FULL PAPER

High filtration in interventional practices reduces patient radiation doses but not always scatter radiation doses

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Objectives: In fluoroscopy-guided interventional practices, new dose reduction systems have proved to be efficient in the reduction of patient doses. However, it is not clear whether this reduction in patient dose is proportionally transferred to operators' doses. This work investigates the secondary radiation fields produced by two kinds of interventional cardiology units from the same manufacturer with and without dose reduction systems.

Methods:
Data collected from a large sample of clinical procedures over a 2-year period (more than 5000 procedures and 340,000 radiation events) and the DICOM radiation dose structured reports were analysed.

Results: The average cumulative $H_p(10)$ per procedure measured at the C-arm was similar for the standard and the dose reduction systems (452 *vs* 476 µSv respectively). The events analysis showed that the ratio

$H_p(10)$/KAP at the C-arm was (mean ± SD) 5 ± 2, 10 ± 4, 14 ± 4 and 14 ± 6 µSv·Gy^{-1}·cm^{-2} for the beams with no added filtration, 0.1, 0.4 and 0.9 mm Cu respectively and suggested that the main cause for the increment of the ratio $H_p(10)$/KAP *vs* the "standard system" is the use of higher beam filtration in the "dose reduction" system.

Conclusion: Dose reduction systems are beneficial to reduce KAP in patients and their use should be encouraged, but they may not be equally effective to reduce occupational doses. Interventionalists should not overlook their own personal protection when using new technologies with dose reduction systems.

Advances in knowledge: Dose reduction technology in interventional systems may increase scatter dose for operators. Personal protection should not be overlooked with dose reduction systems.

INTRODUCTION

Interventional procedures are among the diagnostic medical practices with highest radiation doses. That is why, following the recommendations of the International Commission on Radiological Protection (ICRP),[1,2] the European directive and national regulations stress the importance of optimization in interventional practices.[3] Optimization, which means enough diagnostic information for the clinical task but with the smallest possible radiation dose for patients and operators, is especially challenging for fluoroscopically guided procedures. Interventionists should therefore know the "price in dose" they are paying for each minute of fluoroscopy, each run of cine, of digital subtraction angiography (DSA) or of cone beam computed tomography (CBCT). The ICRP recommends adopting an integral approach for radiation protection during interventional procedures and auditing not

only patient doses but also occupational doses,[2] while never losing sight of the clinical outcome in any medical procedure.

In the last years, there has been considerable progress in the patient dose monitoring technology thanks to the Digital Imaging and Communication in Medicine (DICOM) standard and the radiation dose structured reports (RDSR). Most of the patient dose information at radiation event level is currently available in these RDSR and the possibility of managing all information through new automatic patient dose registries opened up a new era for the optimization of imaging procedures that would have been unthinkable only a few years ago.

The conventional personal dosimeter for interventionists (and other health professionals working in catheterization

rooms) was traditionally the "passive dosimeter" that would give the total cumulative occupational dose for 1 month without any possibility of discriminating the occupational dose for each individual procedure. Today, electronic "active dosimeters" allow the level of occupational dose for each radiation event to be measured, archived and analyzed in an "occupational dose structured report" - in a similar way as with RDSR for patients - and the secondary radiation level (and the occupational doses) to be correlated with the patient doses.[4,5]

Manufacturers of X-ray and imaging systems have also made efforts to optimize their products by improving the post-processing of the images and achieving a reduction of more than 50% in patient doses while maintaining or improving the image quality.[6–13] These dose reduction systems may require increasing the X-ray spectral filters to increase the mean beam energy in order to reduce the patient entrance dose. They also require the use of image post-processing algorithms to maintain image contrast at an acceptable level. A reduction in patient dose that keeps image quality and clinical information acceptable is always welcome. It is in general assumed that a reduction in patient dose leads to a reduction in occupational dose: this would be true if the radiation quality did not change but, in such dose reduction systems, the quantity of primary radiation is reduced but the quality (mean energy of the spectra) is increased. Then, how does the level of secondary radiation around the patients change for the operators? Do occupational doses also decrease in the same way as patient doses do?

There is an agreement among physicists that the secondary radiation level also increases when the primary beam quality is increased.[14–17] Perisnakis et al[18] reported an increment of a factor $\approx$1,5 at interventionalist location when the total beam filtration moved from 5 to 11 mm. Al. Sutton et al[19] showed increments in a factor of $\approx$2.5 when the additional filtration is increased from 0 to 0.99 mm Cu. Using dose reduction systems, among other adjustments beam filtration is likely to increase. However, since the different fluoroscopy systems have different logics of automatic dose rate control and as their application in clinical practice may vary, their impact is difficult to predict. As a consequence, different or even conflicting results are found in the literature. Schueler et al[20] reported a reduction in patient and operator doses when the spectral beam filtration was increased from 0.2 to 0.5 mm Cu, and at the same time a reduction in occupational dose half that of the patient dose. Buytaert et al[21] reported a patient and occupational reduction (at feet level) of more than 60% using a patient dose reduction system which increased the primary beam filtration, but they also said that secondary radiation increases with higher beam filtration. Salinas et al[22] have recently analyzed a series of percutaneous interventions on chronic total occlusions performed with and without dose reduction system and reached a patient dose reduction of 36%, but no significant difference in occupational dose.

The aim of this work is to quantify the effect of one of these dose reduction systems on the secondary radiation measured by a reference dosimeter at the C-arm using a large sample of clinical procedures.

METHODS AND MATERIALS

Occupational and patient doses are routinely supervised by the medical physicists in the three interventional laboratories of the Interventional Cardiology Department at the Hospital Clínico San Carlos (Madrid, Spain). Two of the interventional laboratories are Allura Xper models and the third one is an Allura Clarity (all from Philips Healthcare). All three have the same image detector and X-ray tube and quite a similar generator. The main difference between the Allura Xper model and the Allura Clarity is that the latter has an additional functionality (hardware and software) that can provide an important patient dose reduction.[6–13,21,22] This dose reduction functionality requires the use of higher beam filtration, that has a default value of 0.4 mm Cu +1 mm Al for fluoroscopy and cine. In the Xper model, the cine is delivered with no additional filtration and the fluoroscopy has (in Hospital Clínico San Carlos) a default value of 0.9 mm Cu +1 mm Al. The operator can change the beam filtration if necessary, which very rarely happens, and the most frequent operation modes are in general the default modes. When comparing these two different systems, we shall refer from now on to the Xper model with no added filtration in cine as the "*standard*" system and to Clarity with a patient dose reduction capability and with 0.4 mm Cu +1 mm Al of added filtration in cine as the "*dose reduction*" system. Both systems use pulsed radiation beams with a frequency ranging from 7.5 to 25 pulses/s and a pulse width from 3 to 15 ms. The pulse frequency is fixed for each mode and selected by the user, 7.5 and 15 being the most used, but the pulse width is set by the automatic exposure control according to patient thickness.

Using the dose management system DoseWise Portal coupled with the DoseAware Xtend system (both from Philips Health-Care), the patient dose records from the RDSR are archived along with the occupational dose measurements from the ODSR from all the electronic personal dosimeters model i3 (RaySafe, Sweden) used in the room (Figure 1). The dose information is recorded at event level and includes detailed data relative to beam quality (kV and filtration), beam angle, KAP, etc. as well as the quantity $H_p(10)$ for those electronic dosimeters present in the room. An analysis of $H_p(10)$/KAP can therefore be made at room, procedure or event level.

The personal dosimeter used for this study is the one located at a point of the C-arm (Figure 1). This point is defined by the intersection of a straight line with the C-arm from the isocentre, forming a 45° angle with C-arm rotation axis. It receives high secondary radiation dose rate from patient backscatter and describes the dose rate in the worst cases, *e.g.* in those radiation events where the tube and the professional are on the same side of the patient.[23] Depending on the protection level, in particular if a protection screen is being used, the cumulative dose per procedure over the apron at chest level is expected to under 2% of the secondary radiation dose measured by the C-arm reference dosimeter.[24] For the model of dosimeters used in this work, the manufacturer declares an energy dependence of less than 25%[*](N40-N150), a dose rate uncertainty of 10% for dose rates between 40 and 150 mSv/h and

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* https://www.raysafe.com/products/real-time-dosimetry-systems/raysafe-i3-real-time-radiation-dosimeter

Figure 1. Dose management system used in this experiment, managing occupational and patient dose. The dosimeter located at the C-arm used in this experiment is shown bigger. ODSR, occupational dose structured report.
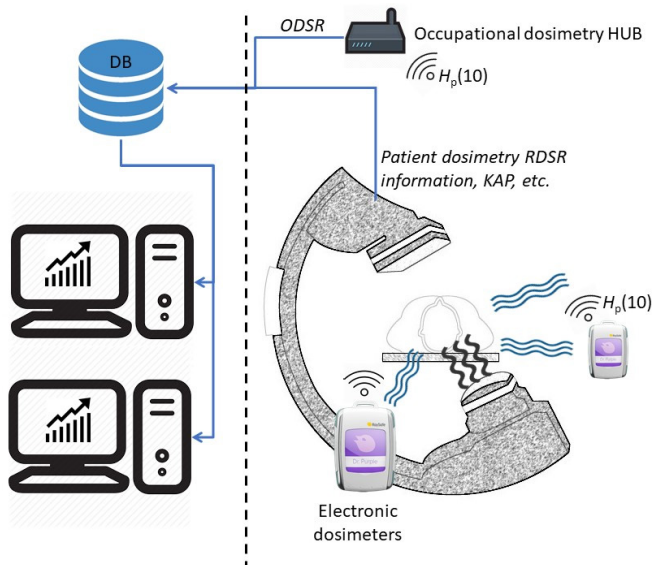
of 20% for dose rates between 150 and 300 mSv/h. Regarding angular dependence, their response can drop to less than 20% for incidence angles under 60°. He also warns that the dosimeters may have temperature dependence of 5% between 15 and 26°C but this dependence could reach 20% for temperatures over 26°C. Some authors[25–29] have brought up an issue regarding the response of electronic personal dosimeters with pulsed radiation fields and the high instantaneous dose rates present during these radiation pulses. That is why the Medical Physics Service in our hospital routinely tests (at least once a year) the performance of their electronic personal dosimeters with pulsed radiation beams and a reference personal dosimeter (EPD Mk2 from Thermo-Fisher Scientific, Walltman, Massachusetts, USA) calibrated in a secondary laboratory. This reference dosimeter was tested[26,29] with acceptable results in cumulative dose measurements for dose rates under 1.8 Sv/h and pulsed frequencies under $20 s^{-1}$. In the in-house verification performed by the Medical Physics Service, dosimeters are irradiated with the scatter radiation produced by a PMMA phantom located over the examination couch on an interventional C-arm, with beams typically used in interventional

radiology and cardiology on several kVs and filtrations (60–120 kV), and pulse frequencies from 3 to 25 p/s. The Medical Physics Service routinely also tests the accuracy of the KAP meter integrated in the C-arms: to this end, a calibrated semiconductor detector is used to measure the incident air kerma and a computed radiography (CR) plate to measure the radiation field size, as recommended by national and international protocols.[30,31] The DoseWise portal allows the user to introduce a correction factor for the KAP, and this factor is rounded to the first decimal figure by the system. Based on this information and considering the energy dependence of the KAP meters as the main source of uncertainty, 10% was considered to be the uncertainty for the KAP provided by the modality in this experiment.

Considering the uncertainty of both measurement quantities, $H_p(10)$ at the C-arm and KAP, the global uncertainty will be dominated by the measurement of $H_p(10)$ whose uncertainty depends on several factors as described previously and could be estimated (with the square root of the quadratic sum) from 27 to 37% in the worst case. The uncertainty of the ratio $H_p(10)$/KAP would then range between 30 and 40%.

A statistical analysis was carried out with SPSS 25 (IBM, USA). The Student's *t* and two-way ANOVA tests were used as hypothesis tests when distributions could be considered normal and variance homogeneity could be assumed, otherwise Mann–Whitney *U* and Kruskal–Wallis tests were used.

The ethics committee of the Hospital Clínico San Carlos gave a favourable opinion on this work (C.I.19/377E).

RESULTS

First, results at event level are presented to investigate how the scatter radiation changes with the beam quality (spectral filters and kV). Secondly, results at procedure level are presented showing the impact in clinical practice.

Table 1 shows the sample sizes managed in this study in the three interventional rooms and the percentage of KAP delivered with the different beam filtrations ($\Sigma KAP_{filter}/\Sigma KAP_{total}$).
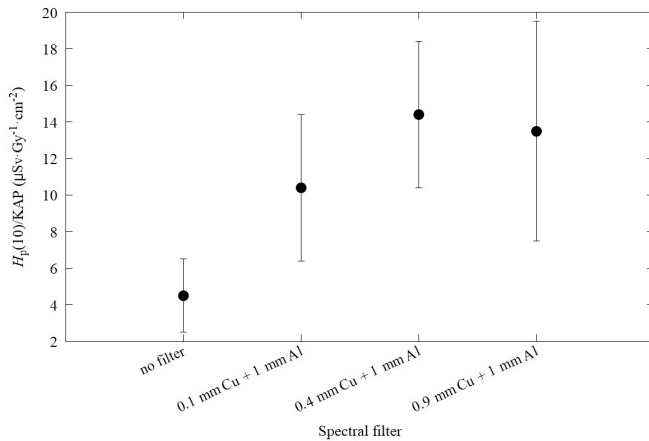
Analysis at event level

Figure 2 shows the average and the standard deviation of the sample for $H_p(10)$/KAP measured at the C-arm for events from

Table 1. Sample sizes for the "standard" systems (rooms 1 and 2) and the "dose reduction" system (room 3)

		Room 1	Room 2	Room 3
X-ray system		Standard	Standard	Dose reduction
No. clinical procedures		1659	2683	667
No. total radiation events		110,676	159,849	70,522
% of total KAP with	No added filtration	74%	72%	10%
	0.1 mm Cu +1 mm Al	2%	2%	20%
	0.4 mm Cu +1 mm Al	4%	4%	70%
	0.9 mm Cu +1 mm Al	20%	22%	0%

The use of the different filtrations in the three rooms in this sample is shown as the % of the total KAP delivered.

Figure 2. $H_p(10)$ at C-arm/KAP *vs* beam filtration for the sample of events with restricted kV and C-arm close to PA projection (±10°). Each point represents the mean value and the standard deviation of the sample for radiation events with 75 < kV < 85 and −10° < C arm angles < 10°. Sample sizes ranged from a minimum of 223 to 6241 radiation events.
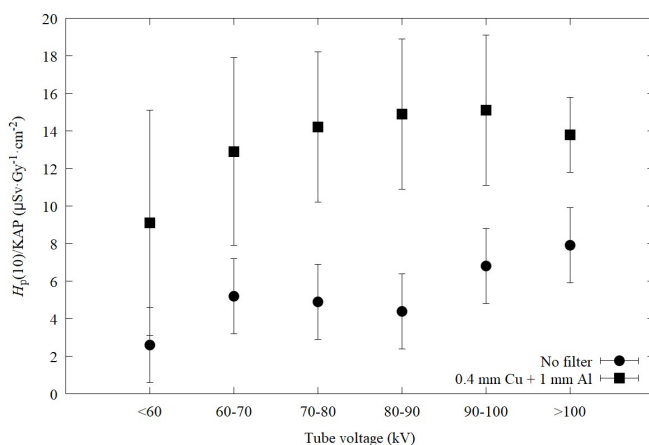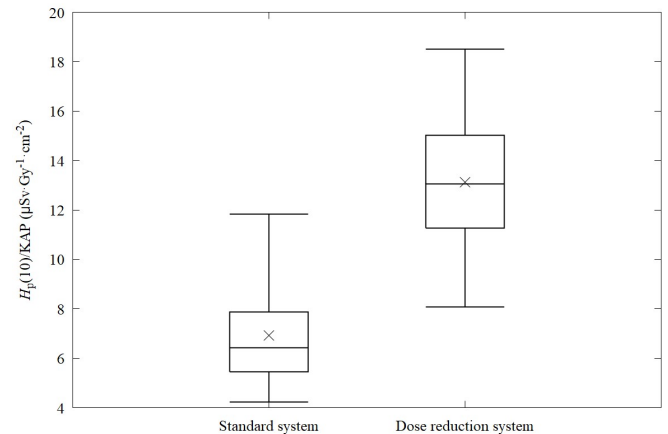

Figure 4. Ratios of $H_p(10)$ at C-arm/KAP for interventional procedures performed with the two X-ray systems used in this survey. The standard system has a cine mode with no added filtration. The "dose reduction" X-ray unit has patient dose reduction system that uses a cine X-ray beam with 0.4 mm Cu +1 mm Al added filtration (default filtration).

clinical procedures performed in the three rooms, with 75 < kV < 85, C-arm angles between −10 and 10 degrees and the four different beam filtrations used in clinics. Differences resulted statistically significant under Kruskal–Wallis ($p < 0.001$), even in the two last groups (0.4 mm Cu +1 Al and 0.9 mm Cu +1 Al) that resulted with $p < 0.001$ under Mann–Whitney U test, probably as a consequence of the high sample sizes (n_1 = 6241 and n_2 = 3882 radiation events).

Figure 3 shows the average and standard deviation of the sample for $H_p(10)$/KAP measured at the C-arm *vs* the kV, for the events with C-arm angles between −10 and 10 degrees. For simplicity's

Figure 3. The ratio $H_p(10)$ at C-arm/KAP *vs* kV for a sample of events for C-arm angles close to PA projection. Each point represents the average and standard deviation (of the sample) for radiation events with −10°< C arm angles < 10°. Minimum sample sizes were of 5 events (for no filter, kV > 100), 17 events (for no filter 90–100 kV) and 56 events (for no filter, kV <60). The rest of the points had sample sizes greater than 100 up to 7474 radiation events.

sake, only the most frequent spectral filtrations (Table 1) are shown. All differences can be considered statistically significant ($p \leq 0.004$ under Kruskal–Wallis and Mann–Whitney tests) with the exception of groups (60,70), (70–80) and (80–90) kV for no filter and groups (60–70) and >100 for 0.4 mm Cu +1 mm Al.

Analysis at procedure level

Figure 4 shows the ratio $H_p(10)$/KAP per cardiac procedure, graphed with boxes, for the two types of systems discussed in this investigation: the "*dose reduction*" system with high filtration (with a default added filtration of 0.4 mm Cu in cine) and the "*standard*" system with low filtration (with no added filtration in cine). The boxes represent the percentiles 5, 25, 50, 75 and 95%. The cross-point is the average. The sample sizes were the ones shown in Table 1. Both distributions are quite symmetric and present similarities with normal distribution at Q-Q graphs (not shown in this paper). The average ± standard deviation resulted in 7 ± 2 μSv·Gy^{-1}cm^{-2} for the "standard" and 13 ± 3 μSv·Gy^{-1}cm^{-2} for the "dose reduction" system ($p < 0.001$ under Student's t test).

Figure 5 shows the cumulative KAP and $H_p(10)$ at the C-arm per procedure for both models of X-ray systems. Student t test resulted in significant differences ($p < 0.001$) even for Figure 5b because of the high sample size.

DISCUSSION

Our results show (Figure 2) an increase of the scatter dose to patient dose ratio $H_p(10)$/KAP by a factor of up to 2.6 when increasing the spectral filtration from 0 to 0.4 mm Cu +1 mm Al. This result is consistent with those phantom measurements published in the literature.[19] Similarly, Figure 3 shows an increase of $H_p(10)$ to KAP ratio with a factor of 2.5 when changing the tube voltage from below 60 kV to above 100 kV, and a similar variation when the beam filtration is increased from no

Figure 5. The KAP per procedure and the $H_p(10)$ per procedure measured at the C-arm. Box graph shows the percentiles 5, 25, 50, 75 and 95%. The cross-point shows the average. As shown in Table 1, in the "dose reduction" system, 70% of the KAP was delivered with 0.4 mm Cu + 1mm Al of added filtration. In the standard system, 70% of the KAP was delivered with no added filtration.
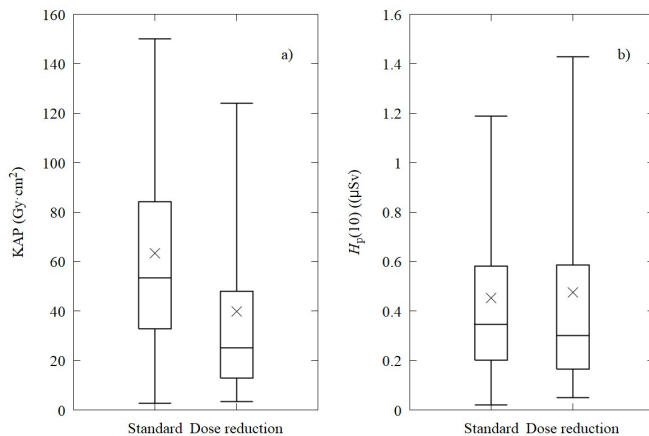
filter to 0.4 mm Cu +1 mm Al. This is consistent with previous publications.[14,15]

Therefore, the factor that affects the most the ratio $H_p(10)$/KAP measured at the C-arm is the beam quality, in particular when using higher beam filtration: a higher $H_p(10)$/KAP ratio is then produced.

In Figure 4, the analysis of $H_p(10)$/KAP is made at procedure level for the two systems investigated. The samples corresponding to rooms 1 and 2 are treated as the "standard" system. As seen from Table 1, the standard system used in rooms 1 and 2 delivers 70% of the KAP with no filtration. In the case of the "dose reduction" system used in room 3, the 70% of the KAP was delivered with 0.4 mm Cu +1 mm Al, which permits to reduce the patient KAP by 50–75% as shown in literature.[6–13,21,22] But this leads to an increment of the ratio of $H_p(10)$/KAP by a factor of almost two as shown in Figure 4. Therefore, the important reduction in patient dose obtained by the "dose reduction" system is not directly transferred to the scatter radiation dose to the operators as the

reduction in KAP is compensated with the increase in $H_p(10)$. In fact, in this sample, the average for the cumulative $H_p(10)$ per procedure measured at the C-arm was quite similar in both systems: for the standard and dose reduction system, the average was 452 and 476 μSv respectively, while the average KAP was higher in the standard system, 63 *vs* 40 Gy·cm^2 (Figure 5a and b).

In the analysis of the cumulative $H_p(10)$ at procedure level, the complexity of the procedures, that has not been considered here, might be different in different rooms and can affect the results. Salinas et al[22] presented an analysis using the same X-ray systems considering the complexity of the procedures: in a sample of chronic total occlusions, a reduction by almost 36% in patient dose was observed, but no reduction in occupational dose was found, neither at the C-arm, nor at operators.

Our study has limitations, the most important of which is that the measurement of secondary radiation was based at a particular point at the C-arm. It certainly gives a general idea of the secondary radiation level present in an interventional laboratory, but the results in operators can behave differently depending on the distance to the source of secondary radiation, the C-arm orientation and the proper use of suspended protection screens during all the procedures.

CONCLUSION

In interventional practices, "dose reduction" systems using high filtration X-ray beams can provide an important reduction in patient dose indicators. Their use should be encouraged in interventional rooms whenever the image quality provided gives enough clinical information. But it is also important to note that they may not provide the same reduction in scatter radiation dose for operators. Therefore, interventionalists must not overlook personal protection even when working with patient dose reduction systems.

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