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Editor's Choice — Angulation of the C-Arm During Complex Endovascular Aortic Procedures Increases Radiation Exposure to the Head☆

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WHAT THIS PAPER ADDS

Increasing complexity of endovascular procedures can expose the vascular interventionalist to higher levels of radiation, particularly to areas of the body not shielded by lead. This study directly measures radiation exposure to the operator's head during complex endovascular aortic procedures and demonstrates that exposure is considerably higher with angulation of the C-arm. This knowledge can help operators to minimise C-arm angulation during procedures with the aim of reducing radiation exposure.

Objectives/Background: The increased complexity of endovascular aortic repair necessitates longer procedural time and higher radiation exposure to the operator, particularly to exposed body parts. The aims were to measure directly exposure to radiation of the bodies and heads of the operating team during endovascular repair of thoracoabdominal aortic aneurysms (TAAA), and to identify factors that may increase exposure.
Methods: This was a single-centre prospective study. Between October 2013 and July 2014, consecutive elective branched and fenestrated TAAA repairs performed in a hybrid operating room were studied. Electronic dosimeters were used to measure directly radiation exposure to the primary (PO) and assistant (AO) operator in three different areas (under-lead, over-lead, and head). Fluoroscopy and digital subtraction angiography (DSA) acquisition times, C-arm angulation, and PO/AO height were recorded.
Results: Seventeen cases were analysed (Crawford II—IV), with a median operating time of 280 minutes (interquartile range 200—330 minutes). Median age was 76 years (range 71—81 years); median body mass index was 28 kg/m^2 (25—32 kg/m^2). Stent-grafts incorporated branches only, fenestrations only, or a mixture of branches and fenestrations. A total of 21 branches and 38 fenestrations were cannulated and stented. Head dose was significantly higher in the PO compared with the AO (median 54 µSv [range 24—130 µSv] vs. 15 µSv [range 7—43 µSv], respectively; $p = .022$), as was over-lead body dose (median 80 µSv [range 37—163 µSv] vs. 32 µSv [range 6—48 µSv], respectively; $p = .003$). Corresponding under-lead doses were similar between operators (median 4 µSv [range 1—17 µSv] vs. 1 µSv [range 1—3 µSv], respectively; $p = .222$). Primary operator height, DSA acquisition time in left anterior oblique (LAO) position, and degrees of LAO angulation were independent predictors of PO head dose ($p < .05$).
Conclusions: The head is an unprotected area receiving a significant radiation dose during complex endovascular aortic repair. The deleterious effects of exposure to this area are not fully understood. Vascular interventionalists should be cognisant of head exposure increasing with C-arm angulation, and limit this manoeuvre.

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INTRODUCTION

Endovascular aortic repair (EVAR) is associated with lower perioperative morbidity and mortality compared with conventional open repair,[1,2] and in many centres is now the technique of choice for treatment of thoracoabdominal aortic aneurysms (TAAAs).[3] The increased complexity of endovascular TAAA repair using branched or fenestrated stent-grafts necessitates longer procedural times and higher radiation exposure to the patient and operator.[4,5] However,

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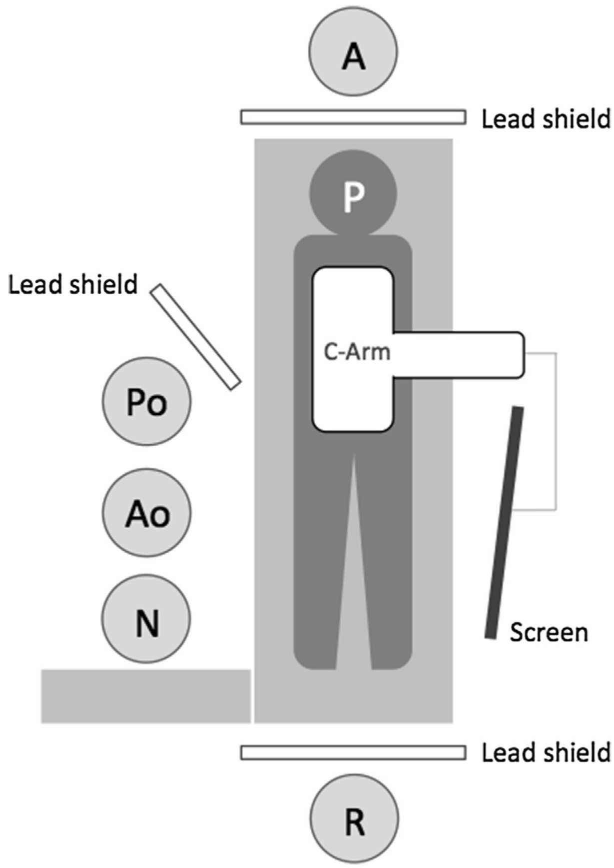

Figure 1. Diagram illustrating fluoroscopic/safety equipment and positions of operating staff. Monitor screens are located on the left-hand side of the patient (P) and the operating team on the right-hand side. The primary operator (PO) stood closest to the X-ray beam, the assistant operator (AO) stood to the right of PO, and the scrub nurse (N) stood to the right of AO. The anaesthetist (A) was positioned at the head end of the theatre table and the radiographer (R) at the foot end. This set-up did not differ between fenestrated and branched procedures.

studies have shown that occupational radiation doses sustained during standard infra-renal and complex thoracoabdominal EVAR procedures are within the limits recommended by the International Commission on Radiological Protection (ICRP).[6,7]

However, recent reports of left-sided brain tumours in interventionalists should raise doubts regarding the validity of these recommended safe limits, particularly to exposed body parts such as the head.[8,9] In view of the paucity of data regarding the radiation dose to the operator's head, the aim of this study was to measure directly radiation exposure to the bodies and heads of the operating team during endovascular repair of TAAAs, and to identify factors that may increase this exposure.

MATERIALS AND METHODS

Consecutive elective endovascular TAAA repairs carried out using branched (BEVAR) and fenestrated (FEVAR) stent-grafts were prospectively studied over a 10-month period (October 2013—July 2014). All procedures were performed under general anaesthesia in a hybrid operating room by a team consisting of vascular surgical and interventional radiology specialists. This observational study was registered and carried out under ethical regulations that govern institutional audits.

Fluoroscopic and protective equipment

All procedures were performed under fluoroscopic guidance using a Philips Allura Xper FD20 system (Philips Healthcare, Eindhoven, the Netherlands). The default positioning of the C-arm was in the anterior—posterior direction (0°). The C-arm was mobile around a free-floating theatre table (ALPHAMAXX; Maquet, Rastatt, Germany) and was capable of rotating 90° about the median sagittal plane to achieve true lateral angulations ("left" and "right" true lateral, depending on the position of the image intensifier relative to the patient), cranial/caudal angulations that were limited only by the patient and table. Angulations between 0° and 90° were termed "anterior oblique". The equipment set-up and operating staff positioning (illustrated in Fig. 1) was similar for both FEVAR and BEVAR procedures. For BEVAR procedures, the aortic arch was approached using right axillary artery access; therefore, the operators continued to work on the right side of the patient.

The fluoroscopy equipment was operated in "low-dose mode" and was controlled by a senior radiographer in each case. Default settings included a pulse rate of 7.5 pulses/second for background fluoroscopy, and two frames/second for digital subtraction angiography (DSA) acquisitions.

The use of radiation protection equipment was recorded for each case. Protective equipment available included a suspended lead drape on the operator's side of table, mobile lead shields for the radiographer and anaesthetist, ceiling-mounted operator lead shields, leaded thyroid collars, and leaded goggles. Lead garments were 0.35-mm thick and were worn by all staff within the hybrid operating room.

Dosimetry

Electronic dosimeters (Hitachi-Aloka Medical PDM-127; Hitachi Aloka Medical Ltd, Tokyo, Japan) were used to measure directly the exposure to radiation of the PO and AO. These devices recorded cumulative measurements of the "dose equivalent" of absorbed radiation in Sieverts (Sv) for each case, with a minimal detectable level of 1 μSv. Further details have been described previously.[6]

Dosimeters were attached to three different areas on the PO and AO: (i) left breast pocket *under* the protective lead garment; (ii) left breast pocket *over* the protective lead garment; and (iii) left temporal region at eye level. The same positions were used in all cases to ensure consistency. Under-lead readings were used as an estimate of total body "effective dose" and eye-level readings served as an indicator of head dose.

Data collection

Data were collected by a trained observer who was familiar with BEVAR and FEVAR procedures, and independent of the operating team. A 2-week preliminary phase was implemented for observer training and to reduce the Hawthorne effect (i.e., any changes in the operators' performance or radiation safety behaviour that may be a consequence of being observed).

For each procedure, operative details (type of repair, operative time, fluoroscopy time, number and total DSA acquisition time, and C-arm angulation), radiation doses, and dose area product (DAP) were recorded. Operator height and radiation safety behaviours were also recorded, including stepping away from the operating table during DSA acquisitions and utilising ceiling-mounted lead shield. All staff were aware of dosimetry monitoring but were blinded to the results during the study.

Statistical analysis

Continuous variables are expressed as median (interquartile range [IQR]). Median radiation doses between groups were analysed with the Mann—Whitney *U* and Kruskal—Wallis tests. Correlations were tested using Spearman's rank test. Simple linear regression modelling was used to identify predictors of increased radiation exposure to the operator. Statistical analysis was performed using SPSS version 22.0 (IBM, Armonk, NY, USA) and *p*-values $<.05$ were deemed to be significant.

RESULTS

Demographics

During the study period, 22 elective FEVAR and BEVAR procedures were assessed for eligibility. The first two cases, considered to be part of the preliminary observer training phase, were excluded, and a further three emergency procedures were also excluded. The remaining 17 cases, with a total operating time of 75.7 hours (median 280 minutes/procedure [range 200—330 minutes/procedure]), were included and analysed in this study. The median age of patients was 76 years (range 71—81 years) and the median body mass index was 28 kg/m^2 (range 25—31 kg/m^2). Stent-grafts used incorporated branches only ($n = 4$), fenestrations only ($n = 10$), or a mixture of branches and fenestrations ($n = 3$). A total of 21 branches and 38 fenestrations were cannulated and stented (Table 1).

In all cases, the PO was a consultant vascular surgeon and the AO was a consultant interventional radiologist. The PO and AO for each procedure were selected from a complex EVAR team consisting of three consultant vascular surgeons and two interventional radiologists.

Operating team radiation exposures

The median fluoroscopy time was 89.1 minutes (range 63.4—119.3 minutes), DSA acquisition time 76.1 seconds (range 57.5—130.0 seconds), and DAP 172.2 Gy.cm^2 (range 134.6—325.6 Gy.cm^2) per procedure. Head dose was significantly higher in the PO compared with the AO (median 54 μSv [range 24—130] μSv vs. 15 μSv [range 7—43 μSv], respectively; $p = .022$), as was over-lead body dose (median 80 μSv [range 37—163 μSv] vs. 32 μSv [range 6—48 μSv], respectively; $p = .003$). The corresponding under-lead ("total body effective") doses were similar between operators (median 4 μSv [range 1—17] μSv vs. 1 μSv [range 1—3 μSv], respectively; $p = .222$), as illustrated in Fig. 2. The over-lead radiation doses correlated with head doses in both the PO and AO (Fig. 3).

Table 1. Classification of aneurysms, type of endovascular repairs, and target visceral vessels.

	n (%)
Crawford classification of aneurysms	
II	4 (23)
III	2 (12)
IV	11 (65)
Type of repair	
FEVAR	10 (59)
BEVAR	4 (23)
Mixed	3 (18)
Target visceral vessel	
Coeliac	13 (76)
SMA	17 (100)
Right renal	17 (100)
Left renal	17 (100)

Note. FEVAR = fenestrated endovascular aneurysm repair; BEVAR = branched endovascular aneurysm repair; SMA = superior mesenteric artery.

Predictors of PO radiation dose

A simple linear regression analysis identified a number of significant predictors of PO head radiation dose (Table 2). Among these, DSA acquisition time in LAO ($p < .001$, $R = .629$) and the degrees of LAO angulation ($p < .001$, $R = .648$) were the most significant predictors of PO head dose.

DSA acquisition time in LAO correlated with PO head radiation dose (rho = .698, $p = .002$), as did the degree of LAO angulation (rho = .656, $p = .004$) (Fig. 5).

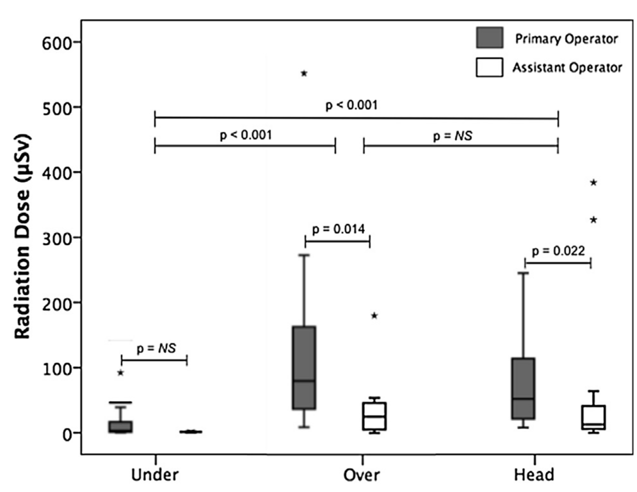

Figure 2. Radiation dose per procedure by type of operator and body region. *Note*. NS = nonsignificant.

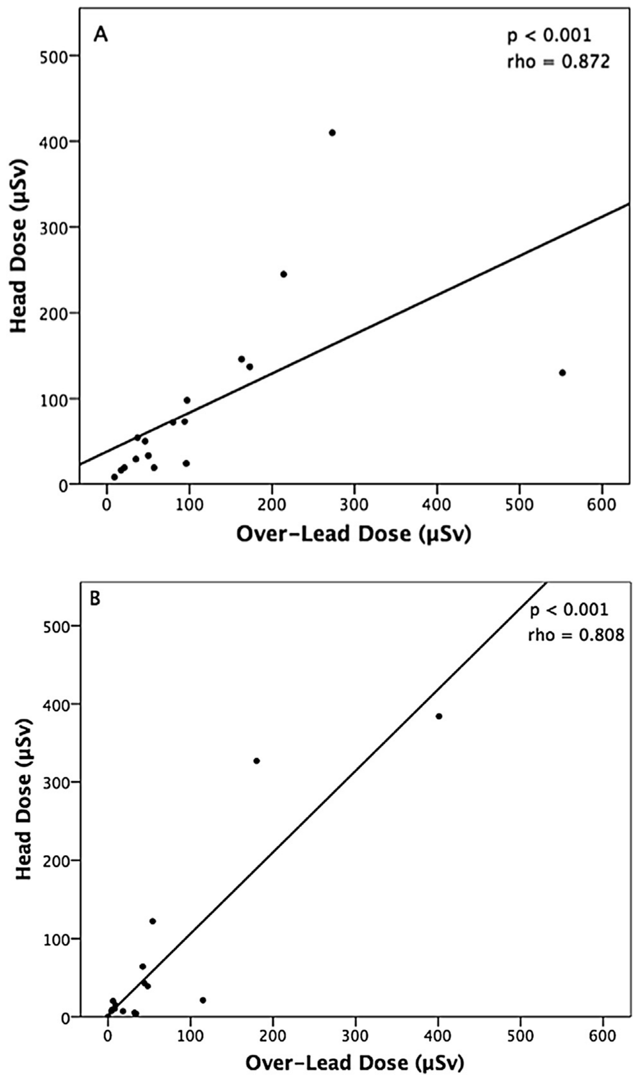

Figure 3. Scatterplot demonstrating relationship between over-lead and head dose to (A) primary operator and (B) assistant operator.

Table 2. Simple linear regression analysis to identify predictors of primary operator head dose.

Variable	Median (IQR)	*R*	*p*
Total operating time (min)	280 (200–330)	.412	.005
Total fluoroscopy time (min)	89.1 (63.4–119.3)	.489	.002
Total patient DAP (Gy.cm^2)	172.2 (134.6–325.6)	.588	.001
Patient BMI (kg/m^2)	28 (25–31)	.002	NS
Total DSA time (s)	76.1 (57.5–130.0)	.471	.002
Total DSA time in C-arm position (s)			
LAO	27.2 (18.0–79.0)	.629	<.001
RAO	16.0 (9.0–29.0)	.092	NS
Cranial	34.0 (12.7–51.1)	.619	<.001
Caudal	11.0 (1.0–25.5)	.013	NS
Degree of C-arm angulation (°)			
LAO	26.8 (20.0–36.5)	.648	<.001
RAO	16.0 (3.6–25.7)	.212	NS
Cranial	5.0 (1.4–11.1)	.010	NS
Caudal	1.1 (0.0–7.2)	.028	NS
Time to visceral vessel cannulation (min)			
Coeliac	15.6 (10.1–26.7)	.244	NS
SMA	15.9 (9.9–21.4)	.391	.010
Right renal	14.3 (6.4–18.2)	.075	NS
Left renal	15.6 (10.0–32.1)	.294	NS

Note. DAP = dose area product; BMI = body mass index; DSA = digital subtraction angiography; LAO = left anterior oblique; RAO = right anterior oblique; SMA = superior mesenteric artery; IQR = interquartile range; NS = nonsignificant. R >.5 or <−0.5 considered strong relationship.

Impact of operator height

The three POs measured 170 cm, 186 cm, and 193 cm in height, respectively, and the AOs were 165 cm and 170 cm in height, respectively. There was an inverse relationship between PO height and head radiation dose ($p = .009$), but not for body under-lead or over-lead doses. There was no correlation between AO height and measured doses (Fig. 4). There were no differences in DSA acquisition times in LAO between each of the three POs (170 cm, 82.5 seconds; 186 cm, 70.5 seconds; 193 cm, 65.2 seconds, respectively).

Impact of procedure type

There was no difference in fluoroscopy time, DSA acquisition time, and DAP between FEVAR and BEVAR procedures. There was also no difference in LAO angulation between FEVAR and BEVAR procedures (median 28.3° and 33.5°, respectively). Similarly, although overall operator radiation doses trended higher in FEVAR compared with BEVAR cases (median over-lead dose 153 μSv [range 76.3–221.5 μSv] vs. 82.5 μSv [range 65.0–87.8 μSv]; median under-lead dose 22.5 μSv [range 8.0–47.0 μSv] vs. 1.0 μSv [range 0.8–5.3 μSv]; median head dose 100.5 μSv [range 34.0–191.8 μSv] vs. 59.5 μSv [range 31.8–85.8 μSv]) but did not reach statistical significance.

Radiation protection

The operating team's compliance with measures that are known to reduce radiation exposure are summarised in Table 3. A side-table lead drape and anaesthetist/radiographer lead shields were used in all cases. Ceiling-mounted lead shields were used by the PO in 41% of cases. Thyroid collars were applied by the PO and AO in 100% and 88% of cases, respectively. Similarly, the use of leaded goggles by the PO and AO was 100% and 94%, respectively. A total of 315 DSA acquisition runs were performed over the study period; stepping away from the operating table was observed in 15 (5%) DSA runs for the PO and 28 (9%) for the AO.

Extrapolation of results

If the mean PO radiation doses are extrapolated over larger numbers of cases, the cumulative radiation exposure to the operator can be estimated. A total of 25 FEVAR or BEVAR repairs performed per year would theoretically yield cumulative head, over-lead, and under-lead radiation exposures of 2.29, 2.96, and 0.37 mSv, respectively. These figures

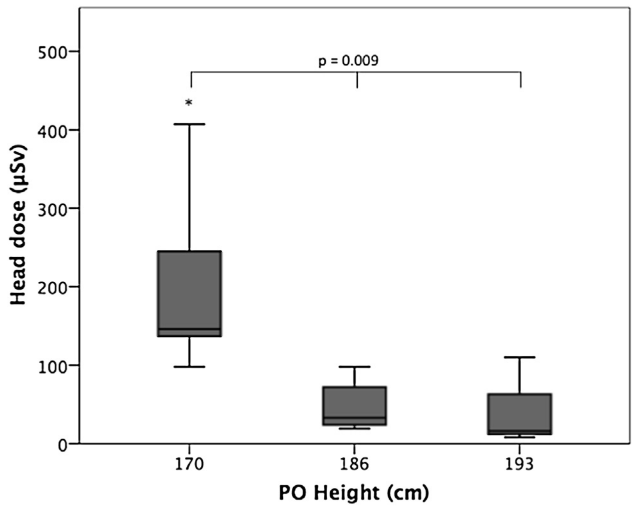

Figure 4. Head radiation dose by primary operator (PO) height. *$p < .05$ (170 cm vs. 186 cm, 170 cm vs. 193 cm).

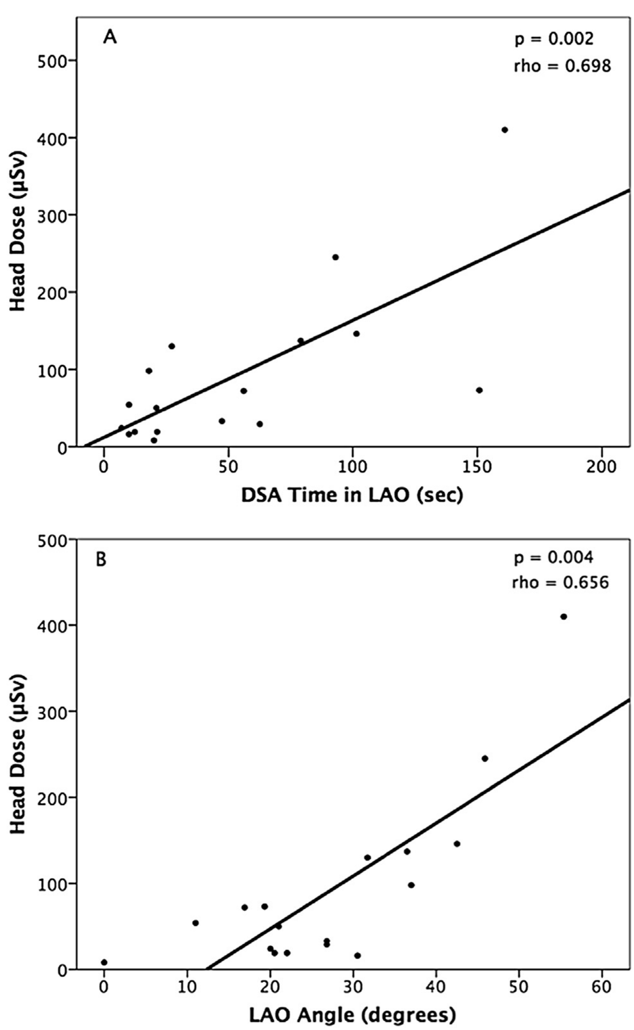

Figure 5. Scatterplots demonstrating relationship between (A) digital subtraction angiography acquisition time in left anterior oblique (LAO) angulation and primary operator head dose, and (B) degree of LAO angulation and primary operator head dose.

Table 3. Operator compliance with safety equipment and behaviours.

<table>
<tr><th rowspan="2">Safety measure</th><th colspan="2">Uptake (%)</th></tr>
<tr><th>PO</th><th>AO</th></tr>
<tr><td>Thyroid collar</td><td>100</td><td>88</td></tr>
<tr><td>Leaded goggles</td><td>100</td><td>94</td></tr>
<tr><td>Stepping away during DSA</td><td>5</td><td>9</td></tr>
<tr><td>Side table lead drape</td><td colspan="2">100</td></tr>
<tr><td>Ceiling-mounted lead shield</td><td colspan="2">41</td></tr>
<tr><td>Anaesthetist lead shield</td><td colspan="2">100</td></tr>
<tr><td>Radiographer lead shield</td><td colspan="2">100</td></tr>
</table>

Note. DSA = digital subtraction angiography; PO = primary operator; AO = assistant operator.

reflect an estimate of the yearly dose depending on the level of operator involvement and complexity of cases performed. This assumes a similar case mix of FEVAR or BEVAR procedures and no emergency cases.

DISCUSSION

The majority of studies to date have reported estimates of occupational radiation exposure to unprotected body parts such as the head by extrapolating from measurements recorded elsewhere on the body.[10] This study reports direct, case-specific measurements of head exposure during complex EVARs, procedures that are likely to be associated with higher radiation exposures compared with standard, infrarenal aortic interventions. To the authors' knowledge, this is the first study to quantify directly radiation exposure to this unprotected region in a real operating environment. It was found that, although effective body radiation exposure to the operating team in these complex cases is low and complies with current recommended limits, there is a significantly higher exposure to the head. This exposure is greatest for the PO, and appears to be inversely related to operator height and related to the degree of C-arm angulation in the LAO position. In the present study, C-arm angulations $>30°$ were associated with much higher levels of head radiation dose. This observation has also been made during percutaneous coronary interventions, where keeping the C-arm in $<20°$ angulation resulted in a greater than threefold reduction in the amount of scatter radiation.[11]

When interpreted in the context of the recommended dose limits for radiological workers, as defined by the ICRP, the measurements obtained in this study are below the threshold at which *deterministic* effects of radiation (e.g., skin erythema, eye cataracts, infertility) occur.[12] However, studies have challenged this "safe dose" notion, suggesting that the damaging effects of radiation may be governed entirely by *stochastic* processes.[13,14] This assumes that the deleterious effects vary between individuals and can occur independently of absorbed dose but with increasing frequency as the dose increases. This is supported by direct epidemiological evidence of a comparable incidence of excess cancers in cohorts exposed to low as opposed to high-dose radiation.[15] This includes occupationally exposed individuals who generally received low doses in daily increments over many years, suggesting that exposure to relatively low doses of radiation may be harmful and associated with long-term health risks.[16]

In the present study the radiation dose absorbed by members of the operating team varied, with the PO receiving significantly higher over-lead and head radiation doses than the AO. This is most likely explained by the proximity of the PO to the primary X-ray beam. Although the PO head dose was low, the health consequences of this are not yet understood. Low-dose exposures in mouse models downregulate the same neural pathways that are downregulated in humans with age and in Alzheimer's disease.[17]

The greatest head radiation exposure to the PO was observed during C-arm angulation in the LAO direction and with increasing LAO angulation, which were the strongest predictors of head dose exposure in linear regression analysis. This may be attributed to the increases in scatter radiation to the operator that occur during LAO manoeuvres, as previously demonstrated in phantom model experiments.[18] Reducing the imaging field of view using collimation is a known manoeuver to decrease scatter radiation exposure to the operator.[18] Although this was difficult to monitor accurately during this study, all operators maximised collimation usage in accordance with ALARA (as low as reasonably achievable) principles. Additionally, there was an inverse correlation between PO height and head radiation dose; the shortest operator in this study had a fivefold increase in measured dose compared with taller counterparts, despite using similar DSA acquisition times in the LAO projection. This is likely owing to the operator's head being closer to the main scatter source and therefore absorbing a greater amount of scatter. Reduced absorption of scatter radiation to the head and neck regions with increasing height has been demonstrated using phantom experiments.[19,20] We found no differences in radiation exposure between FEVAR and BEVAR procedures. This may be attributed to the similar LAO angulations used in both types of procedures and the fact that the operator was positioned on the right of the patient in both instances.

Although there was an improvement in the use of shielding and eye protection in the present study compared with previous observations,[6] the operators stepped away during $<10\%$ of DSA acquisitions. Theoretically, increasing the distance between the operator and radiation source by twofold will yield a 75% reduction in radiation exposure and should be mandatory during manoeuvres such as DSA acquisition in LAO that involve high exposure.[21]

The ceiling-mounted lead shield was used by the PO in only 41% of DSA acquisitions. The three cases with the lowest recorded PO head radiation dose had the highest use of ceiling-mounted shields despite similar DSA acquisition times in LAO when compared with cases with higher PO head dose. This suggests that the use of ceiling-mounted shielding is an important protective factor, although other factors such as operator height may have also influenced our finding. Fetterly et al. used a phantom to show that the use of a ceiling-mounted shield attenuated scatter radiation to the upper body by $> 80\%$.[22] The degree of reduction was highly dependent on the positioning of the shield, with a shield position that is closer to the patient being associated with the greatest reduction in scatter radiation exposure to the operator.

Ceiling-mounted shields are often difficult to position for optimal protection, and leaded goggles serve only to limit eye exposure. Innovations designed to improve protection while reducing the burden of wearing lead and consequent musculoskeletal problems include the ZeroGravity Radiation Protection System (Interventco, Dallas, TX, USA). This solution provides radiation shielding from the top of the head to the calves by using a floating/suspended lead garment and a full facial shield. This type of protection has been shown to reduce radiation exposure to all areas of the body, including the head, when compared with a standard lead apron.[23] Other initiatives that promise to reduce radiation exposure, particularly during complex endovascular procedures, include image fusion technology and robotics used to aid graft positioning and vessel cannulation.[24] Finally, formal education in radiation safety should be mandatory for experienced users and trainees alike, and there may also be a place for an intraoperative radiation safety checklist.

The present study is limited by the relatively small number of cases included, although the analysis of radiation exposure was carried out over a total of 75 hours of endovascular intervention time. In addition, each case involves unique procedure-specific, environmental, and behavioural nuances that may confound the interpretation of individual factors affecting radiation exposure. Examples include variations in ceiling-mounted shield positioning and extent of stepping away during DSA acquisition, which may affect the interpretation of head radiation dose in relation to operator height. Controlling for these variables using a phantom experiment may enable more accurate conclusions to be drawn regarding individual factors but radiation exposures measured would remain a surrogate of actual exposures in clinical practice. Additionally, the relationship between radiation dose and LAO angulation may be confounded by the variation in the amount of time that the C-arm is kept in the LAO position. While the duration of each LAO angulation per DSA acquisition was available, the dosimeters used in this study provided only cumulative radiation dose readings per case. Real-time radiation measurements providing continuous radiation data are required to relate independently the effects of each C-arm manoeuvre on head dose in future studies to overcome this potential bias. Measuring exposure in a larger range of operator heights in future studies will also provide more reliable analysis.

CONCLUSIONS

The head is an unprotected area that receives a significantly higher radiation dose during complex EVAR. The deleterious effects of exposure to this area are not fully understood. Vascular interventionalists should be cognisant of the relationship between operator height and head exposure and the fact that the amount of radiation absorbed by the head increases with angulation of the C-arm. Limiting C-arm angulation and optimal shielding can help operators reduce occupational radiation exposure.

CONFLICT OF INTEREST

None.

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