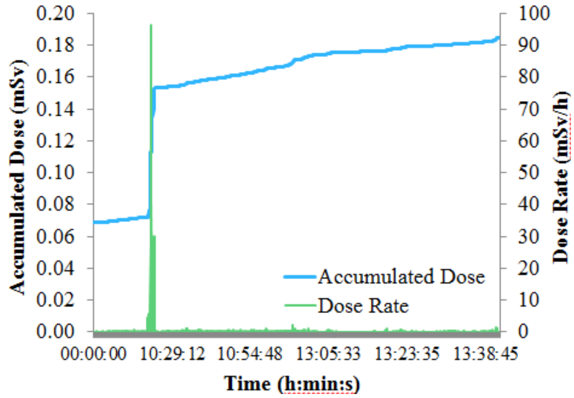

Figure 5 – Plot of the accumulated dose and dose rate for the 2nd operator, considering the region pointed out on the plot of Figure 3.

The plot in Figure 5 shows the accumulated dose and the occupational dose rate registered for the first cardiovascular technologist, taking into account the region signalled in Figure 3. The maximum dose rate recorded for the second operator was 96.5 mSv/h. In the corresponding IC procedure, a total KAP of 41.94 Gy.cm^2 was measured, with 7.2 min of fluoroscopy. The peak of the dose rate, presented on the plot in Figure 5, may be due to a single series acquisition that registered a KAP_{cine} value of 4.85 Gy.cm^2.

Personal radiation doses per IC procedure

In Figure 6, the personal radiation doses per IC procedure, analysed collectively, for each member of the medical staff is shown. Both operators (Cardiologist and Card. Tec .1) registered a median dose of 10 µSv/procedure. Concerning the second cardiovascular technologist (Card. Tec. 2), a median occupational dose of 20 µSv/procedure was received, while the nurse obtained a median dose of 2.7 µSv/procedure.

It can be observed that the range of the measured values and the large variation registered between the professional groups is mainly due to the influence of the position of the medical staff inside the cardiac cath lab, relative to the x-ray source and to the patient. The highest median occupational dose was verified for the second cardiovascular thecnologist, probably due to his working role inside the procedure room. When the technonologist provides the medical devices to the operators, he/she may move around the room, near the radiation source, in high scatter dose areas, which depends on the C-arm angulations used to perform the procedure. This also may explain the range of the occupational dose values observed for this professional. Moreover, factors as the complexity of the procedure, adequate use of the equipment-mounted shields, differences in the use of the imaging angulations and in the selection of the technical parameters of the fluoroscopic equipment and experience of the operators may contribute to the large variations found for the members of the medical staff.

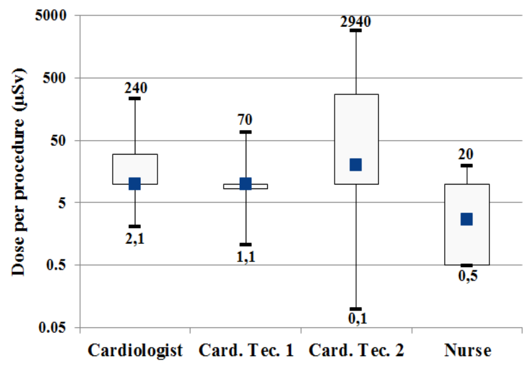

Figure 6 - Box plot showing dose per procedure for each professional group. The lower and upper limits of the box are the first and third quartile, respectively. The marker inside the box is the median value. The bars, with corresponding numbers, represent the range of the measured dose values.

Nevertheless, the radiation doses measured in this study for medical staff working with interventional procedures are consistent to those normally reported in other works found in the literature [5], [6], [7].

Equivalent dose per KAP

Table 1 lists the equivalent dose per KAP results calculated for the critical organs of the medical staff, as a function of energy, for PA, LLAT and RAO30 projections. Regarding PA projection, the eye lenses and thyroid registered high. The second operator (Card. Tec. 1) presents higher values than the cardiologist since he is not completely protected by the suspended lead screen. For LLAT projection, the equivalent doses per KAP are generally higher than for AP projection, and the physician has the highest values due to his proximity to the x-ray tube. Concerning RAO30 angulation, the equivalent doses per KAP are lower than for the other projections, for all the positions assumed by the medical staff evaluated. In this C-arm angulation, the source is further away from the exposed staff than in the other cases.

Occupational scatter dose rate

In Figure 7, the scatter dose rate distribution obtained with MCNPX for 80kVp X-ray energy can be seen for PA, LAT and RAO30 projections. These plots consider both scattered radiation due to the patient and the C-arm fluoroscopic equipment. Generally, a dose rate between 1.3 mSv/h and 41.5 mSv/h was obtained for each angulation studied and a rapid variation of the dose rate from point to point inside the room was observed.

Higher fluxes were achieved for LLAT projection compared with the other projections studied in this work. This fact lead us to believe that this type of angulation should be avoided due to its proximity of the cardiologist to the x-ray source whenever it is possible for the realization of the procedure and for the safety of the patient.

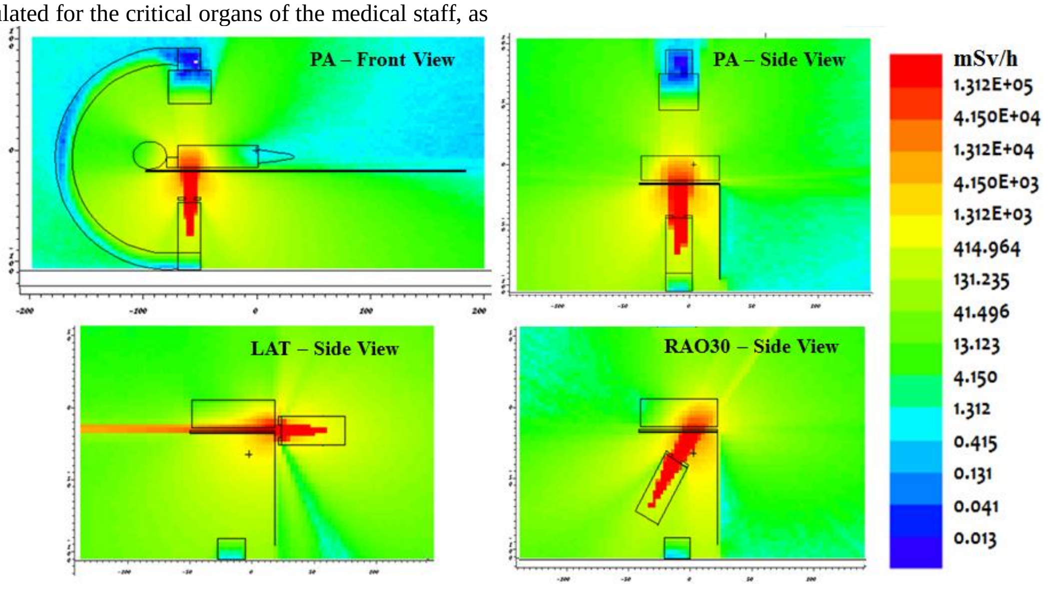

Figure 7 - Scatter dose rate distribution (mSv/h) obtain with MCNPX simulations, for 80kVp X-ray energy, considering PA, LLAT and RAO30 projections.

CONCLUSION

The historical data, together with MC simulations, allowed us to identify actions and behaviors of the medical staff that could be considered a risk under routine working condition: position of medical staff and their experience in the use of protective shielding, play a very important role in terms of radiation protection but, the use of steep angulations such as LLAT should be avoided due to its higher fluxes.

These facts suggest that the implementation of a monitoring system for dosimetry in real time may have a positive effect on optimization of the occupational radiological protection: medical staff can manage their position; optimization of the exposure time; optimization of technical parameters (equipment); possibility of dose data recording to perform retrospective analysis.

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References

1. Ferrari, P., Venturi, G., Gualdrini, G., Rossi, P.L., Mariselli, M., Zannoli, R. Evaluation of the dose to the patient and medical staff in interventional cardiology employing computational models. *Radiat Protec Dosim,* 1-4 (2010).
2. Ingwersen, M; Drabik, A;Kulka, U; Oestreicher, S. Fricle, H. Krankerberg, C. Schwencke; D. Mathey, Physicians' Radiation Exposure in the Catherization Lab *JACC*, 6, 1095-102 (2013).
3. Bozkurt, A., Bor, D., Simultaneous determination of equivalent dose to organs and tissues of the patient and of the physician in interventional radiology using Monte Carlo method. Phys Med Biol, 52, 317-330 (2007).
4. Koukorava, C., Carinou, E., Ferrari, P., Krim, S., Struelens, L.. Study of the parameters affecting operator doses in interventional radiology using Monte Carlo simulations. *Radiat Meas*, 46, 1216-1222 (2011).
5. Sandblom, V; Mai, T; Almen, A; Rystedt, H; Cederblad, A; Bath, M; Lundh, C. Evaluation of the impact of a system for real-time visualisation of occupational radiation dose rate during fluoroscopically guided procedures. *J. Radiol. Prot.*, 33, 693-702 (2013).
6. Vano, E; Fernandez, J; Sanchez, R. Occupational dosimetry in real time. Benefits for interventional radiology. *Radiat Meas,* 46, 1262-65 (2011).
7. Sanchez, R; Vano, E; Fernandez, J; Gallego, J; Staff radiation doses in real-time display inside the angiography room, CVIR , 33, 1210-1214 (2010).
8. Pelowwitz, D. B. MCNPX User's Manual Version 2.7.0. Los Alamos National Security (2011).
9. Zankl, M; Wittmann,A. The adult male voxel model “Golem” segmented from whole-body CT patient data. Radiat Environ Biophys, 40, 153-162 (2001).
10. Carinou, E., Ferrari, P., Koukorava, C., Krim, S., Struelens, L. Monte Carlo calculations on extremity and eye len dosimetry for medical staff at interventional radiology procedures. Radiat Protect Dosim, 144, 492-496 (2011).
11. Baptista, M; Teles, P; Cardoso, G; Vaz, P. Assessment of the dose distribution inside a cardiac cath lab using TLD measurements and Monte Carlosimulations. Radiat. Phys. Chem. In press (2014).
12. Cranley, K; Gilmore, B J; Fogerty, G W. Desponds L. Catalogue of diagnostic spectra and other data. Report No. 78, York, UK : Institute of Physics and Engineering in Medicine (1997).
13. Vano, E.; Fernandez, J; Haskal, Z. Eye Lens Exposure to Radiation in Interventional Suites: Caution Is Warranted. Radiology, 248, 945-53 (2008).

Table 1- Equivalent dose per KAP for critical organs of the medical staff, as a function of energy, considering PA, LLAT and RAO30 projections.

Projections	Energies (kV_p)	Medical Staff	Organs							
			Left leg		Right leg		Eye lenses		Thyroid	
PA	60 kVp	Cardiologist	0.0130	(0.02%)	0.0055	(0.01%)	0.0216	(0.60%)	0.0684	(0.29%)
		Card. Tec 1	0.0069	(0.01%)	0.0042	(0.01%)	0.0271	(0.54%)	0.0146	(0.13%)
		Card. Tec 2	0.0130	(0.02%)	0.0055	(0.01%)	0.0216	(0.60%)	0.0684	(0.29%)
	80 kVp	Cardiologist	0.0273	(0.03%)	0.0109	(0.02%)	0.0504	(1.04%)	0.1816	(0.57%)
		Card. Tec 1	0.0144	(0.02%)	0.0087	(0.01%)	0.0733	(0.85%)	0.0423	(0.23%)
		Card. Tec 2	0.0189	(0.02%)	0.0153	(0.02%)	0.0285	(0.73%)	0.0113	(0.15%)
	100 kVp	Cardiologist	0.0426	(0.03%)	0.0170	(0.02%)	0.0538	(0.88%)	0.3030	(0.71%)
		Card. Tec 1	0.0230	(0.02%)	0.0134	(0.02%)	0.1087	(1.05%)	0.0738	(0.30%)
		Card. Tec 2	0.0263	(0.03%)	0.0207	(0.02%)	0.0479	(0.79%)	0.0208	(0.18%)
LLAT	60 kVp	Cardiologist	0.3024	(0.08%)	0.0157	(0.02%)	0.2555	(2.03%)	0.0355	(0.22%)
		Card. Tec 1	0.0464	(0.03%)	0.0156	(0.02%)	0.0860	(1.19%)	0.0446	(0.26%)
		Card. Tec 2	0.0235	(0.02%)	0.0077	(0.01%)	0.0494	(0.88%)	0.0257	(0.19%)
	80 kVp	Cardiologist	0.3648	(0.09%)	0.0261	(0.02%)	0.2618	(1.87%)	0.0655	(0.28%)
		Card. Tec 1	0.0698	(0.04%)	0.0250	(0.02%)	0.1189	(1.23%)	0.0741	(0.31%)
		Card. Tec 2	0.0698	(0.03%)	0.0250	(0.02%)	0.1189	(0.97%)	0.0741	(0.22%)
	100 kVp	Cardiologist	0.4218	(0.09%)	0.0373	(0.03%)	0.3855	(2.21%)	0.1097	(0.37%)
		Card. Tec 1	0.0893	(0.04%)	0.0337	(0.03%)	0.1617	(1.27%)	0.0982	(0.34%)
		Card. Tec 2	0.0893	(0.03%)	0.0337	(0.02%)	0.1617	(1.20%)	0.0982	(0.25%)
RAO 30	60 kVp	Cardiologist	0.0721	(0.05%)	0.0087	(0.02%)	0.0356	(0.77%)	0.0287	(0.24%)
		Card. Tec 1	0.0138	(0.02%)	0.0057	(0.02%)	0.0180	(0.61%)	0.0113	(0.16%)
		Card. Tec 2	0.0067	(0.01%)	0.0036	(0.01%)	0.0129	(0.39%)	0.0029	(0.06%)
	80 kVp	Cardiologist	0.1482	(0.06%)	0.0199	(0.02%)	0.0802	(1.12%)	0.0913	(0.41%)
		Card. Tec 1	0.0299	(0.03%)	0.0124	(0.02%)	0.0659	(1.04%)	0.0323	(0.28%)
		Card. Tec 2	0.0136	(0.02%)	0.0072	(0.01%)	0.0300	(0.63%)	0.0110	(0.12%)
	100 kVp	Cardiologist	0.2223	(0.08%)	0.0322	(0.03%)	0.1541	(1.42%)	0.1568	(0.53%)
		Card. Tec 1	0.0476	(0.04%)	0.0199	(0.02%)	0.1153	(1.40%)	0.0613	(0.33%)
		Card. Tec 2	0.0208	(0.02%)	0.0113	(0.02%)	0.0419	(0.66%)	0.0194	(0.16%)