Impact of Hybrid Rooms with Image Fusion on Radiation Exposure during Endovascular Aortic Repair

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WHAT THIS PAPER ADDS
Experience has shown that the routine use of fusion during endovascular aneurysm repair has significantly reduced the exposure of patients and operators to X-rays and contrast volume injection during complex repairs, without jeopardising the overall procedure workflow.

Objective: To evaluate exposure to radiation during endovascular aneurysm repair (EVAR) performed with intraoperative guidance by preoperative computed tomographic angiogram fusion.

Methods: All consecutive patients who underwent standard bifurcated (BIF) or thoracic (THO), and complex fenestrated (FEN) or branched (BR) EVAR were prospectively enrolled. Indirect dose–area product (DAP), fluoroscopy time (FT), and contrast medium volume were recorded. These data were compared with a previously published prospective EVAR cohort of 301 patients and to other literature. Direct DAP and peak skin dose were measured with radiochromic films. Results are expressed as median (interquartile range).

Results: From December 2012 to July 2013, 102 patients underwent standard (56.8%) or complex (43.2%) EVAR. The indirect DAP (Gy.cm²) was as follows: BIF 12.2 (8.7−19.9); THO 26.0 (11.9−34.9); FEN 43.7 (24.7−57.5); and BR 47.4 (37.2−108.2). The FT (min) was as follows: BIF 10.6 (9.1−14.7); THO 8.9 (6.0−10.5); FEN 30.7 (20.2−40.5); and BR 39.5 (34.8−51.6). The contrast medium volume (mL) was as follows: BIF 59.0 (50.0−75.0); THO 80.0 (50.0−100.0); FEN 105.0 (70.0−136.0); and BR 120.0 (100.0−170.0). When compared with a previous cohort, there was a significant reduction in DAP during BIF, FEN, and BR procedures, and a significant reduction of iodinated contrast volume during FEN and BR procedures. There was also a significant reduction in DAP during BIF procedures when compared with the literature (p < .01). DAP measurement on radiochromic films was strongly correlated with indirect DAP values (r² = .93).

Conclusion: The exposure of patients and operators to radiation is significantly reduced by routine use of image fusion during standard and complex EVAR.

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Keywords: Aorta, Endovascular procedures, Fusion imaging, Hybrid room, Radiation, Radiation protection

INTRODUCTION
The evolution of device technology has allowed physicians to perform more and more complex minimally invasive aortic endovascular repairs. Imaging systems have also evolved to facilitate these challenging procedures. For example, fixed-room flat panel detectors have demonstrated strong imaging superiority over standard fluoroscopic two-dimensional (2D) fluoroscopy imaging systems (mobile C-arms), which are limited by overheating and image degradation, particularly when performing complex endovascular aneurysm repair (EVAR).1 Hybrid rooms, combining an optimal open surgical environment and advanced imaging capabilities are currently replacing mobile C-arms in the operating room.

The latest hybrid rooms have advanced imaging applications, such as contrast-enhanced cone beam computed tomography (CBCT; three-dimensional [3D] images acquired through a C-arm rotation around the patient), and preoperative computed tomography angiography (CTA) image fusion with live fluoroscopy to provide a "3D roadmap". The latter facilitates endovascular navigation and increases the accuracy of endograft implantation.2–5 Despite the current widespread use of these new imaging applications, little has been published on their impact on exposure to ionising radiation.6–8

Published evidence suggests that repeated injections of contrast medium contribute to the development of lifelong nephropathy.7 The effects of radiation are cumulative and put patients at deterministic risk of radiation injuries after exposure.8 Also, clinical staff regularly exposed to radiation during everyday fluoroscopy-directed procedures are...
exposed to an increased incidence of stochastic injuries. Thus, in addition to sticking to the “as low as reasonably achievable” (ALARA) principle to reduce the dose of radiation during EVAR, new imaging applications should also help reduce exposure to radiation and contrast medium injection. The aims of this study were to evaluate the impact of image fusion in a new-generation hybrid room during aortic endografting on patients, the exposure of physicians to radiation, and the volume of contrast medium injected into patients.

METHODS

Demographics

During the study period, all consecutive patients treated electively in a hybrid room with standard or custom-made endografts for aortic aneurysms or dissections were prospectively enrolled. Preoperative high-resolution CTA scans were always performed to enable design of the endografts, and to perform the fusion 3D models. Emergency procedures or procedures conducted without image fusion were excluded. Endovascular repairs of arch aneurysms with branched endografts were also excluded. All procedures were carried out under general or locoregional anesthesia by experienced operators.

Equipment

Procedures were performed under fluoroscopic guidance in a hybrid room (Discovery IGS 730; GE Healthcare, Chalfont St Giles, UK) with a 30 × 30 cm flat panel detector. Low-dose settings were used by default at a frame rate of 7.5 frames/second. Minimisation of the detector to patient distance was performed automatically by the X-ray system throughout the procedure, using patient contouring with capacitive sensor technology. Additionally, the system is equipped with a 56-inch display monitor that reduces the need for magnification. Following the ALARA principle to reduce X-ray radiation, staff constantly minimised fluoroscopy time, narrowed image detector fields to maximise collimation, used protection barriers, and optimised angulations.

Before each procedure, bone and aortic 3D models were reconstructed from the preoperative CTA scan on a workstation (Advantage Workstation; GE Healthcare) (Fig. 1), and sent to the X-ray system. In the setting of a good quality preoperative CT scan, this process was performed in less than 2 minutes. When no good quality arterial phase was available, an extra 2 minutes of 3D model editing were required. It was then fused with live fluoroscopy (Innova Vision/Heart Vision; GE Healthcare). Registration of this 3D preoperative model was performed using bone landmarks visible on two fluoroscopic orthogonal shots (anterior—posterior and lateral) of the spine (Fig. 2). This step also took approximately 2 minutes. During the procedure, this layout was used to centre the region of interest, and to adjust collimation, without the need for fluoroscopy. The position of the renal arteries was confirmed by a 7-cc contrast medium injection at 30 cc/second performed once the endograft was inserted in the aorta (Fig. 2E). If necessary, registration could be refined at any time during the procedure by the operator. Two types of contrast medium were used (Omnipaque 300 mg I/mL or Visipaque 320 mg I/mL in the setting of renal insufficiency; GE Healthcare).

Dose fundamentals

The air kerma (AK; measured in Gy) is the absorbed dose and is computed at the interventional reference point, defined as 15 cm from the system isocentre toward the anode, which is a good estimation of patient skin entrance position. It is well correlated with the peak skin dose (PSD; measured in Gy), which is defined as the highest dose delivered to any portion of the patient’s skin, including backscattered radiation during a procedure, and was used to assess the risk of deterministic effects, such as skin injuries. The dose—area product (DAP; measured in Gy.cm²) is the product of the AK by the exposed area. The DAP cumulated all along the procedure is linked to the stochastic effect (i.e., the increased risk of cancer) and can be converted in a first approximation to the effective dose (ED), expressed in Sievert (Sv), using a conversion factor. However, there is no consensus on this conversion factor;

Figure 1. (A) A bone and (B) an aortic three-dimensional volume rendering model were reconstructed from the preoperative computed tomography angiography on a workstation (Advantage Workstation; GE Healthcare, Chalfont St Giles, UK).
hence, comparative results on ED should be considered with caution.

**Data collection**

For each procedure, contrast medium volume (mL), operative time (minutes), and type of endovascular aortic repair (bifurcated [BIF], thoracic [THO], fenestrated [FEN], or branched [BR] endografting) were recorded. Indirect DAP (measured in Gy.cm²) and fluoroscopy time (minutes) were collected from the X-ray system. Operator radiation exposure (μSv) during the procedure was determined with an individual live dosimeter (RaySafe i2; Unfors RaySafe, Billdal, Sweden) placed over the lead apron of the operator at chest level. The cumulated dose of the operator was

![Image](image.jpg)

**Figure 2.** Registration is performed with two fluoroscopic orthogonal (antero-posterior and lateral) shots. (A) On the lateral view, the vertebral bodies (white star) from the three-dimensional volume rendering (3D VR) bone model reconstructed from the preoperative computed tomography angiography (CTA) is (B) moved to perfectly match the vertebral bodies from the fluoroscopic image (red star). (C) The 3D VR bone model is then replaced by the aortic 3D VR model reconstructed from the preoperative CTA. (D) Stent graft deployment is performed under 3D guidance after the position of the renal arteries was confirmed by contrast medium injection. (E) Catheterisation of the renal arteries during implantation of a fenestrated endograft can also be performed under 3D guidance.
estimated by the personal active and passive dosimeters, placed at the chest level under the lead apron, and analysed at the end of the study. Immediate technical success—defined as successful access to the arterial system using a remote site, successful deployment of the endoluminal graft, absence of either a type I or III endoleak, and patent endoluminal graft without significant twist, kink, or obstruction—was registered.  

**Direct measurements of DAP and PSD: correlation with indirect DAP provided by the system**

In order to validate the DAP values reported by the system, radiochromic films (GAFCHROMIC XR RV3; Internal Specialty Products, Wayne, NJ, USA) were used, positioned underneath the patient during 19 procedures, as a direct assessment of patient radiation exposure. A radiochromic film is a layer of radiosensitive gel sandwiched between protective sheets. When the film is irradiated the gel undergoes polymerisation and produces a visible darkening. The amount of darkening is proportional to the dose delivered to the gel and is relatively unaffected by visible light. Radiochromic films are accurate for clinical measurement of skin dose.  

The correlation between film optical density and dose was established after confection of a calibration set made of radiochromic samples exposed to successive calibrated doses from 100—2000 mGy in the hybrid room. These were placed under 20 cm of polymethyl methacrylate, around a Radcal 2026 dosimeter with fixed imaging techniques (fluoroscopy mode, 80 kV, 30 frames/second, spectral filter 0.3-mm-thick copper, 100 mA, pulse width 10 ms) simulating the clinical situation, and then used to define the conversion relationship between grey levels on the radiochromic films and real dose values. The red component of the exposed films to X-rays was analysed with Matlab software (MathWorks, Natick, MA, USA) as follows. Exposed films were scanned and then subtracted from non-exposed films to extract grey levels. Then, the intensity of each pixel was correlated to a dose value with the calibration set. The product of surface by pixel intensity provided the DAP and the maximum grey level, provided the PSD. Measured DAP was compared with the DAP provided by the system (indirect DAP). The median value of the measured peak skin dose to DAP ratio, extracted from the films, was applied to the collected DAP for each patient to estimate the peak skin dose. The ED was estimated from DAP using a 0.29 mSv/(Gy·cm²) factor for abdominal procedures on adult patients, as measured by Suzuki et al. Measured values were compared with those found in the literature. Because the films received radiation almost exclusively from frontal angulations, the system-reported DAP was corrected to exclude lateral view-induced DAP.  

**Control group**

The dose measurements from this study were compared with the literature and to a previous prospective cohort of patients treated with a mobile C-arm (GE OEC Medical Systems; Salt Lake City, UT, USA), following the ALARA principles. In the previous study, completed between 2009 and 2011, 301 patients were included (199 infrarenal, 54 fenestrated, 28 thoracic, and 20 branched endografts). Default settings of the mobile C-arm at the beginning of the procedure were low-dose pulsed fluorographic mode (8 pulses/second), and digital subtraction angiography (DSA) runs were performed at a frame rate of 8 frames/second. The image intensifier field size was 31 cm (12 inches). Results were reported as DAP (mGy·m², conversion factor to Gy·cm² = ×10), after calibration of the system were checked by the radiochromic film method on 14 patients. The set up in the hybrid room and in the operating room with the mobile C-arm are presented Fig. 3.  

**Statistical analysis**

Continuous variables are expressed as median (interquartile range) or mean (SD). Categorical variables are presented as percentage and 95% confidence interval (CI). Comparisons between categorical variables were performed with a chi-square test, and between continuous variables with the Student t test, or with the Mann—Whitney test. DAP analysis was also performed after body mass index (BMI) stratification (<25, 25—30, >30). Comparisons with the literature were performed assuming the given data were references, using the Wilcoxon test. A p-value <.05 was considered as significant.  

**RESULTS**

From December 2012 to July 2013, 102 patients were prospectively enrolled (97.1% men, aged 69.8 years [62.9—76.4]). During the study period, only three procedures, performed at the beginning of the experience, were not conducted under fusion guidance because not all operators were familiar with the new workflow. Median BMI was 26.7 kg/m² (23.6—30.7 kg/m²). The procedures are described Table 1. The median intervention time was 120 minutes (85—180). On the final angiogram, the immediate technical success rate was 100% (one distal type I endoleak was seen on one postoperative CTA which was performed in every patient). Median intervention time, contrast medium volume, fluoroscopy time, and DAP per procedure are also given in Table 1. DAP comparisons between groups, per procedure type, after BMI stratification (<25, 25—30, >30) matched the results of the complete cohort (see Supplementary Material). Median DAP was significantly lower for standard (BIF and THO) compared with complex (FEN and BR) procedures (p < .01).  

Comparison with a previously published prospective cohort is reported Table 2. The median DAP was significantly reduced during BIF, FEN, and BR performed in the hybrid room (p < .01), as was the contrast medium volume during FEN and BR (p = .03 and p < .01 respectively). The fluoroscopy time could not be compared as a global “on-pedal” time was recorded with the hybrid room, whereas the C-arm summed the X-ray pulses lengths.  

When comparing the results with the available literature on radiation exposure during bifurcated EVAR performed.
without fusion (Table 3), a significant reduction in DAP was seen ($p < 0.01$).

During the study period, total radiation exposure over the lead apron (individual live dosimeter; RaySafe, Unfors RaySafe) of the operator was 1621.6 μSv. Median radiation exposures of the operators per procedure are given in Table 4. Total radiation exposure during the study period recorded under the lead apron was 7 μSv. The personal dosimeters did not record radiation exposures <1 μSv and they were rebooted between each procedure. Therefore, because radiation exposure under the lead apron was <1 μSv in most cases, total radiation exposure calculation during the study period with this method was underestimated.

Direct measurements of DAP and PSD: correlation with indirect DAP provided by the system

Nineteen radiochromic films were analysed (13 BIF, three THO, and three FEN). As the films were placed underneath the patient, only frontal angulations were analysed. The calibration set was relevant because the correlation between darkening and exposure increments of pixels was high ($r^2 = 0.99$). The correlation between DAP delivered by the fixed system and DAP extracted from the films was highly significant ($r^2 = 0.93$) (Fig. 4).

**Estimation of PSD and ED**

The median PSD/DAP ratio was $5.14 \times 10^{-3}$ cm$^{-2}$ ($4.78 \times 10^{-3}$–$8.12 \times 10^{-3}$). This ratio was calculated with the 13 films from bifurcated procedures (films from thoracic and fenestrated cases were excluded), as only frontal angulations could be accurately analysed. Thus, PSD was only estimated for the 44 bifurcated procedures. Median PSD was $63 \times 10^{-3}$ Gy (range $44 \times 10^{-3}$–$103 \times 10^{-3}$). No procedure crossed the maximum peak skin dose of 2 Gy, considered as the threshold after which deterministic events may occur. Estimated EDs for the abdomen per procedure type are reported Table 4. As the conversion

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**Table 1.** Procedures performed in the hybrid room during the study period.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Number of procedures (%)</th>
<th>BMI</th>
<th>DAP (Gy.cm$^{-2}$)</th>
<th>Contrast medium volume (mL)</th>
<th>Fluoroscopy time (min)</th>
<th>Intervention time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIF</td>
<td>44 (43.1)</td>
<td>27.7 (24.2–29.9)</td>
<td>12.2 (8.7–19.9)</td>
<td>59 (50–75)</td>
<td>10.6 (9.1–14.7)</td>
<td>92.5 (75–120)</td>
</tr>
<tr>
<td>BR</td>
<td>20 (19.6)</td>
<td>24.5 (21.7–29.8)</td>
<td>47.4 (37.2–108.2)</td>
<td>120 (100–170)</td>
<td>39.5 (34.8–51.6)</td>
<td>205 (169–240)</td>
</tr>
<tr>
<td>FEN</td>
<td>18 (17.6)</td>
<td>28.4 (25.9–33.3)</td>
<td>43.7 (24.7–57.5)</td>
<td>105 (70–136)</td>
<td>30.7 (20.2–40.5)</td>
<td>150 (150–160)</td>
</tr>
<tr>
<td>THO</td>
<td>14 (13.7)</td>
<td>24.7 (22.0–28.7)</td>
<td>26.0 (11.9–34.9)</td>
<td>80 (50–100)</td>
<td>8.9 (6.0–10.5)</td>
<td>80 (60–100)</td>
</tr>
<tr>
<td>Bifurcated + Iliac branch endografts</td>
<td>6 (5.9)</td>
<td>29.7 (26.2–31.7)</td>
<td>41.2 (38.2–51.3)</td>
<td>85 (60–120)</td>
<td>27.3 (22.4–30.1)</td>
<td>140 (120–180)</td>
</tr>
</tbody>
</table>

**Note.** Results are expressed as median (interquartile range) unless otherwise indicated. BMI = body mass index; DAP = dose–area product; BIF = bifurcated endografts; BR = branched or four-fenestrated endografts; FEN = two- or three-fenestrated endografts; THO = thoracic endografts.
Table 2. Comparison of cases of endovascular aneurysm repair performed in the hybrid room (HR) versus a previous prospective cohort treated with a mobile C-arm.\(^{10}\)

<table>
<thead>
<tr>
<th></th>
<th>C-arm (n = 301)</th>
<th>HR (n = 96)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAP (Gy.cm(^2))</td>
<td>BIF 30.0 (20.0—43.5)</td>
<td>12.2 (8.7—19.9)</td>
<td>&lt;.01</td>
</tr>
<tr>
<td></td>
<td>FEN 72.9 (52—109.2)</td>
<td>43.7 (24.7—57.5)</td>
<td>&lt;.01</td>
</tr>
<tr>
<td></td>
<td>BR 159.0 (101.8—222.4)</td>
<td>47.4 (37.2—108.2)</td>
<td>&lt;.01</td>
</tr>
<tr>
<td></td>
<td>THO 20.0 (11.4—30.0)</td>
<td>24.7 (22.0—28.7)</td>
<td>.63</td>
</tr>
<tr>
<td>Contrast medium volume (mL)</td>
<td>BIF 80 (65—106)</td>
<td>59 (50—75)</td>
<td>.34</td>
</tr>
<tr>
<td></td>
<td>FEN 138 (100—160)</td>
<td>105 (70—136)</td>
<td>.03</td>
</tr>
<tr>
<td></td>
<td>BR 226 (150—278)</td>
<td>120 (100—170)</td>
<td>&lt;.01</td>
</tr>
<tr>
<td></td>
<td>THO 100 (78—140)</td>
<td>80 (50—100)</td>
<td>.07</td>
</tr>
<tr>
<td>Intervention time (min)</td>
<td>BIF 93 (75—120)</td>
<td>92.5 (75—120)</td>
<td>.97</td>
</tr>
<tr>
<td></td>
<td>FEN 150 (105—180)</td>
<td>150 (150—160)</td>
<td>.39</td>
</tr>
<tr>
<td></td>
<td>BR 210 (150—260)</td>
<td>205 (169—240)</td>
<td>.87</td>
</tr>
<tr>
<td></td>
<td>THO 117 (60—138)</td>
<td>80 (60—105)</td>
<td>.22</td>
</tr>
</tbody>
</table>

Note. Results are expressed as median (interquartile range). Significant values are given in bold. DAP = dose—area product; BIF = bifurcated endografts; FEN = two- or three-fenestrated endografts, BR = branched or four-fenestrated endografts, THO = thoracic endografts.

DISCUSSION

Experience using intraoperative fusion guidance to perform standard and complex EVAR in a new generation hybrid room is reported. It has been demonstrated that this advanced imaging application, routinely used by trained operators applying the ALARA principle, significantly reduces the exposure to radiation for both patients and physicians. A significant reduction of iodinated contrast injection during complex fenestrated and branched EVAR has also been demonstrated.

Few studies in the literature report results of EVAR supported by image fusion. Most relate a reduction in contrast medium volume,\(^{5,6}\) but an equivalent or higher radiation exposure,\(^{16,17}\) as could be expected with high-powered imaging equipment. In 2011, Kobeiter et al.\(^{6}\) reported the first case of zero-contrast thoracic endovascular aortic repair using image fusion; however, no gain was observed on DAP (55.3 Gy.cm\(^2\)). Recently, the group reported a comparison of 14 complex EVARs, performed with image fusion, with 23 similar procedures with 2D or 3D angiography alone.\(^{18}\) A significant reduction in contrast medium volume injected was reported (from 235 ± 145 mL to 65 ± 28 mL), but no differences in DAP values nor in procedure time were seen. Dijkstra et al.\(^{5}\) reported the first cohort of 40 patients treated with fenestrated or branched endografts under intraoperative guidance. A CBCT was performed to overlay the preoperative CTA by 3D/3D

<table>
<thead>
<tr>
<th>Author (year)</th>
<th>n</th>
<th>Median DAP (Gy.cm(^2))</th>
<th>p</th>
<th>Median ED (mSv)</th>
<th>Median PSD (Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current study (2013)</td>
<td>44</td>
<td>12.2 (8.7—19.9)</td>
<td>&lt;.01</td>
<td>3.5 (2.5—5.6)</td>
<td>63 × 10(^{-3}) Gy (44 × 10(^{-3})—103 × 10(^{-3}))</td>
</tr>
<tr>
<td>Maurel et al. (2012)(^{10})</td>
<td>188</td>
<td>40.5</td>
<td>.01</td>
<td>8.7 (2.5—28.1)</td>
<td></td>
</tr>
<tr>
<td>Geijer et al. (2005)(^{13})</td>
<td>24</td>
<td>60.1 (16.6—195.0)</td>
<td>&lt;.01</td>
<td>7.8 (0.1—3.74)</td>
<td></td>
</tr>
<tr>
<td>Weiss et al. (2008)(^{14})</td>
<td>12</td>
<td>151.7 (52.1—245.4)</td>
<td>&lt;.01</td>
<td>7.8 (0.1—3.74)</td>
<td></td>
</tr>
<tr>
<td>Weerakkody et al. (2008)(^{25})</td>
<td>96</td>
<td>150.0 (90.0—659.0)</td>
<td>&lt;.01</td>
<td>27 (16—117)</td>
<td></td>
</tr>
<tr>
<td>Kalef Ezra et al. (2009)(^{26})</td>
<td>62</td>
<td>37.4 (9—139)</td>
<td>&lt;.01</td>
<td>6.2 (1.3—20.0)</td>
<td></td>
</tr>
<tr>
<td>Peach et al. (2012)(^{10})</td>
<td>57</td>
<td>69</td>
<td>&lt;.01</td>
<td>51.2 (1.3—20.0)</td>
<td></td>
</tr>
<tr>
<td>With OCI</td>
<td>65</td>
<td>49</td>
<td>&lt;.01</td>
<td>6.2 (1.3—20.0)</td>
<td></td>
</tr>
<tr>
<td>Fossaceca et al. (2012)(^{17})</td>
<td>C-arm</td>
<td>79</td>
<td>27.0 (19.0—44.0)</td>
<td>&lt;.01</td>
<td>6.8 (3.5—7.8)</td>
</tr>
<tr>
<td>Mobile angiography</td>
<td>26</td>
<td>333.0 (250.0—423.0)</td>
<td>&lt;.01</td>
<td>60.0 (47.0—80.0)</td>
<td></td>
</tr>
<tr>
<td>Fixed angiography</td>
<td>48</td>
<td>410.0 (241.0—619.0)</td>
<td>&lt;.01</td>
<td>110 (71.0—185.0)</td>
<td></td>
</tr>
<tr>
<td>Jones et al. (2010)(^{17})</td>
<td>320</td>
<td>46.9</td>
<td>&lt;.01</td>
<td>11.7 (0.5—51)</td>
<td></td>
</tr>
<tr>
<td>Walsh et al. (2012)(^{18})</td>
<td>111</td>
<td>85.8</td>
<td>&lt;.01</td>
<td>12.4</td>
<td></td>
</tr>
<tr>
<td>Howells et al. (2012)(^{14})</td>
<td>630</td>
<td>173.0 (109.4—3.343.4)</td>
<td>&lt;.01</td>
<td>53.0 (33.0—1,000.0)</td>
<td></td>
</tr>
</tbody>
</table>

Note. ED = effective dose; PSD = peak skin dose; OCI = operator controlled imaging.
registration on bony landmarks. When compared with previous experience, the group also demonstrated a significant reduction in the volume of contrast medium injected, but only a trend toward lower operative and fluoroscopy time, and no difference in radiation exposure.

Kalef-Ezra et al.\textsuperscript{16} reported the exposure to radiation of patients and medical staff during 97 cases of EVAR performed either with a mobile C-arm or a fixed system. DAP and PSD were higher in the high-power fluoroscopic unit for both patients and medical staff. Fossaceca et al.\textsuperscript{17} also compared radiation exposure after EVAR with various X-ray systems. The median EDs reported were 6.8 mSv (3.5–7.8 mSv; mobile C-arm); 60.0 mSv (47.0–80.0 mSv; mobile angiographic equipment); and 110.0 mSv (71–185 mSv; fixed angiographic equipment). The high exposure with the fixed system is of concern as 100.0 mSv is the threshold beyond which a risk of cancer induction has been clearly identified.\textsuperscript{15} Therefore, it is mandatory to develop imaging tools, such as fusion, to help decrease radiation exposure while sustaining image quality in hybrid rooms, particularly when dealing with complex aortic procedures. For example, the median ED in this study decreased to 3.5 mSv.

The exposure of operators in complex cases was specifically studied by Panuccio et al.\textsuperscript{15} Active dosimeters were placed above the lead apron during endovascular thoracoabdominal aneurysm repair performed in a fixed room. The mean exposure per procedure was 560.0 μSv (220.0–270.9 μSv). In comparison, median operator exposure during similar procedures in the present experience was 23.1 μSv (6.3–248.0 μSv).

In the current study, a reduction in the exposure to radiation for both patients and medical staff during standard and complex EVAR when compared with the other studies in the literature, detailed above, is reported. There are three key explanations for these results.

1. The fusion technique used to overlay 3D images on the live fluoroscopy. In this protocol, the preoperative CTA was used to generate the 3D model, and the fusion registration was performed only with two fluoroscopic orthogonal shots to align the bone sub-volume of the CTA on bony landmarks. This protocol is fast, easy, and almost radiation free. The other described techniques to overlay the preoperative CTA require a preoperative CBCT, thus exposing patients and operators to additional radiation.

2. The strict application of the ALARA principle. A previous evaluation of radiation exposure during EVAR performed on a mobile C-arm\textsuperscript{19} has already demonstrated that exposure to radiation can be considerably minimised by applying the ALARA principle.\textsuperscript{8,9} In addition, the table and the C-arm angulation can now be positioned without X-ray, because the 3D mask is connected to the table and gantry movements. Most DSA runs have also been replaced by recorded fluoroscopy runs, including 2D roadmap runs. As a 56-inch monitor with enhanced image quality is used, magnification with a smaller field of view is almost never required. Collimation is used systematically to focus radiation only on the area of interest, and all system settings are set to low auto-exposure mode by default. Working on a latest-generation system also provides the opportunity to benefit from the latest technological advances to reduce radiation without degradation of the image. A capacitive sensor automatically minimises the distance from the detector to the patient, allowing a reduction of the scattered radiation.

3. The imaging system is fully controlled by the operator from table side, which has been proven to reduce exposure to radiation when compared with a radiographer-controlled imaging system.\textsuperscript{20}

The addition to all the above, settings and workflow directly affect the level of radiation delivered, which explains the large variability in data found in the literature.\textsuperscript{21}

### Table 4. Patient-estimated effective dose (ED) and first operator exposure over the lead apron per procedure type (recorded with the RaySafe i2 system; Unfors RaySafe, Billdal, Sweden).

<table>
<thead>
<tr>
<th>Procedure type</th>
<th>Median estimated abdominal ED to patient (mSv)</th>
<th>Median operator exposure (μSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branched + four-fenestrated endografts</td>
<td>13.7 (10.8–31.4)</td>
<td>23.1 (6.3–248.0)</td>
</tr>
<tr>
<td>Two- or three-fenestrated endografts</td>
<td>12.7 (7.2–16.7)</td>
<td>9.1 (1.8–67.7)</td>
</tr>
<tr>
<td>Bifurcated + iliac branch endografts</td>
<td>12.0 (8.0–14.9)</td>
<td>11.6 (3.6–94.4)</td>
</tr>
<tr>
<td>Bifurcated endografts</td>
<td>3.5 (2.5–5.6)</td>
<td>3.7 (0.2–215.7)</td>
</tr>
<tr>
<td>Thoracic endografts</td>
<td>NA</td>
<td>1.9 (0.0–19.7)</td>
</tr>
</tbody>
</table>

Note. NA = not applicable.

**Figure 4.** Correlation between dose–area product (DAP) measured on radiochromic films and DAP given by the system.
At Hôpital Cardiologique, CHRU de Lille, Lille, France, the operator always carries a real-time displayed measuring system for X-rays (RaySafe i2; Unfors RaySafe). It is a personal dosimeter that sends in real-time the information to a base station, and live radiation dose exposure is observed on the monitor of the system. This system makes the operator more conscious of radiation exposure, and should motivate the operator to increase the use of radiation protection shields, find better working positions, limit high-angled gantry positions, use collimation, and avoid unnecessarily prolonged pedal pressure.  

A significant reduction of iodinated contrast injection during complex aortic procedures when compared with previous experience without fusion has also been reported. Tacher et al. 18 have also described, in a small series of patients undergoing endovascular thoracoabdominal aortic aneurysm repair with image fusion, a significant decrease in contrast injection. Those results are consistent with the previous report from Dijkstra et al. 5 In accordance with Dijkstra et al., 5 we did not observe a significant reduction in total operative time when using fusion.

**Study limitations**

This practice may not reflect common EVAR practice because most procedures, in the current study, as in previous experience with a mobile C-arm, have been performed by operators focusing on minimising radiation exposure, in a high-volume centre for aortic repairs. The role of operators’ experience was not evaluated, although procedures were performed by vascular surgeons in training, as well as by experienced physicians.

Advanced imaging applications such as fusion are not currently available on mobile C-arms. Several new technical features that also affect dose are only available in modern hybrid rooms. Therefore, to assess exclusively the radiation reduction due to fusion imaging, a prospective study with patients randomised to EVAR treatment in a hybrid room with or without fusion imaging support would be needed.

PSD and ED were estimated by radiochromic films with validated methods only on bifurcated EVAR procedures. 11,14 Lateral projections during EVAR cannot be recorded by the radiochromic films; therefore, the total radiation during thoracic and fenestrated cases would have been underestimated for PSD measures. ED was estimated from DAP using the global coefficient for the abdomen, suggested by Suzuki et al. 11 However, it is not validated for thoracic procedures.

In conclusion, valuable information is provided regarding patient and operator radiation exposure during standard and complex aortic aneurysm repair, performed in a hybrid room with access to advanced imaging applications. It is the largest patient cohort in the literature to date to evaluate this new technology. Compared with the literature, a significant reduction in radiation exposure for both patients and operators has been demonstrated. To reduce radiation exposure, routine use of fusion, applying the ALARA principle and using real-time displayed X-ray exposure, are recommended.

**ACKNOWLEDGMENT**

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**CONFLICT OF INTEREST**

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None.

**APPENDIX A. SUPPLEMENTARY DATA**

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.ejvs.2014.05.026.

**REFERENCES**