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Radiation Doses to Staff in a Hybrid Operating Room: An Anthropomorphic Phantom Study with Active Electronic Dosimeters

Juan Serna Santos [a,*], **Jouni Uusi-Simola** [b], **Touko Kaasalainen** [b], **Pekka Aho** [a], **Maarit Venermo** [a]

[a] Department of Vascular Surgery, University of Helsinki and Helsinki University Hospital, Helsinki, Finland
[b] HUS Medical Imaging Centre, Radiology, University of Helsinki and Helsinki University Hospital, Helsinki, Finland

WHAT THIS PAPER ADDS

During fluoroscopically guided hybrid operations personnel are at risk of the stochastic effects of ionising radiation. Minimising the absorbed radiation dose is essential to reduce its harm. High quality active electronic dosimeters and an anthropomorphic phantom were used to measure radiation doses to hybrid theatre personnel in seven different positions in the hybrid theatre. Fifteen different settings, including fluoro modes, magnifications, C arm positions, and field sizes were analysed. Six effective rules are provided that help to reduce significantly the radiation dose while working in the hybrid theatre.

Objective: To quantify the effects of different imaging settings on radiation exposure to the operator and surgical team in a hybrid operating room (OR).

Methods: Measurements to determine scatter radiation in different imaging and geometry settings using an anthropomorphic phantom were performed in a hybrid OR equipped with a robotic C arm interventional angiography system (Artis Zeego; Siemens Healthcare, Erlangen, Germany). The radiation dose (RD) was measured with seven calibrated Philips DoseAware active electronic dosimeters and a Raysafe Xi survey detector, which were placed at different locations in the hybrid OR. The evaluated set ups included low dose, medium dose, and high dose fluoroscopy for abdomen; fluoroscopy fade; roadmap; and digital subtraction angiography (DSA), all using 20 s exposures. The effect of magnification, tube angulation, field size, source to skin distance, and RADPAD protection shields were assessed. Finally RD during cone beam computed tomography (CBCT) was obtained.

Results: In the operator position the initial settings with low dose fluoroscopy caused a RD of 1.03 μGy. The use of fluorofade did not increase the radiation dose (1.02 μGy), whereas the roadmap increased it threefold (2.84 μGy). The RD with "normal fluoro" was 4.13 μGy and increased to 6.44 μGy when high dose fluoroscopy mode was used. Magnification or field size varying from 42 cm to 11 cm led the RD to change from 0.86 μGy to 2.10 μGy. Decreasing the field of view to 25% of the initial size halved the RD (0.48 μGy). The RDs for the left anterior oblique 30° and right anterior oblique 30° were 3.26 μGy and 1.63 μGy, respectively. DSA increased the cumulative dose 33 fold but the RADPAD shield decreased the DSA RD to 4.92 μGy. The RD for CBCT was 47.2 μGy.

Conclusion: Radiation exposure to operator and personnel can be significantly reduced during hybrid procedures with proper radiation protection and dose optimisation. A set of six behavioural rules were established.

Keywords: Radiation safety, Radiation protection, Hybrid vascular, Hybrid revascularization, Hybrid operating room, Radiation exposure
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INTRODUCTION

According to the European survey on Interventional Radiology, the annual number of all non-cardiac interventional radiology (IR) procedures varies from 3500 to 9300 per one million inhabitants.[1] The estimation of the National Council on Radiation Protection and Measurements is that 10 000 vascular non-cardiac IR procedures per million inhabitants were performed in the USA in 2006.[2] Since these data were published, the number of fluoroscopically guided procedures has increased annually by about 8.5%.[3] The annual dose limits according to the International Commission on Radiological Protection are 20 mSv per year for eye lens and whole body,[3—5] and the lifetime cumulative radiation exposure for operating personnel should not exceed 400 mSv.[6] According to the literature, type of operation

* Corresponding author. Department of Vascular Surgery, Helsinki University Hospital, Haartmaninkatu 4, Helsinki 00290. Finland.
E-mail address: juan.sernasantos@hus.fi (Juan Serna Santos).

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(lower limb angioplasty *vs.* complex aortic repairs),[7,8] methodological factors (i.e., dosimeters placed under or above lead aprons),[9,10] or even year and origin of the publication (awareness of radiation hazards may vary with time and location),[10–13] could potentially explain these differences. Reported annual measurements vary from 8 to 40 mSv.[10,14]

In the last decade, with the introduction of the "hybrid room" concept, more operations, especially complex hybrid revascularisations and aortic repairs, have been performed by vascular surgeons in these hybrid operating rooms (ORs). Increasing the number of long hybrid procedures has also led to safety concerns regarding the radiation exposure, not only to the patient, but also to personnel working in the hybrid OR.[15] The radiation exposure risks to patients have been described previously.[16–19] Radiation induced biological effects may be divided into two categories: deterministic effects (tissue reactions) and stochastic effects. Deterministic effects do not occur below a certain dose threshold, whereas, once the threshold has been exceeded, the severity of the effect increases with the dose. [20,21] Nurses and surgeons, as well as anaesthetists exposed to radiation in numerous procedures, are at risk of stochastic effects, which are probabilistic in nature, the primary effect being carcinogenesis.[22,23] Lead aprons, suspended shields, eye lens shields, and education of medical workers have been proved to be useful in reducing radiation exposure.[7,16,24–29] However, there are several additional factors, such as fluoroscope settings, distance, angulation, magnification, and collimation that have an impact on radiation exposure to hybrid OR personnel, especially to the operating surgeon who is closest to the radiation source.

In this study, radiation doses were measured in a controlled static fashion at typical staff positions using several fluoroscopic settings and C arm positions. The study aimed to quantify the influence of different image protocols, features, staff locations, and shields on the radiation exposure of personnel in a hybrid OR.

MATERIALS AND METHODS

Measurement set up in the hybrid operation room

Seven active real time dosimeters (AEDs; DoseAware Personal Dose Meter system [Philips Medical Systems, Eindhoven The Netherlands]) and one RaySafe Xi survey detector (Unfors Raysafe AB, Billdal, Sweden) were deployed around the patient table in a hybrid OR, mimicking the position of surgeons, nurses, and anaesthetists. The positions of the Dosimeters´ sites are shown in Fig. 1. Each of the letters represents the static position of a dosimeter, which corresponds to a logical location of the members of the surgical team in a typical hybrid OR intervention. The closest dosimeters B and C mimic the spot of the operating and assisting surgeon, the members most exposed to scatter radiation. Nurses' locations D and E, as in a real life set up, are further from the operating area. On the other side, the F dosimeter was placed representing a hypothetical radiology nurse in charge of handling the contrast injector. Finally, the anaesthetic team (A and G) is expected to be near the head of the patient in a real life situation, and so they were placed accordingly in the set up. The dosimeter simulating the position of the anaesthetist (A) was protected by a lead screen. Table mounted lead screens were placed to the right side of the table, potentially shielding the dosimeters C, E, and D. On the other hand, the dosimeter representing the surgeon (B) was attached to a ceiling mounted lead screen on the side facing the patient, so it did not benefit from its shielding effect. A robotic C arm system (Artis Zeego; Siemens Healthcare, Erlangen, Germany) was the source of radiation, while an anthropomorphic adult female phantom (ATOM-702-D, CIRS) was used to simulate the patient undergoing the hybrid procedure.

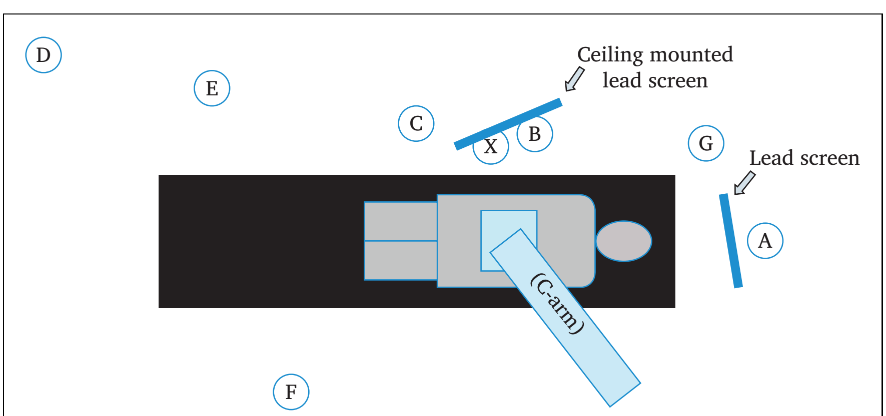

Figure 1. Schematic representation of dosimeter positioning around the operating table in an anthropomorphic phantom study with active electronic dosimeter. Each dosimeter mimics a staff member as follows: A = anaesthetist (behind the lead screen); B = operating surgeon (50 cm from the centre of the phantom surface [CPS]); C = assisting surgeon (150 cm from CPS); D = assisting nurse (380 cm from CPS); E = scrub nurse (250 cm from CPS); F = radiology nurse (160 cm from CPS); G = anaesthesiology nurse; X = reference ray safe. Notice that the detectors in X and B positions are not protected by the lead screen.

Dosimeters

The AEDs used provide real time insights into radiation exposure during procedures. These wireless semiconductor based AEDs are intended to measure the scattered radiation only and should not be positioned in the primary Xray field. The detection threshold (i.e., start trigger level) of the AEDs was 40 μSv/h; lower doses will not activate the dosimeter. The dose rate ranges from 40 μSv/h to 300 mSv/h, and the angular dependence of the response is less than ±5% within the angle range of ±5° and less than ±30% within the angle range of ±50°. Once the activation threshold has been exceeded, AED dosimeters can actually record lower doses than 40 μSv/h. Nevetheless, after several seconds of no exposure the AED requires at least 40 μSv/h again to re-activate. The RaySafe Xi Survey Detector, on the other hand, is a solid state detector that can be used for scatter and leakage measurements in X-ray and nuclear medicine applications. The survey detector consists of 154 silicon diodes, 77 on each side of the circuit board. The detector has high sensitivity and dose rate ranges from 0 μSv/h to 0.15 Sv/h, while there is a relatively constant (±10%) angular response over the front axial range of 150°. The AEDs were calibrated by the manufacturer to give an equivalent dose at the depth of 10 mm, Hp (10) in the tissue. However, the RaySafe Xi Survey Detector measured scattered radiation doses as air kerma. Therefore, to make radiation exposure values comparable between the dosimeters, a calibration factor from Hp (10) to air kerma was determined and used for each AED. Finally, all the scattered radiation dose values measured in the different imaging and geometry settings tested here were expressed as air kerma.

Baseline fluoroscopy setting and settings for additional measurements

The initial fluoroscope technique was set as follows: "low dose mode" with four pulses per second (pps), the radiation field centred over the chest of the phantom, direct vertical position of the C arm with no inclination or rotation, and Xray tube focus to skin distance of 76 cm, while focus to detector distance was set to 120 cm. No magnification or further collimation was used in these initial settings. After 20 s of fluoroscopy under these conditions, the radiation doses were recorded at each dosimeter position (Table 1). These values were considered the initial reference. After this, a set of techniques were tested, as well as different C arm and table positions, to compare how the radiation values change from the reference ones. The dosimeters were always kept in the same static location during each technique and position tested. Variable settings or set ups tested included the following.

Fluoroscopy programmes

There were three different fluoroscopy programmes available at the C arm unit: abdomen low dose (4 pps), normal dose (7.5 pps), and high dose (7.5 pps). The detector entrance dose for normal dose digital subtraction angiography (DSA) examinations in the unit used for the study is 540 nGy/frame. The low dose fluoroscopy level is nominally set at 50% of this standard or normal dose, whereas the high dose level is set at 200% of the normal dose.

Table 1. Cumulative radiation doses measured by the dosimeters after 20 seconds of exposure in an anthropomorphic phantom study

Imaging setting	Radiation dose per dosimeter - μGy							
	A	B	C	D	E	F	G	RaySafe (ref)
Initial setting	0.13	1.03	0.14		0.05	0.24	0.83	0.74
Normal fluoroscopy	0.17	4.13	0.63		0.10	0.76	2.63	3.68
High dose fluoroscopy	0.27	6.44	0.99	0.02	0.16	1.24	3.98	5.32
Fluorofade	0.05	1.02	0.15		0.01	0.21	0.69	0.84
Roadmap	0.14	2.84	0.46		0.10	0.56	1.97	2.52
DSA	1.20	30.98	4.74	0.24	1.50	6.39	20.54	30.92
CBCT*	2.40	47.20	9.91	0.96	2.59	16.00	14.42	79.07
Field reduction to 25%		0.48	0.08			0.12	0.36	0.40
Zoom 2 (32 cm)		0.86	0.12		0.01	0.18	0.55	0.63
Zoom 3 (22 cm)	0.02	0.97	0.16			0.21	0.74	0.74
Zoom 4 (14 cm)	0.09	1.83	0.38		0.06	0.43	1.47	1.55
Zoom 5 (11 cm)	0.09	2.10	0.35		0.07	0.44	1.56	1.57
LAO −30	0.05	3.26	0.17		0.04	0.23	1.24	1.73
RAO +30	0.01	1.63	0.19		0.04	0.22	0.87	1.38
RADPAD® shield†	1.12	4.92	4.24	0.25	1.03	7.62	22.07	5.97

The position of each dosimeter is presented in Fig. 1. Blank cells correspond to non-activated dosimeters; when the radiation did not reach the trigger level (40 μSv/h) no measurement was recorded. DSA = digital subtraction angiography; CBCT = cone beam computed tomography; LAO = left anterior oblique projection; RAO = right anterior oblique projection.

* CBCT was run automatically for 6 s.

† RADPAD was tested during DSA.

Roadmap and fluoroscopy fade (aka fluorofade or mask overlay) modes

A digital roadmap is a guidance fluoroscopic image that is able to show in real time wires and catheters over the vasculature to allow easy navigation during the intervention. While "fluorofade" mode entails overlaying a referenced image from a digital subtraction angiogram onto the real time fluoroscopic display enabling a substantial reduction in radiation exposure.

DSA and cone beam computed tomography modes

DSA is a basic fluoroscopy technique available in all modern C arms. During DSA tissues and blood vessels on a fluoroscopic *first* image are digitally subtracted from a posterior *second* image, leaving a clear picture of the arterial tree, which can then be studied independently and in isolation from the rest of the picture contents. Many floor fixed C arms, such as the one used in this study, also have the capacity to perform an intra-operative cone beam computed tomography (CBCT), which takes 6 seconds to run.

Collimation

Different sizes of the picture/field defined by the collimators that limit the Xray beam were also tested.

Six levels of magnification

Six levels of magnification were defined by the size of the field of view as follows: no zoom: 48 cm; zoom 1: 42 cm; zoom 2: 32 cm; zoom 3: 22 cm; zoom 4: 16 cm; and zoom 5: 11 cm.

Table position

Raising or lowering the table, while maintaining the C arm detector position, changes the distance between the X-ray tube and the patient, also known as the focus to skin distance (FS). Increasing FS distances (raising the table) were measured in the B position under the initial C arm settings.

Left anterior oblique, anteroposterior, and right anterior oblique projections

Left anterior oblique (LAO), anteroposterior (AP), and right anterior oblique (RAO) projections were tested at LAO −30 and RAO +30 positions. Additionally, the dose in B was recorded at short intervals of 15° from LAO −86° to RAO +90°, to analyse the continuous variation of scatter radiation over this 180° angle.

Disposable sterile radiation drape

Finally, the effect of the disposable sterile radiation drape RADPAD (World Wide Innovations & Technologies, Lenexa, KS, USA) in normal fluoroscopy mode and in DSA mode was tested. The drape was placed according to the manufacturer instructions covering the patient's right side (phantom in this case).

In each setting, the accumulated scattered radiation dose was recorded after 20 seconds of exposure, except in the CBCT mode, which runs with no adjustable time for 6 seconds. The data were recorded and analysed using Excel (version plus 2016; Microsoft, Redmond, WA, USA).

RESULTS

The initial settings resulted in cumulative air kerma in the position B "operating surgeon" of 1.03 μGy. The measured doses in all the dosimeters are given in Table 1. Dosimeters A, D, and E did not activate during any of the techniques tested, meaning that the radiation did not reach the trigger level 40 μSv/h

Impact of fluoroscopic modes

The recorded doses showed a correlated increase in all the dosimeter positions. The radiation dose recorded in B position was the highest: 1.03 μGy for low dose fluoroscopy (4 pps), 4.13 μGy for normal dose fluoroscopy, and 6.44 μGy for high dose fluoroscopy.

Impact of the fluoroscopic fade mode or "fluorofade"

The fluoroscopy fade mode caused almost equal exposure dose (1.02 μGy) in the B dosimeter as the low dose fluoroscopy mode (1.03 μGy). Very small differences were registered in other positions (Table 1).

Impact of roadmap

An increase in radiation exposure to all dosimeters of up to three times *vs.* low dose fluoroscopy was measured during roadmap acquisition. The dosimeter most affected by the increased dose was again, B (2.84 μGy).

Impact of DSA and CBCT

These two modes generate the highest amount of radiation over the patient. The highest increase in scattered radiation was measured in the dosimeters closest to the X-ray tube: B (30.98 μGy and 47.20 μGy, respectively), and RaySafe Xi (30.92 and 79.07 μGy, respectively). DSA resulted in about a 30 fold increase in radiation dose to the operating surgeon *vs.* low dose fluoroscopy, while CBCT caused a 47–80 fold increase in these positions. All dosimeters registered the highest measurements during these techniques (Table 1). D position, in the furthest location registered 0.24 μGy and 0.96 μGy, respectively.

Impact of collimation

A reduction of the initial field size to 25% more than halved the doses registered in position B (from 1.03 μGy to 0.48 μGy). Similar scattered dose trends were recorded in other positions (Table 1).

Impact of magnification

Increasing the magnification to zoom level 3 decreased the dose measured by B (0.97 μGy) and all the dosimeters

(Table 1). Increasing the magnification further to zoom levels 4 and 5 caused an increase in the measured radiation dose. All dosimeters showed this variation in dose with increments in magnification. At the highest magnification, dosimeter B recorded the highest dose value (2.10 μGy).

Impact of table position

In the B position, progressive elevation of the table, that is, increase in FS distance, was correlated with a linear growth in doses of 10.2% for each 5 cm.

Impact of LAO/RAO projections

The axial angulation effect was measured in the rest of the positions at −30° and +30° projections. Both caused an increase in doses in the dosimeters close to the patient (C, and RaySafe Xi Survey) as shown in Table 1.

Varying the angulation of the C arm in the axial plane from LAO at −86° to the AP position at 0° resulted in a notable variation of doses received by B dosimeter. Dose was highest at the initial −86° position (38.26 μGy). Repositioning the C arm further into RAO projection showed a decrease in radiation measurements to RAO +15° projection, where a minimum of 1.29 μGy was measured. From this position onwards, the increments in angulation up to +75° degrees caused an increase in scattered radiation up to 3.79 μGy. Finally, from +75° onwards a steeper increase in radiation exposure was evidenced (7.87 μGy) until +90° (Fig. 2).

Impact of the RADPAD shield

The shielding effect of the sterile radiation drape was tested during DSA. The decrease in scattered radiation was notable in the B dosimeter (30.98 μGy—4.92 μGy), as well as in the RaySafe Xi Survey detector (from 30.92 μGy to 5.97 μGy). This powerful protective effect was not observed with the other dosimeters.

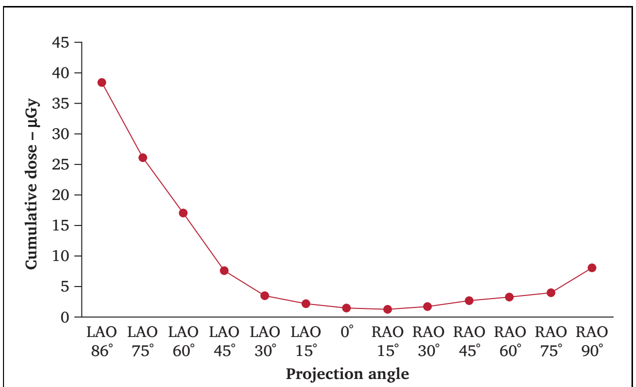

Figure 2. Radiation dose (μGy) *vs.* variations in axial plane projection in an anthropomorphic phantom study with active electronic dosimeter. Exposure measured at B position, as presented in Fig. 1. LAO = left anterior oblique projection; RAO = right anterior oblique projection.

Table 2. Most effective manoeuvres to reduce radiation exposure and their corresponding reduction in an anthropomorphic phantom study with active electronic dosimeters

Manoeuvre	RD reduction - %
Distance from the CPS 50 cm *vs.* 250 cm	95
Distance from the CPS 50 cm *vs.* 160 cm	77
High dose *vs.* low dose	84
Normal dose *vs* low dose	75
Roadmap *vs.* “fluorofade”	64
Open field *vs.* field reduction to 25%	53
Zoom × 5 *vs.* no zoom*	51
DSA *vs.* DSA with RADPAD (50 cm)	84
DSA 50 cm *vs.* DSA 160 cm	79

RD = radiation dose; CPS = centre of the phantom surface; DSA = digital subtraction angiography.
* Under low dose mode.

The manoeuvres that affected radiation dose most powerfully are given in Table 2.

DISCUSSION

In the current study mimicking the real life positions of the patient and personnel, the impact of several factors on radiation dose to hybrid theatre workers was shown. The most powerful shielding effect identified in the study was the distance between staff position and patient/table. This was evident in all settings (Table 1). Dosimeters D and E, situated the furthest away, received the smallest doses throughout the experiment. A distance of more than four metres from the source was enough to reduce the measured doses to non-distinguishable from background radiation. Only DSA and CBCT developed measurable doses at these points. Dosimeter A, behind a ceiling mounted shield, exceeded the doses registered in dosimeter D, indicating that the extra distance provided by D offered more protection than the glass shield. Taking two steps back from the operating surgeon (B) position was enough to reduce the dose drastically, as in position E, mimicking a “scrub nurse”, the measured radiation dose decreased 39 fold from the reference measurement. The doses registered by AED D (i.e., “assisting nurse”) were unmeasurable owing to the low dose in most of the set ups. AED F, mimicking a radiographer at the contrast injector, gained four fold dose increases *vs.* AED E, as the protection shields were on the right side of the table.

Low dose fluoroscopy mode should always be used when possible as it proved to develop the smallest doses, four and seven times smaller than normal and high dose fluoroscopy modes, respectively, in the operating surgeon (B) position. Doses measured during fluoroscopy fade mode were consistently smaller (between three and seven times) than those measured during the roadmap. Although some interventionists are advocates for the routine use of roadmap as a navigation tool, fluoroscopy fade can be equally useful, even in complex vascular cases.[30] Based on the present results, the use of fluorofade over roadmap is recommended, accepting a minimal drawback in image quality. Collimation and minimising the size of the Xray field are known to decrease scatter radiation exposure to personnel. Focusing the radiation to a smaller area within the patient allows for a larger volume of the patient's tissues to attenuate the scattered radiation before it exits the patient.[31] According to the present dose records, collimating the image into the area of interest decreases the doses in all positions inside the hybrid OR, supporting previous studies on the effect of field of view on radiation exposure.[32]

Angulation of the gantry so that the detector is turned towards the operator (RAO) decreased the scatter dose at the operator position. This reduction is due to the direction of the maximum scatter being turned away from the operator and also to the protective effect of the table mounted shields found on the operator side (right in this case). As a practical rule, RAO projections are safer than LAO projections when the operator is on the right side of the table. This observation is consistent with previous studies.[33]

Interventionists know that elevating the table to keep the patient close the detector of the C arm is a good way to minimise radiation exposure to the patient and to themselves. Nevertheless, it was found that raising the table increased the doses measured for the personnel. This may be explained by the fact that raising the table reduced the distance between the phantom and the position of the dosimeters (all but G and F were approximately at a height of 170 cm) therefore reducing the distance for the scatter radiation to reach them. Moreover, when the patient table was positioned lower, the imaged area was also reduced, leaving more attenuating phantom material between the primary beam and OR personnel. Again, the distance was a determining factor for dose level. At the operating surgeon position, even small distances can make a difference, as pointed out in the study by Quan *et al.*, where significant radiation exposures were measured between the right and left side of the operator.[34] Although current practice inside the hybrid OR seems to be within the limits of acceptable exposure,[35] small position adjustments, especially by the operating surgeon, can make a difference, as was confirmed herein: keeping the upper part of the surgeon's body away from the patient when the table is high would prevent unnecessary "extra" radiation.

At low magnification levels (zoom levels 2 and 3, i.e., 32 cm and 22 cm, respectively), the measured doses were lower than with the initial settings. This unexpected effect happened possibly because using the magnification decreased the Xray field size and thus reduced the amount of radiation scattered from the patient. Therefore, the expected increment in scattered dose was mitigated by smaller Xray field size. At higher magnification (zoom levels 4 and 5, i.e., 16 cm and 11 cm, respectively), the measured doses increased further because the imaging system increased the dose rate.

Rules for avoiding radiation exposure during CBCT have been established previously.[36] However, considering the dramatic values recorded in this study during DSA and CBCT acquisition, it is recommended that personnel always leave the hybrid OR during these procedures or at least move as far away as possible from the table.

The disposable sterile radiation protection drape proved to have a significantly protective effect for the operating surgeon reducing the exposure to a fifth. Nevertheless, this effect appears only within short distances, as AEDs further away seem to benefit from the overwhelming protection of the distance. It should be a part of the armamentarium of the vascular interventionist.

Limitations of the present research

Owing to the experimental nature of this study there are limitations in the way measurements are recorded. In a real life intervention staff perform dynamically, moving during the procedure and changing the C arm settings, whereas in this study the dosimeters were immobile. Moreover, the lower dose threshold of the dosimeters is 40 μSv/h with doses below this level not activating them and therefore being indistinguishable from the background radiation. The phantom is an acceptable way of studying scattered radiation; however, it is not made of organic tissue and differences in the way a normal human scatters radiation may exist. The phantom also imitates an average sized human; obese patients or very thin patients may scatter radiation differently.

CONCLUSIONS

Awareness of the risk inherent in fluoroscopically guided procedures is crucial for the vascular surgeons and interventionists. Manoeuvres and settings to reduce the exposure are available to everybody and often demand very little effort. Based on the present findings, it is recommended that the following rules should be made routine in the hybrid theatre:

1. Always use the low dose fluoroscope setting when possible.
2. Choose "fluorofade" rather than roadmap, and RAO instead of LAO angulation.
3. Use as small a size of Xray field as reasonable.
4. Try to avoid excessive magnification and keep judicious manipulations under the Xray beam.
5. Make use of all available physical barriers: table and ceiling mounted shields, lead aprons and thyroid shields, as well as lead glasses and sterile disposable radiation protection drapes.
6. Take a step away from the patient as in the end distance is the most powerful tool to decrease radiation exposure.

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