The influence of operator position, height and body orientation on eye lens dose in interventional radiology and cardiology: Monte Carlo simulations versus realistic clinical measurements

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Abstract

Objective: This paper aims to provide some practical recommendations to reduce eye lens dose for workers exposed to X-rays in interventional cardiology and radiology and also to propose an eye lens correction factor when lead glasses are used.

Methods: Monte Carlo simulations are used to study the variation of eye lens exposure with operator position, height and body orientation with respect to the patient and the X-ray tube. The paper also looks into the efficiency of wraparound lead glasses using simulations. Computation results are compared with experimental measurements performed in Spanish hospitals using eye lens dosemeters as well as with data from available literature.

Results: Simulations showed that left eye exposure is generally higher than the right eye, when the operator stands on the right side of the patient. Operator height can induce a strong dose decrease by up to a factor of 2 for the left eye for 10-cm-taller operators. Body rotation of the operator away from the tube by 45°-60° reduces eye exposure by a factor of 2. The calculation-based correction factor of 0.3 for wraparound type lead glasses was found to agree reasonably well with experimental data.

Conclusions: Simple precautions, such as the positioning of the image screen away from the X-ray source, lead to a significant reduction of the eye lens dose. Measurements and simulations performed in this work also show that a general eye lens correction factor of 0.5 can be used when lead glasses are worn regardless of operator position, height and body orientation.

Keywords: Eye lens dose; Interventional radiology; Lead glasses; Correction factor.

1. Introduction

The International Commission on Radiological Protection has recommended a reduction of the occupational dose limit for the eye lens from 150 mSv to 20 mSv, averaged over 5 years, with no single year exceeding 50 mSv[1]. This change has been incorporated into the European and International Basic Safety Standards [2,3]. Furthermore, several studies performed on operators in interventional cardiology and radiology (IC/IR) have shown that this newly recommended limit of 20 mSv can be exceeded in numerous cases [4–9].

International organizations, such as the International Organization for Standardization and the International Electrotechnical Commission [10,11], have stressed the importance of radiation protection tools for eye lens dose reduction in IC/IR. The ceiling suspended screen, when correctly positioned, and the lead glasses, are two of the most important tools that can provide this protection. Even though the lead screen provides high protection, often its usage is not practical and it can impede the operator's work. In these cases, lead glasses are an alternative solution. Several studies performed using Monte Carlo simulations or phantom studies in clinical environment have investigated the efficiency of lead glasses [12–17]. However, such data correspond to static situations whereas, in clinical routine, operators move along the patient. To this day, very few measurements have been performed during clinical practice on operators. In general, these measurements highlight that the attenuation of the ceiling shielding and lead glasses is lower than the nominal value provided by manufacturer. In fact, primary beam attenuation largely overestimates the glasses protection efficiency. Other factors, such as the radiation impinging on the eyes laterally or from beneath the glasses, through the gap between the face and the glasses themselves, and the contribution from radiation scattered by the unprotected part of the operator's head, are of concern [12].

The present work, organized within the EURADOS working group 12 (Dosimetry in Medical Imaging), aims, on the one hand, at studying the influence on the eye lens exposure of operator position, height and body orientation using Monte Carlo simulations and, on the other hand, at studying the protection efficiency oflead glasses in real clinical conditions. More specifically the following parameters were studied:

– the effect of operator position with respect to the patient when lead glasses are not worn;
– the influence of the presence of the image intensifier, the tube voltage and the operator's height;
– the protection efficiency of lead glasses for different operator positions and body orientations with respect to the patient;
– a comparison of the estimation of lead glasses protection obtained with static Monte Carlo situations against measurements performed in real clinical conditions.

2. Materials and methods

2.1 Monte Carlo simulations

The MCNPX v.2.5 Monte Carlo code was used [18] to study the influence of different parameters on operators' eye lens dose. The simplified IC/IR scenario defined in the framework of the European projects ORAMED [19] and ELDO [14] was adopted in this study. In these simulations, both the patient and the operator, who stands on the right side of the patient, were represented by two modified anthropomorphic ORNL-MIRD phantoms [20].Very thin tally volumes of 4 10^{-3} mm thickness were introduced at a depth of 3 mm in the soft tissue of the eye to calculate the personal dose equivalent $H_p(3)$. $H_p(3)$ was calculated by using the energy deposition tally (F6 tally) in kerma approximation mode, disregarding the transport of secondary generated particles for the left and the right eye. A 90 kV peak-voltage X-ray beam with 3 mm Al added filtration was used. The reference operator height is 178 cm.

A first study was carried out in order to evaluate the influence of operator position and body rotation on eye lens dose when lead glasses are not worn. Several distances (0, 20, 40 and 70 cm) between the operator and the X-ray source were considered together with the following operator body orientations: 0, 10, 30, 45 and 60 degrees, towards and away from the tube. A simplified sketch of the configurations is illustrated in Figure 1. The selected distances represent the position of the operator for jugular access (0 cm), radial access for pediatric (20 cm) and adult patients (40 cm) and femoral access (70 cm). For these simulations (Fig. 2b), a postero-anterior projection is considered. The patient is lying down on the table in the supine position, with the X-ray field centered on the patient's thorax and the radiation going from the back to the front.

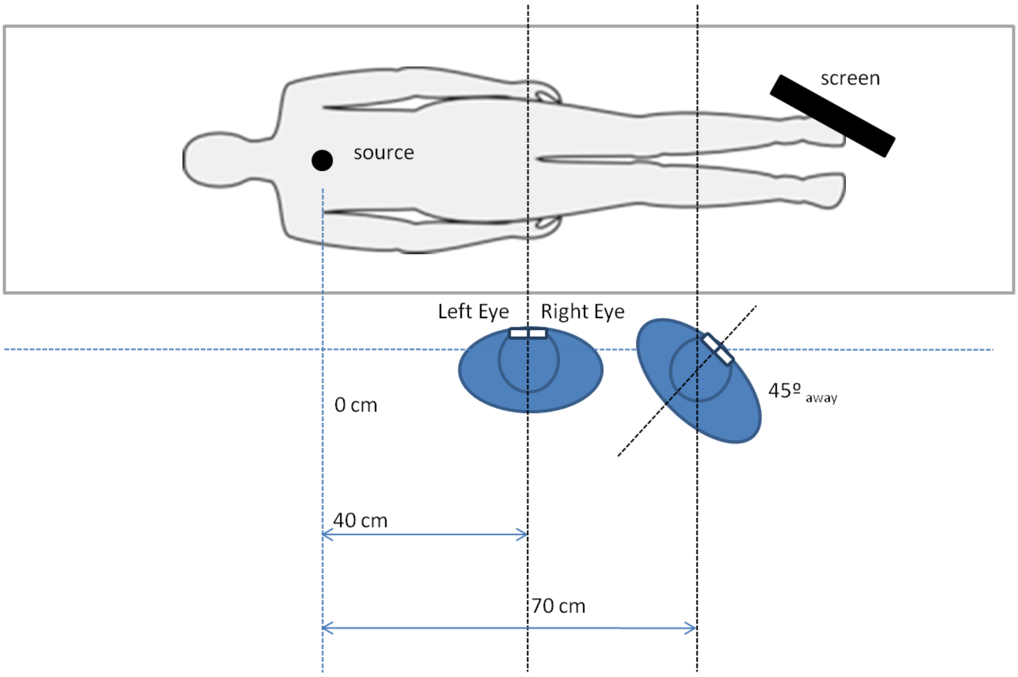


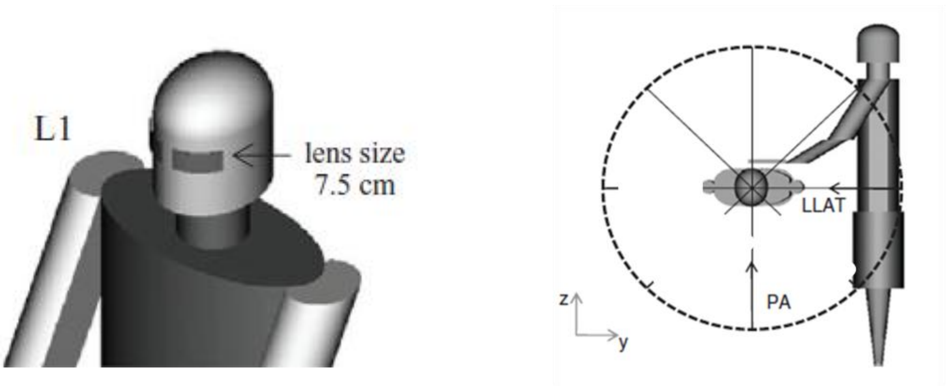
Fig.1: Simplified geometry with some of the possible configurations of the clinical simulated scenario. In this figure the operator is at 40 cm distance and 0° orientation (no rotation) and at 70 cm distance and rotated 45° away from the source (towards the image screen).

Depending on the relative position of the operator, the image intensifier can provide attenuation of the scattered radiation that reaches the operator eye. In order to investigate this, a cylindrical lead shell of 2-mm-thick filled with air and an input window of 1.5 mm aluminum were used to represent the image intensifier. Simulations were repeated by replacing the lead and aluminum materials by air, for the above mentioned distances. The rotation of the operator with respect to the source was not considered.
The effect of tube voltage on the operator eye lens was studied by repeating calculations for a 110 kV peak voltage radiation beam with 3 mm aluminum added filtration at distances of 0, 20, 40, 70 cm and 0° rotation. Eye lens dose values were compared against the beam with lower voltage (90 kV). The higher voltage is usually set for a larger patient.

In order to study the influence of eye lens exposure for an operator who is either shorter or taller than the reference operator, calculations for operator heights of 158, 168 and 188 cm were also included. Simulations were performed for distances of 0, 20, 40, 70 cm and 0° rotation.

In order to study the efficiency of the lead glasses the wraparound style was modeled as defined in Koukorava et al. [14] with 0.5 mm lead thickness and 7.5 mm lens size (Fig. 2a). Two field dimensions were investigated in this scenario resulting in a 30 and 20 cm diameter field at the level of the patient thorax, for postero-anterior and left-lateral projections respectively (Fig. 2b). When using lead glasses, ISO 15382 [10] recommends to use a dosemeter worn, preferably, behind the lead part of the glasses. However, this option is usually not very practical. An alternative solution is to wear a dosemeter close to the eye on an unprotected part and to apply a proper correction factor that takes into account the protection provided by the glasses. In this work, the protection efficiency of the lead glasses was hence estimated as the correction factor (CF) as defined in [10]. CF is the ratio of the dose to the eyes when lead glasses are used and when they are not:

$$CF = \frac{H_p(3)_{with}}{H_p(3)_{without}}$$



(a) (b)

Fig.2(a) Wraparound type lead glasses (L1 model in [14]).
(b) Projections considered in simulations: postero-anterior (PA) and left-lateral (LLAT).

2.2 Measurements in clinics

In order to test the efficiency of lead glasses in protecting the eyes in clinical conditions, eye lens monitoring was performed for six experienced physicians from the hemodynamic unit of four different hospitals in Spain.

Each participant wore their own lead glasses, shown in Figure 3. In one case, wraparound lead glasses were used (Fig. 3a). The others wore the glasses of different designs shown in Figure 3b and 3c, which provided lateral shielding. The frontal lenses of the glasses have a thickness of 0.75 mm of lead equivalent material. The personal dose equivalent $H_p(3)$ was measured using the UPC eye lens dosemeter, as described in Principi et al. [21]. The performance of the dosemeter in realistic fields was verified through the results of the EURADOS intercomparison exercise of eye lens dosemeters [22]. Two dosemeters were assigned to each operator. For (b)- and (c)-type glasses, one dosemeter was set on the left external lateral part of the eyewear while the other was located on the internal side, beneath the shielding. In the case of the type (a) wraparound glasses, a dosemeter was situated on the internal side of the left front glass, since there is no shield on the side, in a position that did not produce visual impairment (Fig. 3a, arrow). The dosemeters were changed periodically. The minimum exposure time for each pair of dosemeter was established from previous studies in phantoms [21] in order to ensure an accumulated dose of at least 70 µSv. The total follow-up period for each operator varied between three and six weeks, depending on operator workload and availability.

(*a*) (*b*) (c)

Fig.3 (*a*) wraparound type glasses; (*b*) lead glasses with side protection; (*c*) lead glasses with side protection, but with smaller frontal and lateral lenses with respect to type *b* glasses.

3. Results

Table 1 shows the ratio of the left and right eye lens personal dose equivalent calculated using Monte Carlo simulations. Data were obtained for a postero-anterior projection and for the different studied operator's positions: configuration *away from the tube* (columns 2 to 5) and *towards the tube* (columns 6 to 8). The latter is a quite unlikely scenario in interventional cardiology and radiology practice. In this case, the left eye is generally the most exposed, but the ratios between the two eyes is almost 1, i.e. the dose cumulated in left and right eye are similar and differences are sometimes within the statistical uncertainty. The statistical uncertainty of the simulation results was 1% (1 sd) in most cases, except for the cases of 45 and 60° rotation away from the tube where the uncertainty was of 3% (1 sd). Simulations were performed without lead glasses since the aim of this part of the study was to evaluate the influence of operator position and rotation on left and right eye lens doses when no protection means are used.

At 0 cm distance (jugular access-typical position) and 0° and 10° rotation, there are no differences between the left and right eye doses, while for larger angles the eye closer to the tube receives the largest amount of dose. When the operator is looking *away from the tube* (Table 1, column 2), this is when the monitoring screen is set to his right, the most exposed eye is the left one. In realistic clinical conditions, the operator always turns towards the screen when hitting the X-ray pedal to be able to visualize the progress of the catheter and to perform the intervention.

At distances of 20, 40 and 70 cm for an operator turning *away from the tube*, which represents the most likely situation in routine practice, the left eye is always the most exposed one. In addition, as shown in Table 1 (col. 3 to 5), the ratio between the dose to the left eye and right eye increases with angle and distance, even though, changing from 45° to 60° away from the tube, it remains almost constant. In these latter cases, the dose to the right eye is almost negligible, since it is mainly due to backscatter from the head [12].

Table 1: Ratios $H_p(3, LE)/H_p(3, RE)$ in configuration - *away from the tube* and *towards the tube* for the postero-anterior projection and when lead glasses are not worn. LE stands for Left Eye and RE for Right Eye.

$H_p(3, LE)/H_p(3, RE)$							
	away from the tube				*towards the tube*		
Angles (°)	0 cm	20 cm	40 cm	70 cm	20 cm	40 cm	70 cm
0	1.0	1.2	1.3	1.5	1.2	1.3	1.5
10	1.0	1.2	1.5	2.3	1.0	1.2	1.4
30	1.1	1.6	2.8	5.4	1.1	1.1	1.2
45	1.3	3.6	6.6	13.1	1.0	1.2	1.1
60	2.2	4.3	6.0	12.6	0.8	0.9	1.0

Figure 4 shows the normalized dose values with respect to the left eye dose at 40 cm distance and for 0° rotation. Values correspond to the configuration *away from the tube*. This condition yields the highest doses to both eyes in case of postero-anterior projection.

It can be seen that increasing the rotation of the head diminishes the dose to both eyes when the operator is standing at distances of more than 40 cm from the X-ray tube. This was also verified by Koukorava et al. [14]. Rotations higher than 45° entail a drop in dose of more than 50% for the left eye with respect to the 0° rotation.

The relative lower dose at 0 cm and 20 cm compared with the dose at 40 cm can be explained by the simulations performed with and without the image intensifier. The ratio between the eye lens dose with and without the image intensifier is about 3 at 0 cm distance, within the limits of the present simulations in terms of imaging device modeling. Thus, it can be confirmed that the image intensifier works as a shield when it is near the operator; in the present simulations this effect can be seen for distances lower than 40 cm from the X-ray beam axis for the postero-anterior projection.

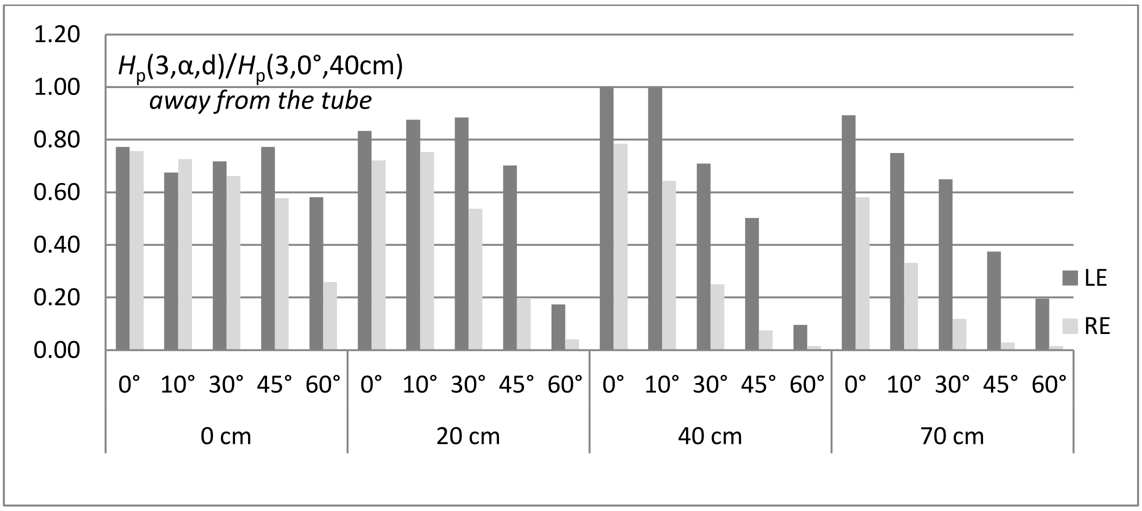


Fig. 4 Eye lens dose distribution for all distances normalized with respect to the left eye dose at 40 cm distance and 0 degree rotation, for the postero-anterior projection (operator is not wearing lead glasses).

Both eye lens dose values were found to increase by about 25% when tube voltage was increased from 90 kV to 110 kV with 3 mm Al filtration for all tested situations and operator-field distances of 0, 40, 70 cm and 0° rotation.

Table 2 highlights the influence of operator height on the left eye lens dose. It shows the ratio between the left eye lens dose for three different phantoms heights, of 158, 168 and 188 cm,and the left eye lens dose of the reference phantom height (ref = 178 cm). The phantom height plays a crucial role in diminishing the cumulated doses. Calculations show that eye lens dose decreases when the "vertical" distance between the operator eyes and the patient surface increases. This effect is important when the operator is close to the X-ray tube (0 and 20 cm): in this case the left eye dose can change by a factor of 2 in case of a 10-cm shorter operator (168/ref case). This effect is mitigated by increasing the lateral distance (e.g. from radial to femoral access). Meanwhile, a taller operator (column 4) leads to doses to the left eye lens reduced by a factor of 2 for 0 and 20 cm distance; this reduction is smaller for 40 and 70 cm distances.

Table 2. Left eye dose ratios for different operator's heights (158 cm, 168 cm and 188 cm) and a reference height of 178 cm.

Distance	158/ref	168/ref	188/ref
0 cm	3.2	2.0	0.5
20 cm	2.8	1.9	0.5
40 cm	1.9	1.4	0.6
70 cm	1.3	1.2	0.8

Monte Carlo results of the ratio of $H_p(3)$ values with and without lead glasses (CF) for postero-anterior and left-lateral irradiation are shown in Table 3. Some relevant data from Koukorova et al. [14] are also included for comparison. It can be seen that, at 0°, the protection effectiveness of the glasses for the left eye increases as distance increases, whilst it decreases for the right eye (as shown in Figure 4, without glasses the right eye is the least exposed).

Likewise, the protection efficiency of lead glasses is generally increased when the operator faces the X-ray tube compared to when he is looking away. This is due to the fact that a larger amount of scattered radiation directly strikes the lens of the glasses. Similar observations have been found by Koukorava et al.[14]. Such a protective effect is reduced at 70 cm distance, where no relevant difference is observed within CF at several angles.

Considering the most likely operator positions, which are 0, 40 and 70 cm distance for rotation angles up to 45°, the correction factor for the most exposed eye (the left one), for 0.5-mm-thick wraparound-style lead glasses, ranges from 0.11 to 0.58. The lowest protection (0.58) belongs to the femoral access configuration (70 cm) with 45° rotation away from the tube: from Figure 4 it can be seen that this value corresponds to the lowest dose, for the considered realistic configurations, and thus the reduction of the protective efficiency should not be of concern.

Table 3. Ratio of $H_p(3)$ values with and without lead glasses (CF) for postero-anterior and left-lateral irradiation (data from Kourokava et al. [14] are also included for comparison). LE stands for Left Eye, RE for Right Eye.

		CF				
		Postero-anterior		Left-lateral		
		LE	RE	LE	RE	Reference
0 cm	0°	0.51	0.52	--	--	[14]
40 cm	0°	0.2	0.78	0.23	0.92	[14]
	30°_towards	0.27	0.31	0.21	0.39	Present work
	30°_away	0.34	1.19	0.32	0.98	Present work
	45°_towards	0.32	0.22	0.29	0.29	Present work
	45°_away	0.41	0.88	0.40	0.79	Present work
	60°_towards	0.53	0.2	0.45	0.2	Present work
	60°_away	0.58	0.8	0.31	0.58	Present work
70 cm	0°	0.15	0.89	0.12	0.97	[14]
	30°_towards	0.15	0.24	0.11	0.31	Present work
	30°_away	0.25	0.95	0.28	0.92	Present work
	45°_towards	0.15	0.16	0.11	0.18	[14]
	45°_away	0.42	0.78	0.58	0.7	[14]
	60°_towards	0.17	0.16	0.12	0.12	Present work
	60°_away	0.84	0.82	0.89	0.76	Present work

Measured CF in real clinical conditions for types of lead glasses shown in Figure 3 are presented in Table 4. The number of collected data is shown in line 6. Uncertainties of $H_p(3)$, calculated following the Guide to the Expression of Uncertainty in Measurement [23], are of the order of 6 % (1sd). The lower detection limit of the employed dosemeters, at a confidence level of 95 %, is 1 μSv. For the wraparound lead glasses (Fig 3a), the measured CF ranged between 0.21 and 0.41, with a mean value of 0.31. Meanwhile, for the (b) and (c) models, the CF ranged from 0.25 to 0.72, with a mean value of 0.37. The highest CF (0.72), which indicates the lowest protection efficiency, belongs to the (c) model that has the less efficient protection design with smaller frontal and lateral lenses if compared to the other glasses type. Glasses type (c) mean CF is about 0.5 (i.e. they halve the doses) while for the (a) and (b) models is around 0.3 (i.e. they reduce doses to 1/3).

Table 4. Ratio of $H_p(3)$ values with and without lead glasses (CF) obtained in experimental measurements. Mean, minimum, maximum and number N of data collected for each model of glasses are listed.

	CF		
Glasses model	Wrap around glasses (Fig.3 type a)	Lateral shielding - large lenses (Fig.3 type b)	Lateral shielding – small lenses (Fig.3 type c)
Mean	0.31	0.32	0.54
Min	0.21	0.25	0.36
Max	0.41	0.52	0.72
N	3	7	3

4. Discussion

As previously stated, one of the main goals of this study was to combine Monte Carlo simulations and experimental results to better understand the eye lens exposure in routine conditions of interventional cardiology and radiology. As a matter of fact, Monte Carlo simulations are useful to study the eye lens dose changing some exposure parameters individually, such as X-ray tube projection, operator position, type of lead glasses, etc. However, calculations fail to realistically reproduce clinical practice and the geometry of the patient, operator and glasses are sometimes over-simplified with respect to clinical conditions. On the other hand, data from clinical practice are, obviously, realistic but suffer from high variability of different parameters depending on patient, operator, difficulty of the procedure, adopted practice etc. Thus, large differences on measurements are not only found among the various hospitals and operators but also for the same operator.

Since a clinical procedure involves different positions and body orientations of the operator with respect to the radiation source, a mean CF is calculated from Monte Carlo results in Table 3. Two hypotheses are considered. Firstly, the mean value of all CFs for the left eye is calculated including all distances and angles and the two projections, postero-anterior and left-lateral. Secondly, and based on feedback from routine practice, the mean CF is obtained by using only the most likely operator positions (i.e. 40 cm and 70 cm) and body orientations (0°, 30° and 45° away from the tube). Following these hypotheses, mean, standard deviation, maximum and minimum values of CF are presented in Table 5 in columns 2 and 3. For the first hypothesis, the mean CF value is 0.33 (sd=0.22). For the second hypothesis, it is 0.31 (sd=0.15):

both results are consistent. Furthermore, the two results agree with findings from the work of Koukorava at al. (column 4) [14]. These data are also consistent with our experimental results for the wraparound glasses (Table 5, column 5).

Table 5. Mean, standard deviation, maximum, minimum values of CF obtained for wraparound glasses with: Monte Carlo (MC) calculations, for hypotheses 1 and 2 (hyp.1: all MC, hyp.2: MC for 0, 30, 45°*away from the tube*), experimental measurements performed here and data from the literature.

	MC calculated **CF**			Measured **CF**				
	This study, hyp.1	This study, hyp.2	Kourokava hyp.2 [14]	This study, table 4, col. 2	Maggie [17]	Moore [16]	Thornton [15]	Van Rooijen [13]
Mean	0.33	0.31	0.32	0.31	0.22	0.24	0.14	0.32
SD	0.22	0.15	0.18	0.10	0.05	0.07	0.04	0.24
Max	0.89	0.58	0.58	0.41	0.53	0.29	0.19	0.62
Min	0.11	0.12	0.12	0.21	0.15	0.14	0.10	0.12

For comparison, other published experimental studies are also shown in Table 5, columns 6 to 9. These were performed on anthropomorphic phantoms and for wraparound model glasses [13,15–17]. In these works, other types of glasses were also studied but are not taken into account in this comparison.

In Magee et al. [17] three different scenarios were considered: 30 cm distance of the operator from the source, 0° rotation; 68 cm distance and 0° rotation; 68 cm with the operator tilted towards the tube by an angle of 60°. The CF ranged between 0.15 and 0.53, with a mean value of 0.22. This result is similar to the range found in the present study for measurements on operators in real clinical conditions. Furthermore, the highest protection efficiency of lead glasses (0.15) is attributed to the configuration with the operator looking towards the tube; this is in line with our Monte Carlo value of 0.17 (postero-anterior projection) obtained for 70 cm distance and 60° rotation towards the tube (Table 3, column 3, line 16).

Meanwhile, in the study by Moore et al. [16], a 3M^R pelvic phantom was used to generate the scattered radiation field, while a phantom head simulated the position of the radiologist's head. Three different geometric configurations were studied: rotation of the operator of 0, 30 and 60 degree towards the tube. No details regarding the distances of the operator to the tube were given, but as a patient pelvic phantom was used, radial/femoral access of the operator, i.e. about 55 cm distance from the source, could be assumed. Their CF values ranged from 0.14 to 0.29 with a mean value of 0.24 obtained as an average of three geometric configurations. The authors showed that the larger the rotation is, the lower the attenuation efficiency becomes.

Additionally, in Thornton et al. [15] the scenarios simulated were jugular, radial and femoral accesses; again no detailed information about the distances from the source was given. No rotation of the head was considered. This study provides the smallest CF range (0.10 - 0.19) with respect to the other publications. The highest attenuation is obtained for jugular access, as opposed to the results of the present work, where a CF of 0.5 was obtained considering 0 cm distance of the operator from the tube and no operator rotation (Table 3, column 3, line 3). It is probably not overbold to consider that the influence of the image intensifier position has an important role in this case. Thornton's values for radial and femoral access of 0.19 and 0.11 agree with our Monte Carlo results of 0.20 and 0.15, respectively.

Finally, Van Rooijen et al. [13] used two different geometrical configurations: firstly, a 50-cm distance was set between the source and the operator who was not tilted and had a height of 1.85 m. Secondly, the distances were maintained, but the operator head was tilted 45° away from the tube. The scattered radiation from the patient was produced by a PMMA slab phantom. Wraparound type glasses, named model 4 and 5 in the quoted paper, were considered. Such glass types are similar to the MC model of this study. A mean CF of 0.32 (column 9) was obtained. This result is in agreement with our experimental measurements and our mean Monte Carlo CF value (columns 1 to 4 in Table 5) but remains larger than the other phantom measurements (columns 6 to 8). This difference can be due to the geometrical configuration involving an operator rotation with 45° away from the tube. Indeed, as previously mentioned, the efficiency of the lead glasses is reduced for the head rotation away from the source (see Table 3) and the highest CF value corresponding to this setup is about 0.62.

In addition, the studies by Moore et al. [16] and Van Rooijen et al. [13] included few measurements on operators in clinical scenarios. Moore et al [16] only provided one value with a corresponding measured CF of 0.19. This value is smaller than the average CF value of 0.31 obtained in this study. Van Rooijen et al. [13] presented CF values for wraparound glasses (model 5 in the original paper) ranging from 0.18 to 0.90, with a mean value of 0.48. This range is broader than our measurements (CF range 0.21 – 0.41), but still consistent with Monte Carlo values (0.15 – 0.84, for postero-anterior, Table 5, column 3). However, as explained in their paper, Van Rooijen et al. [13] indicated that the dose reduction for the left eye lens is probably underestimated because the dosemeter was placed in a poorly shielded position. Based on this consideration, a mean CF of 0.48 for the wraparound model, as proposed, may be too high.

One important issue is to assess correction factors to be used when the dosemeter is not worn behind the protective shielding, but on an unprotected part of the head, close to the left eye. In spite of the shortcomings of both Monte Carlo and experimental measurements, Table 5 shows good consistency between the two approaches, with CF mean values ranging from 0.14 to 0.33 (line 3). Based on our Monte Carlo calculations, our measurements and data available in literature, a correction factor of 0.3 is recommended for wraparound glasses, for radiological protection purposes. This CF value is obtained by averaging all values from the first row of CFs in Table 5. However it is important to underline that the number of collected data from our experimental campaigns is very limited, as shown in line 6 of Table 4.

The recommended correction factor provides a quite realistic estimate of the left eye lens dose reduction when lead glasses are worn and when the eye dose is measured close to the eye in an unprotected position. This finding is in agreement with the recommendation from ISO 15382, which proposes a value between 0.2 and 0.3 as correction factor. However, for nonwraparound glasses, such as type 3c glasses with smaller lenses, a more conservative CF value of 0.5 is recommended. Unfortunately, there are very few clinical data available, and measurements highlight a large variability of eye doses with such types of glasses. Therefore, we believe there is a need to perform further measurements in clinical practice.

5. Conclusions

The Monte Carlo analysis used in the present study highlighted the influence of different parameters studied independently, such as the operator position, height and orientation with respect to the source, on the eye lens exposure during an interventional procedure. It is a powerful tool that can be used to investigate how the eye lens dose can be reduced by optimizing the relative position of the operator with respect to the X-ray source. Generally, at distances of 40 cm and 70 cm from the source, the left eye is the most exposed eye. A rotation of the head of 30° or 45° away from the tube can reduce the eye lens dose by approximately 50%. In fact, for the postero-anterior and left-lateral projections, when considering the operator's orientation and the position of the diagnostic monitor, the doses were found to be generally lower for both eyes when the operator is facing away from the tube, with and without lead glasses than in the case where the operator is facing the tube. It is thus recommended that the monitors are located away from the primary X-ray field. Meanwhile, at distances of 0 and 20 cm the position of the monitor is less critical because the image intensifier works as a shield, reducing the dose up to a factor of 3. It is shown that the operator's height also influences the eye lens dose: a reduction factor up to 2 is observed for a 10-cm-taller operator. Monte Carlo study of the lead glasses protection efficiency provides correction factors in specific static conditions common in clinical practice. It is shown that the average of these calculated factors is in good agreement with the correction factors obtained from measurements in clinics. Thus, considering both Monte Carlo and experimental results, this work recommends using a correction factor of 0.3 for wraparound glasses or a more conservative value of 0.5 when the design of the glasses is unknown.

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Table 1: Ratios $H_p(3, LE)/H_p(3, RE)$ in configuration - *away from the tube* and *towards the tube* for the postero-anterior projection and when lead glasses are not worn. LE stands for Left Eye and RE for Right Eye.

		$H_p(3, LE)/H_p(3, RE)$					
		away from the tube			*towards the tube*		
Angles (°)	0 cm	20 cm	40 cm	70 cm	20 cm	40 cm	70 cm
0	1.0	1.2	1.3	1.5	1.2	1.3	1.5
10	1.0	1.2	1.5	2.3	1.0	1.2	1.4
30	1.1	1.6	2.8	5.4	1.1	1.1	1.2
45	1.3	3.6	6.6	13.1	1.0	1.2	1.1
60	2.2	4.3	6.0	12.6	0.8	0.9	1.0

Table 2. Left eye dose ratios for different operator's heights (158 cm, 168 cm and 188 cm) and a reference height of 178 cm.

Distance	158/ref	168/ref	188/ref
0 cm	3.2	2.0	0.5
20 cm	2.8	1.9	0.5
40 cm	1.9	1.4	0.6
70 cm	1.3	1.2	0.8

Table 3. Ratio of $H_p(3)$ values with and without lead glasses (CF) for postero-anterior and left-lateral irradiation (data from Kourokava et al. [14] are also included for comparison). LE stands for Left Eye, RE for Right Eye.

		CF				
		Postero-anterior		Left-lateral		
		LE	RE	LE	RE	Reference
0 cm	0°	0.51	0.52	--	--	[14]
40 cm	0°	0.2	0.78	0.23	0.92	[14]
	30°_towards	0.27	0.31	0.21	0.39	Present work
	30°_away	0.34	1.19	0.32	0.98	Present work
	45°_towards	0.32	0.22	0.29	0.29	Present work
	45°_away	0.41	0.88	0.40	0.79	Present work
	60°_towards	0.53	0.2	0.45	0.2	Present work
	60°_away	0.58	0.8	0.31	0.58	Present work
70 cm	0°	0.15	0.89	0.12	0.97	[14]
	30°_towards	0.15	0.24	0.11	0.31	Present work
	30°_away	0.25	0.95	0.28	0.92	Present work
	45°_towards	0.15	0.16	0.11	0.18	[14]
	45°_away	0.42	0.78	0.58	0.7	[14]
	60°_towards	0.17	0.16	0.12	0.12	Present work
	60°_away	0.84	0.82	0.89	0.76	Present work

Table 4. Ratio of $H_p(3)$ values with and without lead glasses (CF) obtained in experimental measurements. Mean, minimum, maximum and number N of data collected for each model of glasses are listed.

	CF		
Glasses model	Wrap around glasses (Fig.3 type a)	Lateral shielding - large lenses (Fig.3 type b)	Lateral shielding – small lenses (Fig.3 type c)
Mean	0.31	0.32	0.54
Min	0.21	0.25	0.36
Max	0.41	0.52	0.72
N	3	7	3

Table 5. Mean, standard deviation, maximum, minimum values of CF obtained for wraparound glasses with: Monte Carlo (MC) calculations, for hypotheses 1 and 2 (hyp.1: all MC, hyp.2: MC for 0, 30, 45°*away from the tube*), experimental measurements performed here and data from the literature.

	MC calculated **CF**			Measured **CF**				
	This study, hyp.1	This study, hyp.2	Kourokava hyp.2 [14]	This study, table 4, col. 2	Maggie [17]	Moore [16]	Thornton [15]	Van Rooijen [13]
Mean	0.33	0.31	0.32	0.31	0.22	0.24	0.14	0.32
SD	0.22	0.15	0.18	0.10	0.05	0.07	0.04	0.24
Max	0.89	0.58	0.58	0.41	0.53	0.29	0.19	0.62
Min	0.11	0.12	0.12	0.21	0.15	0.14	0.10	0.12

Figure

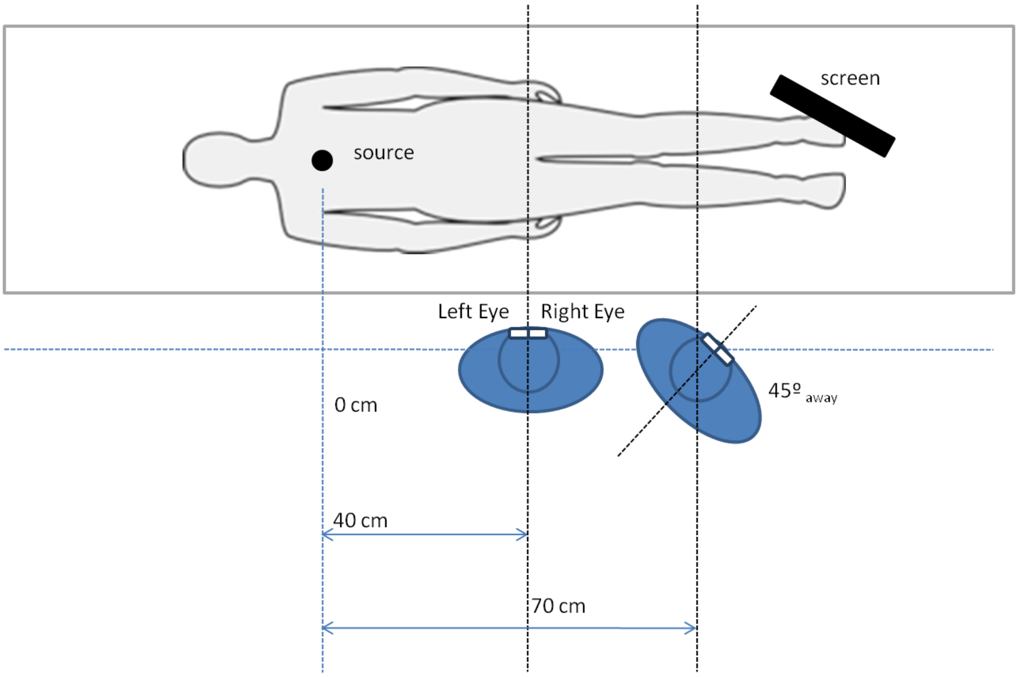
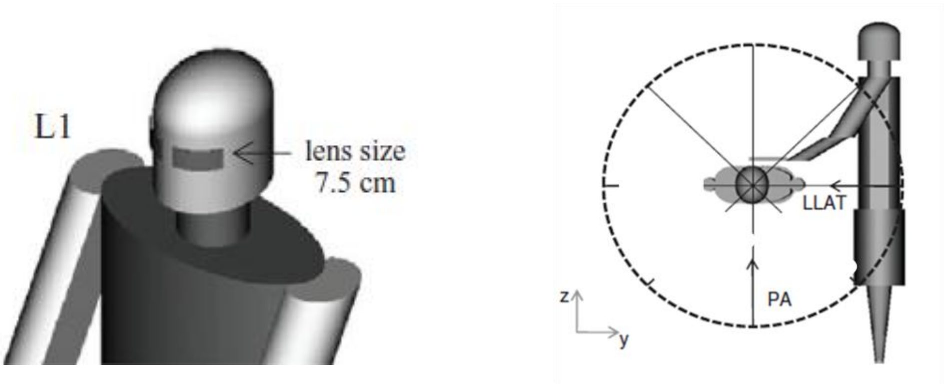


Fig.1: Simplified geometry with some of the possible configurations of the clinical simulated scenario. In this figure the operator is at 40 cm distance and 0° orientation (no rotation) and at 70 cm distance and rotated 45° away from the source (towards the image screen).



(a) (b)

Fig.2(a) Wraparound type lead glasses (L1 model in [14]).

(b) Projections considered in simulations: postero-anterior (PA) and left-lateral (LLAT).

(*a*) (*b*) (c)

Fig.3 (*a*) wraparound type glasses; (*b*) lead glasses with side protection; (*c*) lead glasses with side protection, but with smaller frontal and lateral lenses with respect to type *b* glasses.

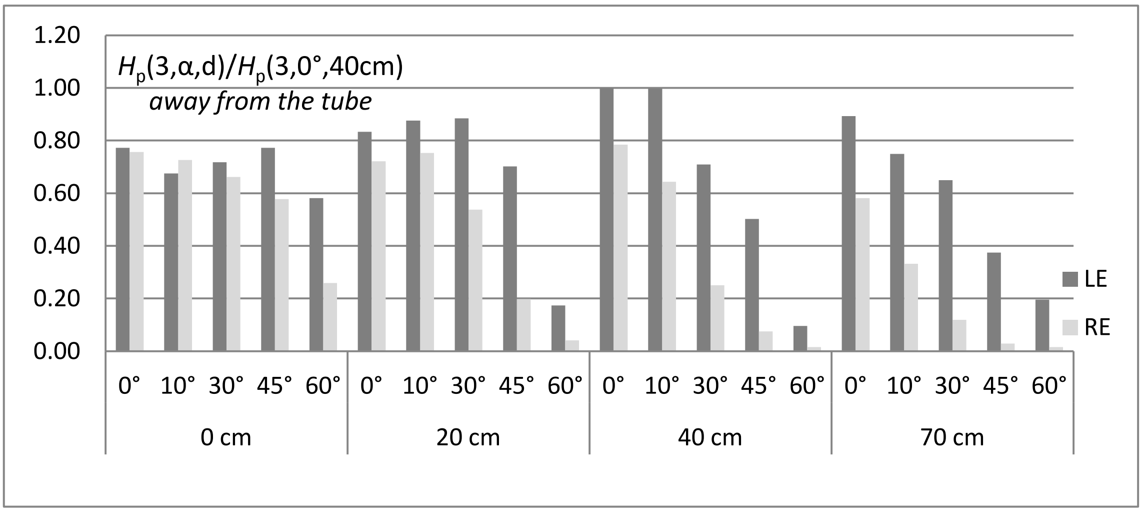


Fig. 4 Eye lens dose distribution for all distances normalized with respect to the left eye dose at 40 cm distance and 0 degree rotation, for the postero-anterior projection (operator is not wearing lead glasses).