Applied Radiation and Isotopes 117 (2016) 100–105

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Correlation between scatter radiation dose at height of operator's eye and dose to patient for different angiographic projections

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HIGHLIGHTS

- A method is presented to estimate the scatter radiation dose at operator eye height.
- The method allows estimating scatter radiation dose measuring ambient dose equivalent.
- Operator could exceed threshold for lens opacities if protection tools are not used.
- There is a good linear correlation between kerma-area product and scatter radiation dose.
- Different C-arm angulations can modify the scatter dose rate.

ARTICLE INFO

Article history:
Received 30 October 2015
Received in revised form
6 January 2016
Accepted 7 January 2016
Available online 19 January 2016

Keywords:
Scatter radiation dose
Angiography
Ambient dose equivalent
Occupational dose
Patient dose
Eye lens dose

ABSTRACT

Studies have reported cases of radiation-induced cataract among cardiology professionals. In view of the evidence of epidemiological studies, the ICRP recommends a new threshold for opacities and a new radiation dose to eye lens limit of 20 mSv per year for occupational exposure. The aim of this paper is to report scattered radiation doses at the height of the operator's eye in an interventional cardiology facility without considering radiation protection devices and to correlate these values with different angiographic projections and operational modes. Measurements were taken in a cardiac laboratory with an angiography X-ray system equipped with flat-panel detector. PMMA plates of 30 × 30 × 5 cm were used with a thickness of 20 cm. Measurements were taken in two fluoroscopy modes (low and normal, 15 pulses/s) and in cine mode (15 frames/s). Four angiographic projections were used: anterior posterior; lateral; left anterior oblique caudal (spider); and left anterior oblique cranial, with a cardiac protocol for patients weighing between 70 and 90 kg. Measurements of phantom entrance dose rate and scatter dose rate were performed with two Unfors Xi plus detectors. The detector measuring scatter radiation was positioned at the usual distance of the cardiologist's eyes during working conditions. There is a good linear correlation between the kerma area product and scatter dose at the lens. Experimental correlation factors of 2.3, 12.0, 12.2 and 17.6 μSv/Gy cm2 were found for different projections. PMMA entrance dose rates for low and medium fluoroscopy and cine modes were 13, 39 and 282 mGy/min, respectively, for AP projection.

1. Introduction

Of all the practices that involve ionizing radiation, medical exposures are responsible for the greatest contribution to population exposure. Interventional cardiology procedures are the third largest contributor to collective effective dose after computed tomography and nuclear medicine procedures (UNSCEAR, 2008).

Cases of radiation-induced cataract among cardiology

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http://dx.doi.org/10.1016/j.apradiso.2016.01.013
0969-8043/

professionals have been reported in several studies (Vano et al., 1998; ICRP 85, 2000; ICRP, 2010). Recent surveys have shown the high prevalence of lens changes that are likely induced by radiation exposure. In this regard, a study by Ciraj-Bjelac et al. (2010) has demonstrated a dose-dependent increased risk of posterior lens opacities for interventional cardiologists and nurses when radiation protection tools are not used. Vano et al. (2013a) showed that posterior subcapsular lens changes characteristic of ionization exposure were noted in almost 50% of interventional cardiologists and 41% of nurses and technicians examined, compared with findings of similar lens changes in fewer than 10% of controls. Another study conducted by Jacob et al. (2010) provided further evidence of the potential risk of radiation-induced cataracts at low doses. Hence, many studies strongly suggest an urgent need to raise cardiologists' awareness of the importance of radiation protection, to encourage the use of eye protection during interventional procedures and to optimize staff protection in addition to improving occupational dosimetry.

In view of the evidence of radiation injuries, the International Commission on Radiological Protection (ICRP) recommends a new threshold for lens opacities of 0.5 Gy, limiting eye lens radiation dose to 20 mSv per year for occupational exposure (ICRP, 2011).

It is apparently straightforward to apply measures to reduce eye lens dose: “Combining various types of shielding (table-suspended drapes, ceiling-suspended screens, protective aprons, leaded eye-glasses, mobile shields, and disposable drapes) results in a dramatic dose reduction for the operator. This should be the norm, rather than the exception” (Duran et al., 2012).

Unfortunately, several studies show that radiation protection devices and personal dosimetry are still not commonly used by operators during interventional procedures. In Latin America, these interventional procedures are usually performed by medical specialists in collaboration with nurses, technologists and technicians, who often do not have adequate training in radiological protection (Leyton et al., 2014a). A study carried out by Vano et al. (2011) with cardiologists from 11 countries in Latin America showed that only 64% of cardiologists used their personal dosimeters regularly, only 36% were aware of their personal dose values, only 41% used protective ceiling-suspended screens, only 14% had detailed knowledge of the X-ray system they were using and only 27% knew the quality control results. The results of another IAEA (2014)-conducted survey covering cardiologists from 56 countries showed that only between 33% and 77% of interventional cardiologists used their personal dosimeters regularly.

The ORAMED (Optimization of RAdiation protection for MEDical staff) European program showed the frequency of use of personal and collective protective equipments during interventional procedures. No collective protective equipment was used in 31% of cases. Furthermore, only 44% of cases involved the use of both table- and ceiling-suspended screens (Donadille et al., 2011).

1.1. *Operational dose quantities to monitor eye lens*

The crucial issue is preventing cataracts in staff members in intervention rooms. Within this context, occupational dosimetry remains a challenge in fluoroscopy-guided procedures where numerous variables must be taken into account in estimating eye lens dose.

The appropriate operational dose quantities to monitor the eye lens are the personal and directional dose equivalents at 3 mm depth, Hp(3) and H′(3,Ω), respectively. There are no available conversion coefficients from air kerma to H′(3,Ω) and these coefficients have not been internationally agreed, although in the future H′(3,Ω) may also be important for area monitoring (Behrens, 2012, 2015).

The most accurate method is to measure Hp(3) with a dosimeter worn as close as possible to the eye and calibrated on a phantom representative of the head. As this procedure may be impractical in clinical practice, other methods may be used such as evaluating Hp(3) through Hp(10) or Hp(0,07) both measured with dosimeters worn on the trunk of the body or an Hp(0,07) dosimeter worn near the eyes, or monitors for measuring H′(0.07,Ω), H′(3,Ω) or H*(10) (IAEA, 2013). Behrens and Dietze (2010) show that for the radiation qualities used in current interventional cardiology facilities, Hp(0.07) is suited best to monitor eye lens dose. However, another alternative is Hp(10). Though the latter is conservative, it must be kept in mind that an overestimation of the eye lens may occur in both Hp(0.07) and Hp(10).

The ambient dose equivalent, H*(10), at a point of interest in the real radiation field, is the dose equivalent that would be produced by the corresponding aligned and expanded radiation field, in the ICRU sphere at a depth of 10 mm, on the radius vector opposing the direction of radiation incidence. H*(10) should give a conservative estimate of the effective dose a person would receive when remaining in this position. This is always the case for photons below 10 MeV. For such photons, the situation for Hp(10,0°) for radiation incidents on the front of the body is similar to H*(10) (Dietze, 2001; Stadtmann, 2001).

Area dosimeters or dose rate meters should be calibrated in terms of the ambient dose equivalent, H*(10), or the directional dose equivalent, H′(0.07) (IAEA, 2000). Consequently, area monitors or survey meters are used for the real-time monitoring of exposure and hence for estimating the potential risk to which members of the public and employees working in public areas or examination rooms are exposed. The precision of measurements can be greatly improved by properly understanding the detector in use.

The IAEA's Technical Reports Series no. 457 states that for survey meters, where “the uncertainty in the absolute risk for stochastic effects is high, a required accuracy of 20% in dosimetry measurements should be sufficient” (IAEA, 2007).

The H*(10) measurement can provide an adequate estimate of the dose to the lens of the eye and represents an alternative approach when there is no availability of radiation monitoring instruments calibrated at Hp(3) or Hp(10). However, the qualified expert in radiation protection should be aware that the eye lens dose estimate is less accurate and the uncertainty of the measurement is hence likely to increase. In such a case, an eye lens dose that is close to the limit should be carefully considered.

A further advantage of H*(10) is that area monitors calibrated at this level are widely used and most dosimetry laboratories provide calibration at H*(10). Moreover, area monitors allow dose level estimates before undertaking individual monitoring with other systems.

This paper offers another approach to estimate the doses that workers will receive, using workplace monitoring at relevant locations such as the typical cardiologist position during interventional procedures. These results may help to raise awareness about the safe use of ionizing radiation. Moreover, interventional staff, medical physicists and regulatory bodies, which uniformly require that a worker does not receive occupational exposure higher than the dose limits, could all use the results.

This paper presents the experimental results of scatter radiation doses at operator eye height and phantom entrance dose (ESAK) in an interventional cardiology facility from procedures performed when radiation protection devices are not used, correlated with different angiographic projections and operation modes.

2. Materials and methods

Experimental measurements were taken in a cardiac laboratory

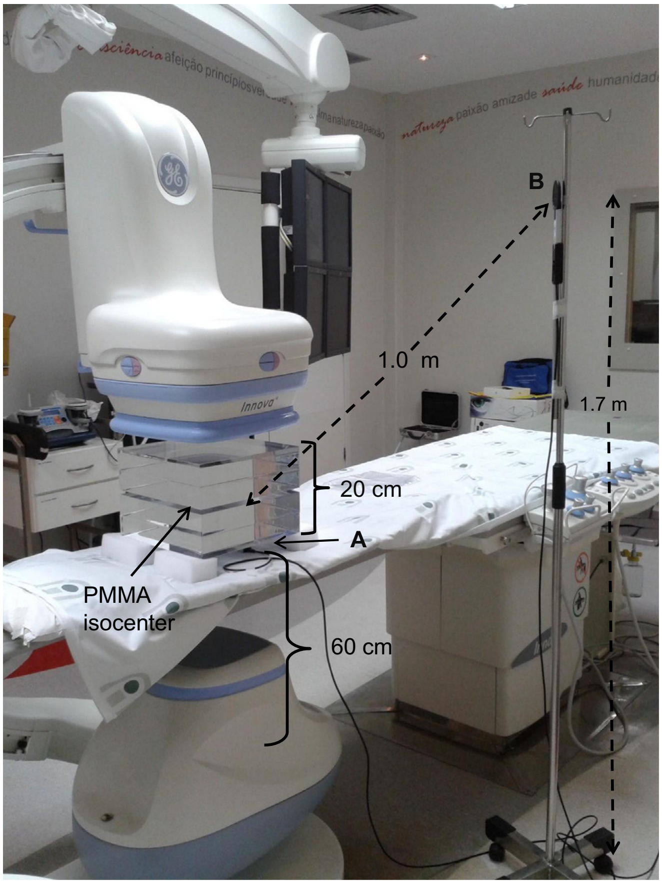

Fig. 1. Experimental arrangement, AP projection with a PMMA phantom of 20 cm for measurement of (a) phantom entrance dose (ESAK) and (b) scatter radiation dose. X-ray tube undercouch.

using an Innova 2100 IQ angiography X-ray system (General Electric Medical Systems, France) equipped with an amorphous silicon flat-panel detector of 20 cm^2. A diagonal dimension of 20 cm was used for field of view during the experimental measurements. Three operational modes were used. Two fluoroscopy modes were available: low (FL) and normal (FN) dose, both configured at 15 pulse s^{-1}, whereas a cine mode (CI) was typically used at 15 frame s^{-1} with the most common cardiac protocol for patients weighing between 70 and 90 kg.

Measurements were taken in four angiographic projections, of which three projections corresponded to higher dose rates according to the literature (Kuon et al., 2004; Vano et al., 2008, 2015). Anterior–posterior projection, which is used to characterize and commission the X-ray system, was also used. The nomenclature for radiographic projection used in interventional cardiology (Abbas, 2015) is as follows: anterior–posterior (AP) (X-ray tube undercouch, see Fig. 1); left anterior oblique 90° (LAT) (X-ray tube in the lateral C-arm); left anterior oblique 45° with caudal 26° (LAO 45° and CAU 26° or “spider”); and left anterior oblique 45° with cranial 30° angulations (LAO45CRA30), as simulating clinical conditions.

PMMA plates of 30x30 $\times$ 5 cm^3 were used, building a thickness of 20 cm to simulate an adult patient chest thickness of around 30 cm (Rassow et al., 2000). The flat-panel detector was always positioned at 5 cm from the PMMA. A test object developed at the University of Leeds for image quality, TOR 18-FG (TOR 18FG test object, 2015), was positioned at the isocenter and in the middle of the PMMA phantom.

Clinical working conditions were reproduced during the experiments. Voltages ranged from 75 to 120 kV and current values of between 6.5 and 14.8 mA were required for the fluoroscopy modes. The current values typically used for the cine (at 15 frames s^{-1}) ranged from 41.8 to 75.5 mA, while pulse width ranged from 7 to 10 ms and added copper filtrations were not possible to record because they were not shown in the monitors (the Innova 2100 IQ X-ray system can add 0.0, 0.1, 0.3, 0.6 and 0.9 mm Cu filters to the beam).

2.1. *Patient entrance dose measurements*

This report uses the terminology proposed by the International Commission on Radiation Units and Measurements (ICRU, 2005). The “entrance dose” quantity is used for the PMMA phantom as an equivalent to ESAK with backscatter (BS). An Unfors Xi model 8201023-C Xi Platinum Plus dosimetry system with solid-state detector model 8202031-HXi (RaySafeTM product, 2015) was used to measure phantom entrance dose, ESAK with BS, in two angiographic projections and three operational modes. The total traceable uncertainty for the calibration is 9.2% (k=2, at the 95% confidence level) (IAEA, 2007). The focus-to-detector phantom entrance distance was 60 cm to AP projection and focus-to-flat-panel detector distance was 90 cm. The PMMA phantom was positioned at the isocenter. To facilitate comparison of our results with other measurements, a BS factor of 1.3 was used to calculate ESAK (ICRU, 2005). The angiography system was equipped with an ionization transmission chamber integrated into the collimator housing to measure kerma area product (KAP) (ICRU, 2005). During fluoroscopy and cine modes, KAP was recorded and displayed on the in-room monitors.

2.2. *Staff scatter dose measurements*

For staff exposure, the area monitoring, referred to as ambient dose equivalent and recorded as H*(10), is the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a 10 mm depth. The definition of expansion and alignment is only required to define the quantity and is not relevant to measurements taken with the area monitors (IAEA, 2000). For staff exposure, measurements were obtained in four angiographic projections and three operational modes. Scatter doses were measured using the Unfors Xi model 8201023-C Xi with solid-state detector model 8202062-CXi survey detector (RaySafeTM product, 2015), calibrated in H*(10). The total traceable uncertainty for the calibration is 10% (k=2, at the 95% confidence level) (IAEA, 2007).

The IAEA's Technical Document 1731 (IAEA, 2013) states that the most accurate method for monitoring the equivalent dose to eye lens is measuring the personal dose equivalent at a 3 mm depth, Hp(3). As this procedure may be impractical, other methods may be used such as evaluating Hp(3) through Hp(10) or Hp(0,07), or monitors for measuring H*(10). The value of H′(10,0°) is equal to H*(10) (Dietze, 2001).

ISO 4037-3 (1999) describes the methods and the conversion coefficients to be used for determining the response of radiation-monitoring instruments. Considering the conversion coefficients from air kerma to ambient dose equivalent and air kerma to personal dose equivalent, it is possible to apply a conversion factor of 1.09, 1.10 and 1.10 (Hp(10)/H*(10)) to estimate Hp(10) from H*(10) for the specific reference radiations for the narrow spectrum series dedicated to radiation protection, N80, N100 and N120, respectively.

The detector to measure scatter radiation was positioned at the usual distance of the cardiologist's eyes during working conditions (1 m from the isocenter and 1.7 m from the floor), allowing a more realistic estimation of dose at operator eye height without use of ceiling-suspended screens or shields. Fig. 1 shows the experimental arrangement with detectors, PMMA phantom and test object.

3. Results and discussion

Table 1 shows phantom (patient) entrance dose rate (ESAK) and scatter radiation dose (H*(10)) at operator eye height for different projections (C-arm angulations) and modes of operation. The ESAK rate at AP projection for FL, FN and cine modes were 13 ± 1, 39 ± 3 and 282 ± 26 mGy min^{-1}, respectively. Comparing results with other research employing similar methodologies shows that the ESAK rate values reported in this study are lower than those in the IAEA Safety Reports Series N59 (IAEA, 2009). In the latter study, the reported values were 12, 30 and 337 mGy min^{-1} at 70 cm for FL, FN and cine modes, respectively.

The highest ESAK rate was 1411 ± 130 mGy min^{-1} for LAT projection and cine operation mode. The ESAK rate values were higher in the LAT projection because the focus-to-skin distance (phantom) was decreased to 50 cm and phantom thickness at LAT projection is 30 cm.

Table 1 shows a large range of scatter radiation dose at operator's eye height, from 0.37 ± 0.04 to 60.19 ± 6.02 mSv h^{-1}. Therefore, when turning C-arm from AP projection in FL mode to LAO45CRA30 projection in cine mode, the factor of increase in scatter dose rate was 163 times.

The highest scatter radiation dose rate was 60.19 ± 6.02 mSv h^{-1} for LAT projection at cine operation mode (Table 1). This means that the operator would reach the eye lens dose limit of 20 mSv per year in 20 min. An interventional operator may therefore easily exceed the lens dose limit if radiation protection tools are not used.

When operation mode changed from FL to FN, the scatter dose rate increased by an average factor of 2. When operation mode changed from FN or FL to cine, scatter dose rate increased by an average factor of 6 or 13, respectively.

From the values shown in Table 1, it is possible to calculate average approximate factors of 0.02 and 0.05 (mSv h^{-1} /mGy min^{-1}) for AP and LAT projection, respectively. This could be used as a rough approach for estimating scatter radiation dose rate levels based on the ESAK rate (mGy min^{-1}), which is shown on the monitor inside the intervention room.

Table 1 shows a characterization of the X-ray system used in interventional cardiology. It is thus important that operators and staff are aware of the behavior of their X-ray system. Becoming familiar with typical ESAK and scatter radiation dose rates for the different C-arm projections and operation modes in use in interventional laboratories is essential to optimize both patient and staff protection. It should therefore form a part of training programs in quality assurance and radiation protection (IAEA, 2009).

To estimate the scatter dose to operator, for example, the data in the DICOM header of an interventional procedure provide the total fluoroscopy time and cine time for each projection, with a total fluoroscopy time of 180 s and a cine time of 3, 4, 6 and 5 s for AP, LAT, spider and LAOCRA, respectively. Using scatter dose rate (Table 1) from FN and cine modes for each projection, scatter dose at operator eye height could therefore be 0.52 mSv if protection tools were not used.

Table 2 shows the multiplicative factor modifying the scatter dose rate at operator eye height during the move from AP to three different C-arm projections and different modes of operation. The AP projection is used for characterization of the angiography system. This process helps cardiologists to optimize procedures by knowing patient dose levels.

The highest multiplicative factor was 16, from AP to LAO45-CRA30 projection in cine operation mode (Table 2). The factor of increase in scatter dose to eyes is approximately 11 times greater with a C-arm running from AP to all other projections. During movement of the C-arm from the projections with greatest scatter radiation dose rate, the average multiplicative factor was 1.12.

The multiplicative factors reported in this study were higher than those reported by Leyton et al. (2014b) and Vano et al. (2015) when the C-arm moves from AP to the other projections. However, the multiplicative factor values for moving the C-arm from LAT to spider or LAO45CRA30 projections were similar to those reported by Leyton et al. (2014b) and Vano et al. (2015).

Fig. 2 shows that the coefficients of determination R^2 values are greater than 0.9925. Therefore, a good linear correlation exists between phantom entrance dose rate, ESAK, and scatter dose rate (H*(10)) at the height of the operator's eye, measured for AP and LAT projections. Multiplicative factor ranges of 0.01–0.04 (AP projections) and 0.03–0.06 (LAT projections) correlate the ESAK to the phantom with the scatter dose at the height of the operator's eye. The respective mean multiplicative factors of 0.02 and 0.05 for AP and LAT projections could be used as practical tools for estimating scatter radiation dose rate levels based on the ESAK rate (mGy min^{-1}), which is shown on the monitors of the intervention room and is recorded in the digital imaging and communications in medicine (DICOM) format.

Several factors may affect radiation risk for staff, but if operators reduce patient dose this always results in staff dose reduction (Figs. 2 and 3). As shown in Fig. 2, coefficient of determination R^2 values are greater than 0.9925. Hence, a good linear correlation exists between ESAK rate and scatter dose rate at operator eye height for AP and LAT projections. With these three points representing ESAK rates for different operation modes for a phantom of 20 cm PMMA, it is possible to begin to characterize the angiography. Several studies with a similar methodology also show a strong correlation for R^2, calculated with 3, 4 or more points (Vano et al., 2009; Ubeda et al., 2010; Leyton et al., 2014b). It can be seen that 50 mGy min^{-1} at the patient entrance involves scatter dose rates at the typical cardiologist eye position of approximately 0.93 and 4.68 mSv h^{-1}, respectively.

Fig. 3 shows the correlation between KAP (patient) and scatter radiation dose (H*(10)) at the usual position of the operator's eye, measured for AP, LAT, spider and LAO45CRA30 projections. The R^2 value for each projection was greater than 0.9986. These good correlations are partly explained because all parameters of the X-ray productions remained constant and R^2 was calculated for each projection. Furthermore, there was no operator intervention

Table 1
Phantom entrance dose rate and scatter radiation dose (H*(10)) at eye position for different projections: AP; lateral (LAT, LAO90°: left anterior oblique 90°); spider (left anterior oblique 45° with caudal 30° (LAO45CAU30)); and LAO45CRA30 (left anterior oblique 45° with cranial 30°). Three modes of operation: low fluoroscopy (FL), normal fluoroscopy (FN) (both at 15 pulse s^{-1}) and cine mode (CI) at 15 frame s^{-1}.

Operation mode	PMMA entrance dose rate, *AP mGy/min*	Scatter dose rate, AP *mSv/h*	PMMA entrance dose rate, *LAT mGy/min*	Scatter dose rate, LAT *mSv/h*	Scatter dose rate, SPIDER *mSv/h*	Scatter dose rate, LAO45-CRA30 *mSv/h*
FL	13 ± 1	0.37 ± 0.04	86 ± 8	4.00 ± 0.40	3.59 ± 0.36	4.00 ± 0.40
FN	39 ± 3	0.89 ± 0.09	133 ± 12	8.25 ± 0.83	6.88 ± 0.69	7.64 ± 0.76
cine	282 ± 26	3.79 ± 0.38	1411 ± 130	37.12 ± 3.71	48.53 ± 4.85	60.19 ± 6.02

Table 2
Values of multiplicative factor modifying scatter dose rate at eye position during the move from different C-arm projections for low fluoroscopy (FL), normal fluoroscopy (FN) and cine operation modes.

Operation mode	AP to LAT	AP to spider	AP to LAO45CRA30	LAT to spider	LAT to LAO45CRA30	spider to LAO45CRA30
FL	11	10	11	0.90	1.00	1.11
FN	9	8	9	0.83	0.93	1.11
cine	10	13	16	1.31	1.62	1.24
Average	10	10	12	1.01	1.18	1.16

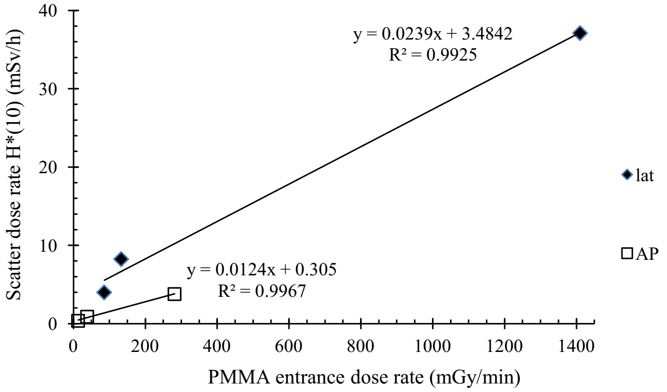

Fig. 2. Correlation between phantom (PMMA) entrance dose rate and scatter radiation dose rate, H*(10), at typical cardiologist eye position for AP and LAT projections and three operation modes.

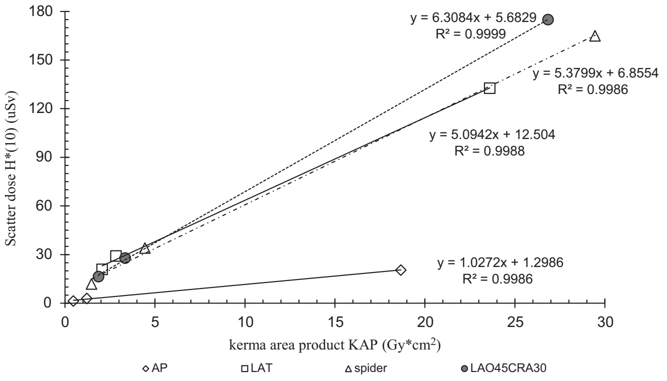

Fig. 3. Correlation between kerma area product, KAP, and scatter dose, H*(10) at typical cardiologist eye position, measured for AP, lateral (LAT), spider and LAO45CRA30 projections and three operational modes.

or misuse of radiation protection devices such as the ceiling-suspended screen. These results are consistent with other studies that also reported a strong correlation between KAP and eye lens scatter dose without radioprotection devices (Geber et al., 2011; Vano et al., 2009, 2013b; Leyton et al., 2014b).

Experimental correlation factors of 2.3, 12.0, 12.2 and 17.6 μSv at the height of the operator's eye for 1 Gy cm^2 were found for AP, LAO45CRA30, spider and LAT projections, respectively. The average and median experimental correlation factors were 11.0 and 12.1 μSv/Gy cm^2, respectively.

Fig. 4 shows the correlation between KAP and scatter radiation dose (H*(10)) at the usual position of the operator's eye, measured for all angiographic projections. When we calculated the coefficient of determination considering all angiographic projections in this study, the R^2 value decreased to 0.83 and an experimental factor of 8.3 μSv/Gy cm^2 was calculated from equation 1 in Fig. 4.

Concerning other projections, Vano et al. (2013b) showed that for 1969 cardiology procedures, considering all angiographic projections, the correlation between scatter dose (Hp(10)) values and KAP was fairly linear. Scatter dose at the C-arm and KAP were directly correlated with R^2=0.85 and an experimental correlation factor of between 10.3–11.3 μSv/Gy cm^2 was calculated. Actual unprotected eye level doses were about 30–40% of the C-arm dosimeter readings.

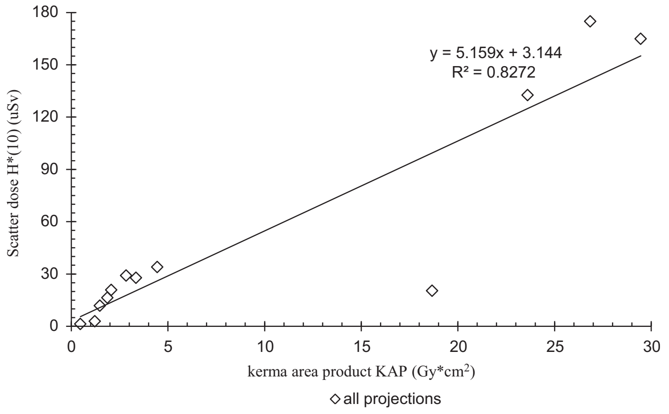

Fig. 4. Correlation between kerma area product, KAP and scatter dose, H*(10) at typical cardiologist eye position considering all angiographic projections.

Another study conducted using a different methodology by Krim et al. (2011) reported R^2 values of 0.78 for measurements taken directly from the operator during clinical procedures.

The 8.3 μSv/Gy cm^2 value calculated in this study without using a ceiling-suspended screen is within the ranges observed in the study conducted by Vanhaverea et al. (2011) using different methodologies such as placing dosimeters near the eye, which was calibrated in Hp(0.07).

Typical kerma area product values for interventional cardiology procedures in patient range from 20 to 281 Gy cm^2 per procedure, depending on complex cardiac catheterization procedures (Vargas et al., 2012; Vano et al., 2013b). Applying linear equation 1 from Fig. 4 to typical kerma area product values in patient, this means scatter dose values at cardiologist eye height vary from 0.106 to 1.452 mSv per procedure when protection tools have not been used.

These dose values are consistent with the results reported by Vano et al. (2013b) (0.158–1.005 mSv per procedure). Otherwise, however, these values seem overestimated in comparison with those dose values used in the O'CLOC and ORAMED studies (Jacob et al., 2013; Vanhaverea et al., 2011) with dose ranges from 0.055 to 0.439 mSv and 0.046 to 0.102 mSv per procedure, respectively. Nonetheless, it should be noted that these values depend heavily on the proper use of radiation protection tools, especially the ceiling-suspended screen, and differences in one order of magnitude (or more) can be found.

Furthermore, the methodology used in this paper has the advantage that the operator can estimate, during or immediately following the procedure, the level of scattered radiation received at eye level if protection shielding has not been used (lead glasses and/or ceiling suspended screen).

The main limitation associated with this study is that the dose assessment has only been made using a phantom of 20 cm PMMA. Also, the movement and height of the operator could affect the application of the results of our study. However, when the operator approaches the patient for the procedure, a first measurement of scatter dose evaluated by this methodology can be corrected using the inverse square law of the distance (Vano et al., 2008, 2013b); for example, a variation of 30 cm may increase the dose by a factor of 2.

4. Conclusions

The experimental results of this paper provide a methodology and data to estimate dose at operator eye height for the evaluated X-ray system when radiation protection devices have not been used or radiation monitoring instruments calibrated at Hp(3) are unavailable.

Scatter dose rates increased linearly with patient entrance dose (ESAK) rate. For operators, large ranges of scatter radiation dose rate were found at operator eye height, ranging from 0.37 ± 0.04 to 60.19 ± 6.02 mSv h^{-1}.

The factors of increase for scatter dose at operator eye height were approximately 10–12 times greater for an X-ray tube running from AP to LAO, spider or LAO45CRA30 projections. The factor of increase for the other projections was approximately 1, however, the results may present a percentage difference of 31%.

A linear correlation has been verified between scattered radiation doses at operator eye height and patient KAP. An experimental correlation factor of $8.3\ \mu\text{Sv/Gy cm}^2$ at cardiologist eye height was found. A conservative estimate was calculated for scatter dose values at cardiologist eye height using scatter radiation dose equation $(\mu\text{Sv}) = 5.159{*}\text{KAP}(\text{Gy cm}^2) + 3.144$. This varied from 0.106 to 1.452 mSv per procedure when protection tools have not been used. Therefore, cardiologists may exceed the threshold for lens opacities if protective tools are not used.

Acknowledgments

The authors wish to thank Prof. Eliseo Vano for providing additional motivation with his comments made in this paper. The authors (F. Leyton and M S Nogueira) wish to acknowledge the support received from the doctoral fellowship of the National Commission of Nuclear Energy, CNEN, and from the Nuclear Technology Development Center, CDTN (grant number 080633).

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