Asymmetric collimation can significantly reduce patient radiation dose during pulmonary vein isolation†

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Aims
Current fluoroscopic and 3D image-guided treatment of atrial fibrillation (AF) by radiofrequency ablation is characterized by a substantial amount of X-ray radiation. We investigated the potential of an asymmetric collimation technique to reduce dose.

Methods and results
For 30 patients, referred for AF ablation, we determined the received fluoroscopy dose for various collimation scenarios: a single collimation window encompassing all veins as used in most labs (Sc 1), an optimal adjusted symmetric collimation window encompassing each two ipsilateral veins (Sc 2) or each individual vein (Sc 3) and an optimal asymmetric collimation window encompassing each two ipsilateral veins (Sc 4) or each individual vein (Sc 5). Twenty patients were studied retrospectively and 10 were studied prospectively. Total fluoroscopy effective dose for all collimation strategies amounted to 45 ± 31 mSv for a single collimation field (Sc 1), 36 ± 25 mSv (Sc 2), and 24 ± 14 mSv (Sc 3) for a symmetrically adjusted collimation window and 15 ± 10 (Sc 4) and 5 ± 3 mSv (Sc 5) for an asymmetrically adjusted collimation approach. Validation of symmetric (Sc 2) and asymmetric (Sc 4) collimation in 10 patients confirmed the retrospective analysis.

Conclusions
Implementation and effective application of an optimal asymmetric collimation approach would yield an average three- to nine-fold reduction of fluoroscopy dose during AF ablation procedures. This reduction exceeds what has been previously reported by implementing an electromagnetic catheter tracking approach. Furthermore, it can be easily integrated in the clinical workflow with limited additional one-time cost. Manufacturers of imaging systems should consider its implementation a priority, and physicians should adopt it in their workflow.

Keywords
Radiation risk • Catheter ablation • Fluoroscopy • Atrial fibrillation

Introduction
The conventional treatment of atrial fibrillation (AF) by radiofrequency ablation (RFA) uses fluoroscopic imaging to visualize both a circular catheter, inserted in each of the pulmonary veins (PVs), and an ablation catheter that is guided around the ostium for ablation. While fluoroscopic imaging provides a very high level of accuracy, it is associated with a considerable amount of X-ray radiation, potentially inflicting harm to the patient.

Electro-magnetic (EM) catheter tracking systems, like LocalLisa™ (Medtronic), Carto™ (BioSense-Webster), and NavX/EnSite™ (St Jude Medical), have been introduced to reduce radiation dose for electrophysiology procedures, particularly for AF ablation. Several studies have shown that the use of these systems reduces radiation time for ablation of atrio-ventricular nodal reentry tachycardia (AVNRT), atrial flutter, and AF with a potential dose reduction ranging from 46 to 66%. However, successful AF ablation is largely reliant upon accurate definition of the
anatomy of the left atrium (LA) and, thus, integration of pre-procedural 3D computed tomography (CT) reconstructions is frequently employed in conjunction with EM tracking systems. This increases patient radiation exposure by 1.5-fold when compared with traditional fluoroscopy-guided procedures. The increase can be attributed not only to the CT image acquisition but also to the registration process that is needed to correctly align the CT image to EM coordinate system. In addition, the use of EM tracking systems may require the use of special purpose catheters which can increase the procedural cost substantially.

Because of its high registration accuracy, reliance on a single-imaging system, and cost-effectiveness, another approach has been developed that relies solely on integration of 3D image data with fluoroscopy (3D–2D overlay). The effective use of such an approach has been demonstrated for AVNRT and AF treatment. However, this approach results in an even greater radiation dose when compared with conventional fluoroscopy-based AF ablation.

Thus, all current systems employed for AF RFA involve substantial radiation doses. Nevertheless, operators should be aware of radiation risks and should make all efforts to reduce radiation dose. Relatively simple strategies such as verbal reinforcement of radiation risks and should make all efforts to reduce radiation dose. Relatively simple strategies such as verbal reinforcement of fluoroscopy times, effective collimation, minimizing the source–intensifier distance, and effective lead shield use have been applied to effectively reduce radiation dose during routine clinical work.

Current fluoroscopy systems only allow symmetric collimation. This implies that the object of interest should always be central to the fluoroscopic image and therefore requires movement of the table position in addition to adjusting collimation. Table movement adds considerable complexity to the procedure in that 2D–3D overlay adjustments are required on each occasion which entails the risk of not using it. In addition, table movement may increase the risk of registration mismatches in the 2D–3D overlay. Finally, when performing the intervention following the conventional workflow, angiographic imaging should be repeated for each of the PVs. If the considerable complexity of table movement is not undertaken, then it is rarely possible to restrict the imaging window so as to encompass a single PV without irradiating a significant and unnecessary, wider region. Asymmetric collimation, on the other hand, can redirect X-rays to visualize a single PV and minimal adjacent structures. In a similar manner, asymmetric collimation is commonly used in oncologic radiation therapy to reduce harmful radiation for the patient and/or provide more flexibility in the ability to shield sensitive organs.

In this study, we examined the potential impact of introducing an asymmetric collimation technique in the electrophysiology lab for use in fluoroscopy-guided treatment of AF. We compared the effective dose for both optimal symmetric and asymmetric collimation approaches to assess the potential impact of a simple collimation measure on total patient radiation exposure.

**Methods**

**Patients and procedures**

This study consists of a retrospective simulation study and a prospective validation study which were performed on a series of 20 consecutive patients (17 males and 3 females, age 32–65) and 10 patients (8 males and 2 females, age 36–69), respectively. All patients underwent point-by-point radiofrequency AF ablation, guided by 3D–2D overlay guidance using custom locally developed software, Leuven Augmented Reality Catheter Ablation-software (LARCA).

Clinical routine included the recording of patient parameters relevant for radiation dose calculations like age, sex, height, weight, and body mass index. In addition, procedural parameters included scope angle for the right and left anterior oblique (RAO and LAO) views, and procedural dose area product (DAP) for each view individually. The imaging tubes in RAO and LAO were individually adjusted based on the orientation of the His bundle and mitral plane annulus, with the LA centrally in the image.

During the ablation the patient was kept under general anaesthesia with propofol and was mechanically ventilated. A femoral approach was used to introduce four catheters of which two were positioned in the LA (SL-0 sheaths, St Jude Medical, Daig Division Inc., Minnetonka, MN). Mapping of PV potentials was performed with a deflectable decapolar catheter with a distal ring configuration (Lasso, Cordis-Webster, Diamond Bar, CA). To accurately plan the target ablation lines, the LA was imaged by rotational angiography (syngo DynaCT, Siemens AG, Erlangen, Germany) using direct injection of diluted iodine contrast agent (Iomeron 400, Bracco, Milan, Italy) as described previously. During imaging cardiac standstill was obtained by either adenosine administration or rapid ventricular pacing. Semi-automated segmentation was performed to obtain a 3D surface model of the LA by custom ‘in-house’ software (EPSegmenter).

Target ablation points were marked on the 3D surface model and shown together with a semi-transparent 3D model of LA and PVs overlaid on the live fluoroscopy images as depicted in Figure 1A. During ablation, the operator guided the ablation catheter to the target points by using the biplane overlay images. Ablation was performed with a standard EPT catheter using temperature feedback with a target temperature of 50 °C and a maximum power output of 30 W or with an irrigated tip catheter at 20–30 W and 17 cc/min perfusion rate. The endpoint for PV isolation was the creation of bidirectional conduction block between the atrium and PV. This endpoint was reached by ablation of the circumference of each vein individually or of each ipsilateral vein pair. For each target line the collimation window was adjusted asymmetrically around the centre of the LA, minimizing its surface but keeping all ablation targets around the individual PVs visible.

**Asymmetric collimation approach**

In a retrospective study, we compared three different collimation approaches (single symmetric, adjusted symmetric, and adjusted asymmetric) in combination with two common treatment scenarios (encircling of ipsilateral veins and per vein ablation). This results in the following five scenarios:

1. a single collimation window for the entire procedure (Sc 1).
2. a symmetric collimation window adjusted for two ipsilateral veins (Sc 2).
3. a symmetric collimation window adjusted for each individual vein (Sc 3).
4. an asymmetric collimation window adjusted for two ipsilateral veins (Sc 4), and
5. an asymmetric collimation window adjusted for each individual vein (Sc 5).

An example of a single procedural collimation window (Sc 1) is given in Figure 1A. Asymmetric collimation was simulated assuming that each of the four collimation borders could be individually set while symmetric...
Figure 1 3D–2D fluoroscopy overlay views, treatment, and collimation scenarios. (A) Biplane overlay of a 3D left atrium model with target ablation points and fluoroscopic images as used during real-time ablation and offline in this study, to determine optimal symmetric/asymmetric collimation windows. The overlay shows the location of the right superior right inferior, left superior, and left inferior pulmonary vein. The figure shows a single collimation window in right and left anterior oblique for use throughout an entire procedure, as is still commonly used in many labs today ('Sc 1' in this manuscript). (B) Illustration of the different collimation and treatment scenarios used in this study depicted over an uncollimated fluoroscopic image with 3D surface and target ablation lines in overlay. Both the right and left anterior oblique views are shown with collimated regions visualized by grey semi-transparent rectangles. The remaining, visible part, entirely encompassing each vein or vein pair, determines the field size and is used as input to the Monte-Carlo simulations. When comparing symmetric to asymmetric collimation, a large discrepancy becomes apparent between the useful radiated tissue and the currently used symmetric collimation.
Dose calculation

Effective doses originating from fluoroscopic imaging were calculated by a Monte-Carlo technique for every patient in all collimation scenarios. Monte-Carlo simulation was performed using the PCXMC software suite (Radiation and Nuclear Safety Agency, Helsinki, Finland). This software package enables calculation of the effective dose based on the amount of exposure to X-ray radiation, imaging parameters like LAO and RAO angles, focus to skin distance and field size, and patient characteristics. The patient characteristics determine the size and shape of the modified hermaphrodite phantom, originally proposed by Cristy and Eckerman, and which is used in the organ dose simulations. Filtering was set with an aluminium filter of 2.5 mm thickness and a copper filter of 2.8 mm which are average values determined on a number of procedures. X-ray tube anode angles for the LAO and RAO plane were set, respectively, at 12.5 and 8.5°. The received radiation dose of each organ was converted to an effective dose by using the ICRP 103 tissue weighting factors.

In a retrospective study, DAP for the RAO and LAO views during procedural fluoroscopy was computed by subtraction of the DAP values of acquisition images, which include DynaCT rotational angiography images, from the total procedural DAP value. Acquisition image DAP values were retrieved from the DICOM image header. We assumed that each PV required approximately the same fluoroscopy time for ablation. The radiation concentration at the skin entrance point for a specific PV was calculated by

$$DAP_i = \frac{A_i \times DAP_i}{\sum_{i=1,\ldots,n} A_i}$$

in which DAP, and DAP_, are the fluoroscopy DAP for, respectively, a specific PV and all PVS; and $A_i$ is the field size of the $i$th PV at skin entrance of the radiation beam. The radiation concentration can then be computed by dividing DAP by $A$, $A_i$ was derived from the source-to-skin distance, the source-to-image distance, and the field collimation width and height. The first two could be retrieved from the DICOM images while the latter two could be determined from an overlay image as depicted in Figure 1A. The overlay image visualizes the 3D model, generated from rotational angiography, the planned encirclement lines, and the real-time fluoroscopic images. The location of the target lines could easily be determined by observing the location of coloured spheres. Simulation of all collimation scenarios was conducted under the assumption of equal radiation concentration at the skin entrance and by modification of the field size.

In the prospective study, the effective dose per frame was simulated based on the quotient of the DAP value that was recorded in a stored DICOM fluoroscopy sequence and the number of recorded frames of each sequence. Other imaging parameters, including collimation window size and focal distance, were also retrieved from the stored DICOM header.

Statistical analysis

All summary values are reported by their mean and standard deviation. Data comparison is performed by a paired t-test.

Results

Patient and procedural characteristics are summarized in Table 1. All PVS in all patients could be isolated.

Retrospective study

Conventional treatment using a single collimation field for the entire procedure (Sc 1) would have resulted in an effective dose of $45 \pm 31 \text{ mSv} (DAP: 223 \pm 149 \text{ Gy cm}^2)$. When treating both ipsilateral veins using a single ablation target the radiation dose would be $36 \pm 25 \text{ mSv} (DAP: 173 \pm 115 \text{ Gy cm}^2)$ for symmetric collimation (Sc 2) or $15 \pm 10 \text{ mSv} (DAP: 73 \pm 49 \text{ Gy cm}^2)$ for asymmetric collimation (Sc 4) as shown in Figure 1B. The procedural effective radiation dose received during fluoroscopy with symmetric collimation and a per vein approach (Sc 3), as it was clinically used in all 20 patients, was $24 \pm 14 \text{ mSv} (DAP: 120 \pm 71 \text{ Gy cm}^2)$. Asymmetric collimation in a per vein approach (Sc 5) would result in an effective dose radiation of $5 \pm 3 \text{ mSv} (DAP: 23 \pm 15 \text{ Gy cm}^2)$ (see Figure 2) i.e. a reduction by $80 \pm 5\% (P < 0.001)$ compared to Sc 3. Comparison of all adjusted collimation window approaches with the conventional single collimation window approach (Sc 1) leads to effective dose reductions of $22 \pm 9\% (Sc 2; P < 0.001), 43 \pm 9\% (Sc 3; P < 0.001), 66 \pm 6\% (Sc 4; P < 0.001), and 89 \pm 2\% (Sc 5; P < 0.001).

The proportional reduction in dose is similar for the RAO and LAO view when applying asymmetric collimation. This holds both for an ipsilateral vein approach ($-58\% RAO$ vs. $-55\%$...
LAO, \( P = 0.22 \)) and a per vein approach (80% RAO vs. 79% LAO, \( P = 0.88 \)). However, as illustrated in Figure 3, for all five col-
limation scenarios the effective dose originating from the LAO
view is significantly larger than from the RAO view. Thus, asym-
metric collimation has the largest absolute impact on the LAO
view independent of the collimation and treatment approach.

Prospective study
Comparison of symmetric collimation around the LA centre and
symmetric collimation around each of the ipsilateral vein pairs,
thereby mimicking asymmetric collimation, resulted in a single
frame effective dose of 1.8 ± 0.8 μSv (DAP: 4.37 ± 2.3 mGy cm\(^2\))
and 0.7 ± 0.4 μSv (DAP: 1.83 ± 1.0 mGy cm\(^2\)), respectively. Thus,
in a clinical setting asymmetric collimation can realize an effective
dose reduction of 56% (\( P < 0.001 \)) when treating both ipsilateral
veins by a single ablation line. This reduction is not significantly differ-
ent from the result obtained in the retrospective study (\( P = 0.95 \)).

Also the view dependency of the effective doses is confirmed in
the clinical validation experiments: RAO and LAO reductions by
the use of asymmetric collimation are not significantly different
(51 vs. 57%, respectively, with \( P = 0.41 \)).

The time required for centring one vein pair by repositioning the
patient and for performing symmetric collimation around each
ipsilateral vein pair, added up to 177 ± 116 s of which the
largest part could be attributed to repositioning of the patient
the table.

Discussion
Our data, including both simulation and clinical measurements,
indicate that the implementation of asymmetric X-ray beam shield-
ing has the potential to substantially reduce radiation dose during
PV isolation procedures. While it is technically feasible as shown in
other applications and even hardware enabled by some modern
systems, we are not aware of a study investigating or suggesting
the possibility of asymmetric collimation for ablation. Using asym-
metric collimation, the effective radiation dose from fluoroscopic
imaging during PV isolation can be reduced to an average of
5 mSv, which is comparable with the effective dose received by a
patient during coronary angioplasty (percutaneous coronary
intervention).17

Although use of EM catheter tracking systems without any
imaging integration has been shown to reduce fluoroscopy
dose up to 66%, the combination of EM catheter tracking with 3D anatomy integration tends to increase radiation dose rather than decrease it while providing a highly detailed, more accurate 3D anatomical surface. Della Bella et al. reported an effective dose for conventional treatment of 44 mSv, including an acquisition of a venogram, while an image integration approach required 65 mSv radiation dose (of which 1 mSv was attributed to CT imaging). The large difference in obtained fluoroscopy radiation dose compared with our results (44 vs. 24 mSv) could be explained by a difference in frame rate (for instance 6 fps instead of 3 fps), the use of a single collimation window, the additional radiation of the venogram, or a combination of these. Also, a recent randomized study did not show superiority concerning procedural outcome and radiation dose of electro-anatomic mapping vs. a 3D-fluoroscopy overlay approach. Although this study reports lower fluoroscopy times than we, the effective dose may be similar because of the low fluoroscopy framerate used in our centre.

Additionally, radiation dose for 3D imaging should be considered. Depending on the 3D-imaging modality around 5 mSv for cardiac CT, around 6.6 mSv for rotational angiography and zero radiation dose for magnetic resonance imaging should be added. The combined radiation of both 3D imaging and fluoroscopy with asymmetric collimation would still result in a substantially reduced overall radiation dose and since all catheters of interest remain visible, it will most likely not affect procedure outcome. The 3D image overlay allows very precise collimation of only the target ablation points, which can be precisely determined from the 3D surface of the LA. Therefore, no visualization of other reference structures, like the spine, is needed.

Our results also indicate the importance of adjusting collimation as a function of the vein location. Indeed, even optimal symmetric collimation adjusted for each pair of veins or each individual vein can reduce dose by 22 and 43%, respectively, compared to using a single collimation for all veins.

Although the use of a wide fluoroscopic view on the heart to monitor pericardial effusion is no longer available when applying...
narrow field asymmetric fluoroscopic collimation, this complication could be detected by monitoring other vital signs, like heart rate, central venous pressure, and non-invasive blood pressure as is routinely performed in our centre.

In order to be used as described above, asymmetric collimation should be implemented in a way which requires minimal user intervention. This will also ensure that using it will result in a minimal increase in procedure duration. If it is properly integrated in the clinical workflow, we estimate that the increase will be <1 min.

The availability of an asymmetric collimation technique in the EP room and its associated radiation benefits may also have an impact on the choice of treatment strategy. Indeed, a number of studies have shown that a wide encircling of both PVs results in an improved outcome compared to the traditional ostial isolation of each vein individually, although there is no universal agreement. Our results show that effective dose of radiation by asymmetric collimation with individual PV ablation is three times lower than by encircling two ipsilateral PVs. These data need to be taken into account when weighing pros and cons of an ablation strategy. Another option for an approach encircling both ipsilateral PVs by one line could be to divide this line in a number of segments and to collimate asymmetrically for each segment. The impact of these alternatives on the success and effectiveness of PV ablation should be evaluated in further studies.

An alternative to asymmetric collimation would be to reposition the patient table for each PV, combined with simultaneous adaptation of the symmetric collimation window, as we performed in the prospective validation study. This approach does, however, require much more user intervention and more fluoroscopy during the repositioning. In the prospective study, an accurate centring around one vein pair took about 3 min which would add up to 12 min of additional time when centring around each individual vein. Additionally, it would also require re-registration for each vein, although that may become fully automated in the future. From an ergonomic and cost-effective viewpoint, this approach would be suboptimal. In case automated registration would fail, it would also increase the risk of severe harm to the patient since it could lead to applying ablation energy at undesired locations with risk of perforation or PV stenosis. Ideally, in the future, the imaging system could automatically suggest the collimation window on the basis of the treatment plan (i.e. target lines).

Limitations

We simulated asymmetric collimation by moving a symmetric beam towards a different location centred on a specific target area. It has been shown that asymmetric collimation may cause a different dose distribution than the corresponding symmetric dose distribution, which could result in an associated change in radiation dose. The values we obtained here may therefore differ slightly from the true obtainable reduction. However, implementation details of the filters and the automated exposure regulators on the imaging system may counteract these distortion effects.

In this study, we assumed an equal radiation time for each vein. In reality isolation of the left PVs may require a larger percentage of the procedure and imaging time. This can impact on the resulting absolute effective doses but will probably have a negligible effect on the obtained dose reductions.

Conclusion

Alternative collimation strategies during PVI show that implementing an asymmetric collimation approach can greatly diminish the effective dose for the patient. This decrease ranges from 66 to 89% when compared with a single collimation field for all veins, which is still commonly used in clinical practice, depending on whether ablation is performed on both ipsilateral PVs or on each individual PV.

Since asymmetric collimation can have an important impact on the reduction of harmful effects related to ablation treatment, imaging system manufacturers should prioritize its implementation and physicians should adopt it in their workflow when available.

Conflict of interest: The authors wish to make known the following disclosures. H.H. is a member of the scientific advisory board of Siemens Medical Solutions, Bayer, Daiichi-Sankyo, Merck, Sanofi-Aventis, Boehringer-Ingelheim and Bristol-Myers Squib, and receives unconditional research grants through the University of Leuven from St Jude Medical, Medtronic, Biotronik, and Boston Scientific Inc. S.D.B. and H.H. receive research funding through the University of Leuven from Siemens Medical Solutions for related topics. This research was academically driven and not supported by specific grants.

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