Adenosine-induced ventricular asystole or rapid ventricular pacing to enhance three-dimensional rotational imaging during cardiac ablation procedures

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Aims
Rotational angiography with digital three-dimensional reconstruction (3DRA) allows per-procedural 3D imaging to facilitate cardiac ablation procedures. We developed a new approach that allows per-procedural 3D imaging of the atria and ventricles with a single C-arm rotation, combining higher 3D image quality with a lower contrast and radiation dose.

Methods and results
Forty patients underwent 3DRA of the left atrium (LA, n = 26), right atrium (RA, n = 11), left ventricle (LV, n = 2), or right ventricle (RV, n = 1) during ablation procedures performed under general anaesthesia. Contrast agent (60 ± 12 mL) was diluted and injected directly in the chamber of interest, during adenosine-induced ventricular asystole (n = 31) or rapid RV pacing (n = 9, atrial imaging only) to reduce cardiac motion artefacts and enhance contrast opacification during rotational imaging. Reconstructed 3D data sets were graded according to predefined quality criteria (n = 40) and quantitatively compared with cardiac computed tomography (CT) (LA, n = 14). Adenosine-induced ventricular asystole and rapid pacing both allowed a sustained and homogeneous contrast opacification of target cardiac chambers, resulting in useful 3D data sets in 39 of 40 (98%) patients. Moreover, it was possible to achieve ‘good’ or ‘optimal’ 3D image quality in the majority of patients (adenosine: 61%, pacing 78%, P = 0.69). When compared with rapid pacing, the total elimination of cardiac motion artefacts with adenosine more frequently resulted in ‘optimal’ 3D image quality (42% vs. 11%, P = 0.01) and added the possibility for single-rotation 3D imaging of the ventricles. Quantitative analysis showed an excellent agreement between pulmonary vein diameters measured on cardiac CT and 3DRA images. Integration of 3DRA-based LA surfaces with real-time fluoroscopy was easy and highly accurate.

Conclusion
Adenosine-induced ventricular asystole or rapid ventricular pacing allow acquisition of 3DRA with an excellent direct contrast opacification of any cardiac chamber and a reduction of cardiac motion artefacts, resulting in high-quality per-procedural 3D imaging with a single C-arm rotation.

Keywords
Rotational angiography • Ablation • Atrial fibrillation • Image integration • Fluoroscopy

Introduction
X-ray imaging in the electrophysiology room was limited until very recently to the acquisition of two-dimensional (2D) fluoroscopic or angiographic projection images. While ideal for showing the position of intracardiac catheters, detailed three-dimensional (3D) information on the anatomy of cardiac chambers could not be obtained during the procedure. Therefore, many centres...
perform cardiac computed tomography (CT) or magnetic resonance imaging (MRI) before the ablation procedure to reconstruct patient-specific 3D models of the cardiac chamber of interest. These 3D models can now be integrated with 3D mapping systems or shown as a 3D overlay on real-time fluoroscopic images to guide catheter navigation and ablation. The current approach has a few drawbacks: (i) the possibility of changes in cardiac anatomy between pre-procedural imaging and ablation owing to changes in cardiac loading conditions, (ii) the need for inter-modality 3D image registration, which is still operator-dependent and not always accurate, and (iii) the extra logistical overhead of an additional ambulatory hospital visit or earlier hospitalization to perform pre-procedural imaging.

Early efforts to perform per-procedural 3D imaging were undertaken in the 1990s with conventional image intensifiers, but remained limited to high-contrast vessel imaging. The introduction of flat-panel fluoroscopy systems allowed the reconstruction of CT-like images during interventions, by acquiring projection data over an angular range of 180° or more. This image modality, generally called flat-detector CT, is often referred to as 3D rotational angiography (3DRA) in the setting of cardiac examinations. Such imaging offers a new way of combining 2D fluoroscopic and 3D CT imaging in one unit. For cardiac imaging, the low temporal resolution of 3DRA (4–5 s per C-arm rotation) remains an important limitation when compared with cardiac CT (<0.5 s per gantry rotation). While methods for ECG-gating over multiple rotations have been developed, they require an increased imaging time, contrast dose, and radiation dose.

We evaluated a new methodology for acquisition of 3DRA during cardiac ablation procedures, in which diluted contrast agent is injected directly into the target chamber of interest during a single C-arm rotation. Adenosine-induced ventricular asystole or rapid right ventricular (RV) pacing were used to optimize contrast filling of relevant cardiac structures (e.g., PVs) and to reduce cardiac motion artefacts.

**Methods**

**Patients and procedures**

This study comprises 40 patients (M/F: 29/11) aged 55 ± 12 years who underwent per-procedural 3DRA of the left atrium (LA, n = 26), right atrium (RA, n = 11), left ventricle (LV, n = 2) or RV (n = 1; Table 1, see Appendix for procedure types). Mean patient weight, height, and body-mass index were 81 ± 14 kg, 175 ± 10 cm, and 26.5 ± 3.8 kg/m², respectively. Exclusion criteria were a history of asthma, symptoms suggestive of angina or congestive heart failure, and therapy with dipyridamole or theophylline. All ablation procedures were performed under general anaesthesia with propofol and mechanical ventilation, which is the standard in our centre. A Siemens Axiom Artis dBC fluoroscopy system with one large area (30 × 40 cm) detector was used for biplane fluoroscopic guidance (at 3 frames/s) and 3DRA acquisition. Mapping and ablation were performed as described before for the different types of procedures. In brief, AF ablation procedures consisted of Lasso-guided electrical isolation of the four PVs, with the addition of linear lesions in patients with persistent AF. Selective angiography of the four PVs was performed after DynaCT acquisition to evaluate 3D-fluoroscopy integration accuracy. In the first 14 patients undergoing AF ablation, non-ECG-gated cardiac CT of the LA was performed one day prior to the ablation procedure on a Philips Brilliance 64 scanner, for comparison of PV diameters with 3DRA-based images and in case the 3DRA data would be of insufficient quality. CT was acquired after intravenous administration of 60–80 mL of non-diluted iodine contrast agent (Iomeron 400, Bracco, Milan, Italy) at a rate of 5 mL/s to obtain contrast opacification of the LA and PVs. In one patient, 64-slice cardiac CT with ECG-gating had recently been performed to rule out coronary artery disease and was used for comparison of PV diameters. Given the quality of LA models obtained with 3DRA in the first 14 patients, pre-procedural cardiac CT was no longer performed in the subsequent nine patients undergoing AF ablation.

**Acquisition of three-dimensional rotational angiography**

Three-dimensional rotational angiography was performed using the Siemens syngo™ DynaCT cardiac image acquisition protocol without ECG-gating. Contrast agent (60 ± 12 mL) was diluted and injected directly in the chamber of interest, during adenosine-induced ventricular asystole (n = 31) or rapid RV pacing (n = 9, atrial imaging only) to reduce cardiac motion artefacts and enhance contrast opacification during rotational imaging. Two-dimensional projection images were acquired with the large area detector at a rate of 60 frames/s during a single 5-s C-arm rotation over 200°. These projection images were then automatically transferred to a Siemens 3D workstation for reconstruction to a data set of CT-like axial images, using a 3D Feldkamp reconstruction algorithm with additional corrections for scatter, truncation, and ring artefacts (Figure 1). A detailed description of the practical workflow for DynaCT acquisition can be found in the Appendix.

**Qualitative three-dimensional image analysis**

DynaCT-based 3D visualization was performed with three different methods in all patients (Figure 2). Qualitative 3D image analysis of the atria was performed for the three visualization methods using a semi-quantitative scale adapted after Thiagalingam et al. grading the quality of LA and RA 3D models from 0 (not diagnostic) to 3 (optimal quality). The different quality criteria for LA and RA models are shown with examples in Figure 3. In addition to these qualitative criteria, the visualization of each of a predefined set of (RA or LA) anatomical structures was verified in each patient for both volume and surface-rendering techniques. Analogous quality criteria, ranging from not diagnostic to optimal, were used for evaluation of the three ventricular 3D data sets, based on the presence of image noise, artefacts, and the ability to visualize detailed anatomical structures such as the cardiac valves, papillary muscles, and chordae tendineae.

**Quantitative image analysis of left atrial three-dimensional rotational angiography**

In the first 14 patients undergoing DynaCT of the LA, the diameter of the four PVs was measured as a straight line on the axial DynaCT images at the site of entry into the LA, and compared with the diameter measured in a similar fashion on the cardiac CT images the day before. Moreover, the mean and SD image pixel intensity (in Hounsfield units) were measured in a 1 cm² circular region of interest at each PV ostium, the LA body, and the LA appendage (LAA) on the axial DynaCT and CT images. Signal-to-noise ratio (SNR) was defined as the ratio of the mean pixel intensity to the SD of the pixel intensity, reflecting not only image noise, but also the homogeneity of contrast opacification.
Automatic integration of DynaCT-based three-dimensional models and fluoroscopy

Assuming that no patient movements occur during general anaesthesia, patient position is identical during DynaCT acquisition and fluoroscopic imaging. The location of the reconstructed 3D model relative to the fluoroscopic imaging geometry is therefore exactly known, and allows for a fully automatic calibration and registration of the acquired 3D model to the fluoroscopy images. This method is implemented under the name syngo iPilot in the fluoroscopy unit, and allows DynaCT-based 3D volumes to be projected as an overlay on fluoroscopic images, currently only in the primary imaging plane. For the purpose of our ablations, we integrated the 3D models with real-time images in both fluoroscopy planes using an in-house developed software for electro-anatomical mapping (LARCA).4

The accuracy of automatic iPilot-registration was evaluated during AF ablation procedures by performing selective angiographies of the four PVs to assess their alignment with the integrated 3D overlay.

Statistical analysis

Summary values are given as mean ± SD or median (interquartile range, IQR) for not-normally distributed values. The Shapiro-Wilk W test was used to test for normality. Normally distributed data were compared using an unpaired t-test for independent samples, or with one-way analysis of variance for comparisons between multiple groups. Comparisons of not-normally distributed data were performed with a Mann–Whitney U-test for independent samples or a Wilcoxon-matched pair test for dependent samples. A Kruskal–Wallis test was used for multiple comparisons between not-normally distributed data.

Table 1 Patient characteristics and image acquisition parameters

<table>
<thead>
<tr>
<th>Patient characteristics</th>
<th>All chambers</th>
<th>Left atrium</th>
<th>Right atrium</th>
<th>Left ventricle</th>
<th>Right ventricle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of acquisitions (n)</td>
<td>40</td>
<td>26</td>
<td>11</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Patient characteristics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>55 ± 12</td>
<td>53 ± 10</td>
<td>61 ± 12</td>
<td>68 ± 0.7</td>
<td>23</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>81 ± 14</td>
<td>82 ± 15</td>
<td>80 ± 14</td>
<td>76 ± 8</td>
<td>78</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.75 ± 0.10</td>
<td>1.78 ± 0.10</td>
<td>1.68 ± 0.08</td>
<td>1.74 ± 0.06</td>
<td>1.76</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>26.5 ± 3.8</td>
<td>25.8 ± 3.3</td>
<td>28.2 ± 4.7</td>
<td>25.4 ± 4.7</td>
<td>28.0</td>
</tr>
<tr>
<td>Contrast administration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Contrast volume (mL)</td>
<td>60 ± 12</td>
<td>61 ± 12</td>
<td>58 ± 13</td>
<td>68 ± 4</td>
<td>70</td>
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<tr>
<td>Contrast concentration</td>
<td>0.45 ± 0.07</td>
<td>0.46 ± 0.07</td>
<td>0.43 ± 0.09</td>
<td>0.50 ± 0.0</td>
<td>0.50</td>
</tr>
<tr>
<td>Diluted volume (mL)</td>
<td>134 ± 12</td>
<td>133 ± 14</td>
<td>135 ± 7</td>
<td>135 ± 7</td>
<td>140</td>
</tr>
<tr>
<td>Motion reduction</td>
<td></td>
<td></td>
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<tr>
<td>Use of rapid pacing, n (%)</td>
<td>9 (23)</td>
<td>6 (23)</td>
<td>3 (27)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Use of ATP, n (%)</td>
<td>31 (77)</td>
<td>20 (77)</td>
<td>8 (73)</td>
<td>2 (100)</td>
<td>1 (100)</td>
</tr>
<tr>
<td>ATP 50 mg, n (%)</td>
<td>1 (2.5)</td>
<td>0 (0)</td>
<td>1 (8)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>ATP 60 mg, n (%)</td>
<td>17 (43)</td>
<td>9 (35)</td>
<td>7 (64)</td>
<td>1 (50)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>ATP 100 mg, n (%)</td>
<td>13 (33)</td>
<td>11 (42)</td>
<td>0 (0)</td>
<td>1 (50)</td>
<td>1 (100)</td>
</tr>
<tr>
<td>Complete ventricular asystole</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATP 50 mg</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ATP 60 mg</td>
<td>12/17 (71%)</td>
<td>7/9 (88%)</td>
<td>5/7 (71%)</td>
<td>0/1 (0%)</td>
<td>–</td>
</tr>
<tr>
<td>ATP 100 mg</td>
<td>12/13 (92%)</td>
<td>11/11 (100%)</td>
<td>–</td>
<td>0/1 (0%)</td>
<td>0/1 (0%)</td>
</tr>
<tr>
<td>ATP-induction of</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hiccups</td>
<td>3/31 (9%)</td>
<td>3/20 (15%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Atrial fibrillation</td>
<td>1/31 (2.5%)</td>
<td>1/20 (5%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>VPBs/nsVT</td>
<td>3/31 (9%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>2/2 (100%)</td>
<td>1/1 (100%)</td>
</tr>
<tr>
<td>3D model quality</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean quality score</td>
<td>2.0 ± 0.9</td>
<td>2.0 ± 0.9</td>
<td>1.9 ± 0.8</td>
<td>1.5 ± 0.7</td>
<td>2.0 ± 0.7</td>
</tr>
<tr>
<td>Quality scores, n (%):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0: not diagnostic</td>
<td>1 (2.5)</td>
<td>1 (4)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>1: useful</td>
<td>13 (32.5)</td>
<td>8 (31)</td>
<td>4 (36)</td>
<td>1 (50)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>2: good quality</td>
<td>12 (30)</td>
<td>6 (23)</td>
<td>4 (36)</td>
<td>1 (50)</td>
<td>1 (100)</td>
</tr>
<tr>
<td>3: optimal quality</td>
<td>14 (35)</td>
<td>11 (42)</td>
<td>3 (27)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Radiation dose</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dose-area product (Gy cm²)</td>
<td>45 ± 7</td>
<td>45.2 ± 6.0</td>
<td>44.0 ± 8.0</td>
<td>50.3 ± 5.5</td>
<td>52.9</td>
</tr>
<tr>
<td>Collimation in height (cm)</td>
<td>16.0 ± 1.9</td>
<td>16.0 ± 2.0</td>
<td>15.9 ± 1.7</td>
<td>17.5 ± 0.9</td>
<td>18.2</td>
</tr>
</tbody>
</table>

Overview of patient characteristics, contrast administration protocol, motion reduction methods, 3D image quality, and radiation dose for 3DRA acquisitions in different cardiac chambers. Complete ventricular asystole refers to image acquisition without a single interfering ventricular contraction. (BMI, body mass index; ATP, adenosine-triphosphate; VPBs, ventricular premature beats; nsVT, non-sustained ventricular tachycardia.)
Differences in proportions between groups were evaluated with Fisher’s exact test. A \( P \)-value \( \leq 0.05 \) was considered significant. Absolute differences between PV diameters were subjected to Bland-Altman analysis by calculating the mean difference and the limits of agreement (2SD around the mean difference). Multiple linear regression analysis was used to evaluate the independent effects of patient weight, collimation height, and detector dose settings on the received patient radiation dose. The local Ethics Committee approved this study and informed consent was obtained from all patients. The authors had full access to the data and take responsibility for its integrity. All authors have read and agree to the manuscript as written.

**Results**

**DynaCT acquisition and three-dimensional image quality**

The total time needed for DynaCT acquisition was 17 ± 3 min. Direct injection of diluted contrast agent during ventricular asystole or rapid pacing resulted in excellent contrast opacification of target cardiac chambers. For the LA, contrast intensity was typically more pronounced than observed during the lepophase of pulmonary artery injections. Rotational imaging resulted in useful 3D image data sets in 39 of 40 patients (98%). The only non-diagnostic result was obtained for the LA, in a patient in whom 60 mg ATP caused only one beat of atrioventricular block, with subsequent contrast injection and image acquisition during normal cardiac activity. In this patient, the ostia of the right pulmonary veins were not visible on the reconstructed 3D model (Figure 3, non-diagnostic category), whereas the ostia of the four PVs could be identified in all other 25 LA reconstructions. The quality distribution of 3D data sets for all cardiac chambers is shown in Table 1. Good or optimal 3D image quality could be achieved in the majority of patients (adenosine: 61%, pacing 78%, \( P = 0.69 \)). When compared with rapid pacing, the total elimination of cardiac motion artefacts with adenosine more frequently resulted in ‘optimal’ 3D image quality (42% vs. 11%, \( P = 0.01 \)), which was comparable to the best achievable quality with pre-procedural ECG-gated.
Ventricular asystole or rapid pacing to enhance 3DRA

The patient radiation dose owing to DynaCT acquisition, presented by the fluoroscopy system as dose-area product (DAP) value, was 45.0 ± 7.0 Gy cm². Collimation in height was performed during DynaCT acquisition in 23 of 40 patients, resulting in a DAP of 40.7 ± 3.7 Gy cm², vs. 51.9 ± 3.5 Gy cm² in patients in whom no collimation was used (P < 0.001). In multivariate analysis, the collimation height and patient weight were independently associated with DAP, with partial correlation coefficients of 0.87 and 0.45, respectively (P < 0.001). The use of lower detector dose settings also resulted in a modest decrease in patient radiation dose, with a partial correlation coefficient of 0.37 (P = 0.02).

In one patient, a large contrast tag remained visible at the inter-atrial septum after DynaCT acquisition, because of contrast injection in the inter-atrial space through the most proximal hole of the pigtail catheter, which was positioned too septally. Echocardiographic evaluation after the procedure, however, did not show any abnormalities and the patient had an uneventful clinical course.

Adenosine-induced ventricular asystole and rapid ventricular pacing

Sustained ventricular asystole, without a single ventricular contraction occurring during image acquisition, was achieved in 12 of 17 patients (71%) receiving 60 mg adenosine-triphosphate (ATP) vs. in 12 of 13 patients (92%) receiving 100 mg ATP (P = 0.15). For atrial ablation procedures, complete ventricular asystole was achieved in all patients with 100 mg ATP. In patients undergoing ablation of ventricular tachycardia, complete ventricular asystole was not achieved because of ventricular premature beats (n = 2) or non-sustained VT (n = 1) occurring during image acquisition (Table 1). However, useful (n = 1) or good (n = 2) 3D image quality was still achieved in these patients, because of the limited cardiac motion and contrast washout occurring during abnormal ventricular activation (Figure 5). Ventricular premature beats or non-sustained VT were only seen in the three patients undergoing VT ablation, and not in any of the 37 other patients undergoing atrial ablation procedures (P < 0.001).

Ventricular asystole occurred 17 ± 3 s after injection of ATP (range 11–23 s). In all but one patient, backup RV pacing was initiated after DynaCT acquisition because of residual complete or incomplete atrioventricular block. Pacing was discontinued after 1 min with recovery of spontaneous conduction in all patients.

The increase in LA pressure associated with direct contrast injection during ventricular asystole was measured in one initial patient and showed a slow evolution of LA pressure from 15 mmHg to 20 mmHg during injection of 100 mL diluted contrast over 5 s. In five patients, invasive blood pressure (BP) profiles were registered to characterize ATP-induced hypotension owing to vasodilation. The mean time needed for the BP to recover (from a baseline mean value of 72 mmHg) to a mean value of 60 mmHg after onset of ventricular asystole was 81 s for three patients receiving 60 mg ATP and 106 s for two patients receiving 100 mg ATP. Administration of ATP-induced diaphragmatic contractions (hiccups) in 3 of 31 patients (9%). Hiccups occurred just before onset of ventricular asystole and image acquisition in two patients, but during DynaCT acquisition in the other patient, in whom DynaCT acquisition was aborted and successfully

Figure 2 Methods used for three-dimensional (3D) visualization of DynaCT cardiac data sets. (A) Direct volume rendering (InSpace 3D). (B) Surface reconstruction with a segmentation method based on interactive graph cuts (InSpace EP). (C) Surface reconstruction based on a 3D isosurface, computed around structures with a high target intensity (Amira 4.1, Mercury Computer Systems SAS). The three methods are illustrated for the same patient as in Figure 1, showing the left atrium from a posterior view. (LA, left atrium; LSPV, left superior pulmonary vein; LIPV, left inferior pulmonary vein; RSPV, right superior pulmonary vein; RIPV, right inferior pulmonary vein.)
repeated after administration of cisatracurium, a muscle paralyzing agent, to prevent diaphragmatic contraction. Atrial fibrillation was induced after administration of ATP in one patient (2.5%).

Rapid RV pacing at a cycle length of 250 ms could be successfully performed with 1:1 ventricular capture in all nine patients in whom it was attempted. There were no adverse events associated with the use of ATP or rapid RV pacing in any of the patients.

Quantitative image analysis of left atrial three-dimensional rotational angiography

The mean differences between PV diameters measured on axial DynaCT vs. CT images were $-0.3 \pm 1.3$ mm for the LSPV, $-0.4 \pm 1.1$ mm for the LIPV, $0.1 \pm 1.7$ mm for the RSPV and $-0.1 \pm 0.9$ mm for the RIPV. The 95% limits of agreement...
calculated using Bland-Altman analysis were (−2.9 to 2.2 mm) for the LSPV, (−2.7 to 1.8 mm) for the LIPV, (−3.2 to 3.4 mm) for the RSPV, and (−1.7 to 2.0 mm) for the RIPV.

Our injection protocol resulted in very intense contrast enhancement of the LA on the DynaCT images, with mean pixel intensities more than three times higher than measured on the cardiac CT images (P < 0.001 for all regions, Figure 6A). While the highest contrast intensity was typically observed in the LAA and the LSPV, the difference with intensities in other LA structures was not significant (P = 0.09 for LAA vs. LA body). DynaCT SNR was significantly higher than for cardiac CT in all regions except the RIPV ostium, which showed a significantly lower SNR compared with all other LA regions (P < 0.05 for all comparisons, Figure 6B). Mean signal intensity was higher in all LA regions for DynaCT acquisitions during ventricular asystole than for acquisitions during ventricular pacing; however, the difference

### Table 2 Patient and image acquisition characteristics in different categories of three-dimensional image quality

<table>
<thead>
<tr>
<th>Quality score</th>
<th>All scores</th>
<th>0: not diagnostic</th>
<th>1: useful</th>
<th>2: good quality</th>
<th>3: optimal quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>All patients n (%)</td>
<td>40</td>
<td>1 (2.5)</td>
<td>13 (32.5)</td>
<td>12 (30)</td>
<td>14 (35)</td>
</tr>
<tr>
<td>Motion reduction method</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATP n (%)</td>
<td>31</td>
<td>1 (3)</td>
<td>11 (35)</td>
<td>6 (19)</td>
<td>13 (42)</td>
</tr>
<tr>
<td>Rapid pacing n (%)</td>
<td>9</td>
<td>0 (0)</td>
<td>2 (22)</td>
<td>6 (67)</td>
<td>1 (11)</td>
</tr>
<tr>
<td>Patient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>81 ± 14</td>
<td>92 ± 0</td>
<td>86 ± 12</td>
<td>76 ± 16</td>
<td>79 ± 14</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>26.5 ± 3.8</td>
<td>28.1 ± 0</td>
<td>26.9 ± 3.1</td>
<td>27.2 ± 5.2</td>
<td>25.4 ± 3.2</td>
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<tr>
<td>Contrast agent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrast volume (mL)</td>
<td>60 ± 12</td>
<td>70.0 ± 0</td>
<td>57 ± 13</td>
<td>63 ± 11</td>
<td>62 ± 12</td>
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<tr>
<td>Contrast concentration</td>
<td>0.45 ± 0.07</td>
<td>0.50 ± 0</td>
<td>0.43 ± 0.08</td>
<td>0.46 ± 0.06</td>
<td>0.45 ± 0.07</td>
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<tr>
<td>Diluted volume (mL)</td>
<td>134 ± 12</td>
<td>140 ± 0</td>
<td>131 ± 16</td>
<td>134 ± 7</td>
<td>136 ± 11</td>
</tr>
<tr>
<td>Radiation</td>
<td></td>
<td></td>
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<tr>
<td>Dose/Frame (μGy)</td>
<td>0.47 ± 0.11</td>
<td>0.54 ± 0</td>
<td>0.50 ± 0.09</td>
<td>0.44 ± 0.13</td>
<td>0.46 ± 0.12</td>
</tr>
<tr>
<td>DAP (Gy cm²)</td>
<td>45.1 ± 6.7</td>
<td>40.0 ± 0</td>
<td>45.9 ± 6.9</td>
<td>47.2 ± 6.8</td>
<td>43.4 ± 6.2</td>
</tr>
</tbody>
</table>

Different DynaCT quality groups showed no significant differences in patient weight, the volume or dilution of administered contrast agent, the selected radiation dose setting per frame, or the dose-area product (DAP) for the entire acquisition. BMI, body mass index; ATP, adenosine triphosphate.

Figure 4 Comparison of a left atrial three-dimensional (3D) surface reconstruction based on ungated DynaCT cardiac (acquisition during adenosine-induced ventricular asystole, optimal quality) and ECG-gated 64-slice cardiac computed tomography. Both 3D models are of comparable high quality. Note the two TS visible on the DynaCT-based 3D reconstruction. (LA, left atrium; LAA, left atrial appendage; RSPV, right superior pulmonary vein; RIPV, right inferior pulmonary vein; LSPV, left superior pulmonary vein; TS, transseptal sheaths.)
Direct contrast injection during transient ventricular asystole

The major findings are:

- Injected in the cardiac chamber of interest, during adenosine-ablation procedures, in which diluted contrast agent is directly injected in the left ventricle with a transseptal pigtail catheter, after administration of 100 mg ATP to induce ventricular asystole during rotational imaging. Despite a short run of non-sustained VT (four beats) during image acquisition, the reconstructed 3D surface was of good quality and showed the LV cavity, aortic cusps, coronary ostia, and origin of a coronary bypass graft. An antero-posterior projection view of the entire 3DRA volume is shown as an overlay on the 3D left ventricular surface to demonstrate its anatomical relationship with intracardiac catheters. (RCA, right coronary artery; LCA, left coronary artery; LV, left ventricle; Ao, aorta; ICD, implantable cardioverter-defibrillator; ATP, adenosine-triphosphate; VT, ventricular tachycardia.)

(2) The combination of enhanced contrast opacification and elimination/reduction of cardiac motion artefacts resulted in high-quality 3D data sets of the atria and ventricles, acquired during a single ungated 5-s C-arm rotation.

(3) The combination of 3D imaging and fluoroscopy in one unit allows for automatic 3D-fluoroscopy integration with a high level of accuracy, without the need for user-dependent inter-modality image registration.

Comparison with other methods for three-dimensional rotational angiography image acquisition

Previous studies on the per-procedural use of 3DRA during cardiac ablation procedures have concentrated on rotational imaging of the left ventricle in the setting of interventional procedures for congenital heart disease and endovascular stenting.17 – 21

Automatic DynaCT-based three-dimensional model and fluoroscopy integration

Automatic integration of DynaCT-based 3D models of the LA with fluoroscopy could be performed with high accuracy, as was demonstrated with selective PV angiographies and during catheter manipulation in and around the PV ostia in the 23 patients undergoing ablation of atrial fibrillation.

Discussion

This study presents a new approach for 3DRA during cardiac ablation procedures, in which diluted contrast agent is directly injected in the cardiac chamber of interest, during adenosine-induced ventricular asystole or rapid ventricular pacing. Our major findings are:

(1) Direct contrast injection during transient ventricular asystole or rapid pacing allows a sustained and homogeneous contrast opacification of the atria and ventricles, with a low contrast dose for the patient.

(2) The combination of enhanced contrast opacification and elimination/reduction of cardiac motion artefacts resulted in high-quality 3D data sets of the atria and ventricles, acquired during a single ungated 5-s C-arm rotation.

(3) The combination of 3D imaging and fluoroscopy in one unit allows for automatic 3D-fluoroscopy integration with a high level of accuracy, without the need for user-dependent inter-modality image registration.

Adenosine-induced ventricular asystole and rapid ventricular pacing

The injection of contrast media in the body of the LA after delivery of a bolus of adenosine to induce atrioventricular block was recently proposed as a method for PV venography in an expert consensus statement on AF ablation.1 Based on our experience from PV venography, a 40 mg dose of ATP induced sustained ventricular asystole of more than 5 s in only 50% of the patients (unpublished data). The higher doses of 60 mg and 100 mg ATP used for acquisition of 3DRA in this study resulted in sustained ventricular asystole in, respectively, 71% and 92% of the patients. It has been suggested that the cardiac and haemodynamic effects induced by ATP correspond to those induced by half the dose of adenosine, as both products have a molar equipotency and the molecular weight of adenosine is approximately half that of ATP.16 The safe use of adenosine and ATP to induce transient atrioventricular block was recently proposed as a method for PV venography in an expert consensus statement on AF ablation.1 Based on our experience from PV venography, a 40 mg dose of ATP induced sustained ventricular asystole of more than 5 s in only 50% of the patients (unpublished data). The higher doses of 60 mg and 100 mg ATP used for acquisition of 3DRA in this study resulted in sustained ventricular asystole in, respectively, 71% and 92% of the patients. It has been suggested that the cardiac and haemodynamic effects induced by ATP correspond to those induced by half the dose of adenosine, as both products have a molar equipotency and the molecular weight of adenosine is approximately half that of ATP.16 The safe use of adenosine and ATP to induce transient atrioventricular block was recently proposed as a method for PV venography in an expert consensus statement on AF ablation.1 Based on our experience from PV venography, a 40 mg dose of ATP induced sustained ventricular asystole of more than 5 s in only 50% of the patients (unpublished data). The higher doses of 60 mg and 100 mg ATP used for acquisition of 3DRA in this study resulted in sustained ventricular asystole in, respectively, 71% and 92% of the patients. It has been suggested that the cardiac and haemodynamic effects induced by ATP correspond to those induced by half the dose of adenosine, as both products have a molar equipotency and the molecular weight of adenosine is approximately half that of ATP.16

Rapid ventricular pacing has the advantage over adenosine-induced ventricular asystole of being more predictable in timing.
and response, while also inducing a shorter period of hypotension owing to the absence of ATP-induced vasodilatation. This method too has been safely used in interventional procedures for congenital heart disease, endovascular stenting, and valve replacement.22–25 The theoretical risk for induction of ventricular tachycardia or fibrillation is small in patients without structural heart disease, and could be adequately reacted upon in the setting of an electrophysiology room.

Clinical value of three-dimensional rotational angiography during ablation procedures

The results of our study indicate that ungated 3DRA with a single C-arm rotation can result in 3D data sets with an excellent quality, comparable to ECG-gated 64-slice cardiac CT (Figure 4). In 32.5% of the patients, 3D image quality was ‘useful’ and
showed all relevant anatomical structures, but did not reach the quality usually obtained by pre-procedural cardiac CT. Nonetheless, based on the excellent image quality obtained in the majority of patients, 3DRA of the LA has now replaced pre-procedural cardiac CT in our clinical workflow for AF ablation procedures. Further modifications of the acquisition protocol could increase the proportion of ‘optimal quality’ data sets in the future. In our experience, one of the major advantages of 3DRA is the possibility for automatic and highly accurate integration of 3D cardiac models with real-time fluoroscopic imaging. This option is present only commercially available in the primary imaging plane. Automatic DynaCT cardiac integration in a biplane fluoroscopy environment is however already performed in our research setting using an in-house developed software and will be available in later versions of commercial systems. Accurate 3D-fluoroscopy integration could be of particular interest for balloon-based ablation procedures in which no 3D mapping systems are used. Moreover, 3DRA can in the future provide a possibility for direct image integration with electro-anatomical mapping systems, obviating the need for registration with 3D geometries acquired with a roving catheter during the procedure. Although no data have been published on the effective radiation dose of 3DRA, the un gated single-rotation approach used in this study probably imposes a lower effective dose on the patient than pre-procedural ECG-gated cardiac CT. Detailed dose studies and comparison with the radiation dose of un gated cardiac CT are currently ongoing in our centre.

Study limitations

Rotational imaging was performed in all patients with the arms next to the body, resulting in a darker image in lateral projections, caused by superposition of both arms and the thorax in its maximal lateral dimension. This might result in degradation of image quality and, given the use of automatic exposure control, in a higher radiation dose for the patient. However, positioning the patient with the arms up for the entire duration of a procedure under general anaesthesia carries a significant risk for brachial plexus injury.26 Moreover, raising the arms above the head only during rotational imaging is impractical and can result in 3D-fluoroscopy registration errors when the rest of the procedure is performed with the arms next to the body.

Administration of high doses of ATP is only possible in procedures under general anaesthesia and is therefore not applicable in patients undergoing ablation without sedation or receiving only conscious sedation. Although this did not occur in our study population, ATP or rapid pacing could potentially terminate tachycardias during the procedure, thereby interfering with mapping and/or ablation of the arrhythmia.

The finding that measured signal intensity and SNR were higher for DynaCT than for cardiac CT images does not allow any conclusion on the final image quality of both modalities, which is influenced by image contrast, resolution, noise, and artefacts. These measurements were rather used to assess DynaCT contrast filling in different anatomical regions, whereas a semi-quantitative scale was used to evaluate DynaCT image quality. Measurements of PV diameters were performed in a non-blinded fashion by a single operator with only one day between CT and DynaCT measurements. However, measurements were performed in a standardized fashion to minimize operator bias. Moreover, the close agreement between PV diameters measured on CT and 3DRA images has been reported in three previous studies.12–14

The accuracy of automatic iPilot-registration was evaluated during AF ablation procedures by performing selective angiographies of the four PVs, to assess their alignment with the integrated 3D overlay. A more detailed and quantitative evaluation of integration accuracy by off-line measurements of PV alignment errors, as was previously described for 3D-fluoroscopy integration of the LA,4 will be performed as part of a future study on automatic biplane 3D-fluoroscopy integration. Biplane overlay of 3D images with fluoroscopy provides the possibility for enhanced catheter navigation and ablation. Unlike 3D mapping systems however, this method requires real-time fluoroscopy to localize the catheter tip during navigation, thereby contributing to patient radiation exposure during the procedure.

Conclusion

Adenosine-induced ventricular asystole and rapid ventricular pacing allow acquisition of 3DRA with an excellent direct contrast opacification of the atria and a reduction of cardiac motion artefacts, resulting in high-quality per-procedural 3D imaging with a single C-arm rotation.

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Appendix: Practical workflow for DynaCT cardiac image acquisition

Procedure types

Three-dimensional rotational angiography of the left atrium (LA) was performed during ablation procedures for atrial fibrillation (AF, n = 23; 16 paroxysmal and 7 persistent AF), a left accessory pathway (n = 1), and LA tachycardia (n = 2). Right atrial three-dimensional rotational angiography (3DRA) was performed during ablation procedures for atrial flutter (n = 7) and intra-atrial reentrant tachycardia after mitral valve surgery (n = 1) or tetrology of Fallot repair (n = 1). Left ventricular (LV) 3DRA was performed in two patients undergoing ablation of post-infarction ventricular tachycardia, and right ventricular 3DRA in a patient with ventricular tachycardia after tetralogy of Fallot repair.
A. Preparation

(1) All patients were under general anaesthesia and positioned on the examination table with their arms next to the body for the entire duration of the procedure.

(2) A 6F pigtail catheter (Pro-flò, Medtronic Inc., MN, USA) was inserted into the cardiac chamber of interest under biplane fluoroscopic guidance. In AF ablation procedures, two transseptal punctures were performed under fluoroscopic guidance, and the pigtail catheter was inserted into the LA through one of the transseptal sheaths (SL 0, Daig Corp., Minnetonka, MN, USA). The right atrial appendage catheter was placed at the RV apex for backup or rapid ventricular pacing and ventricular capture was confirmed. The coronary sinus catheter, if present, was partially or fully withdrawn to limit catheter artefacts in the area of the left PV ostia.

(3) The C-arm of the secondary imaging plane was put in its parking position and the ungated DynaCT acquisition protocol was selected from the fluoroscopy console. As DynaCT acquisition is performed under automatic exposure control, X-ray tube current and voltage are modulated during image acquisition to obtain a specified radiation dose at the detector. Acquisition was performed with the standard detector dose setting of 0.54 μGy/frame in the majority of patients (28 of 40, 70%), while dose settings of 0.36 μGy/frame and 0.24 μGy/frame were used in 7 of 40 patients (18%) and 5 of 40 patients (13%), respectively, to evaluate their influence on radiation dose and 3D image quality.

(4) After selection of the DynaCT protocol, the primary C-arm was sequentially put in a 0°-anterior and 90°-lateral position to perform isocentering under fluoroscopic guidance. In this phase, collimation in height (but not width) could be applied to reduce radiation dose. After isocentering, a C-arm test-rotation was done to ensure that no obstacles stopped the 200° C-arm rotation.

B. Reduction of cardiac motion

- Respiratory motion was eliminated by applying apnea during image acquisition.
- Cardiac motion was eliminated or reduced by one of the two following methods:
  
  (i) Administration of adenosine triphosphate (ATP; n = 31/40), an endogenous purine nucleoside which is rapidly converted to adenosine after intravenous injection and induces transient asystole and/or high-grade atrioventricular block.27 ATP (Ate-podim®, Medix S.A., Guadalajara, Spain) was administered as a rapid bolus injection through a femoral venous access sheath followed by a 10 mL saline flush. A standard dose of 60 mg of ATP was administered in the first 17 patients, while a higher dose of 100 mg of ATP was used in the subsequent 13 patients (Table 1). A reduced dose of 50 mg was administered in one initial patient with sick sinus syndrome. Backup ventricular pacing was initiated if ventricular asystole persisted after the completion of DynaCT image acquisition.

  (ii) Rapid right ventricular pacing (n = 9/40) at a cycle length of 250 ms, to reduce cardiac output and cardiac motion during contrast administration and image acquisition.

C. Contrast injection and DynaCT acquisition

(1) Contrast injection was triggered by pushing the DynaCT acquisition pedal at the onset of stable ventricular asystole or after the initiation of rapid RV pacing. The standard contrast injection protocol consisted of 70 mL contrast agent (Iomeron 350, Bracco, Milan, Italy), which was diluted with saline to a total volume of 140 mL (concentration: 50%) and injected at a rate of 20 mL/s. In 17 of 40 patients, lower contrast doses and dilutions were used to evaluate the impact on image quality.

(2) After a programmed delay of 2 s from the start of contrast injection, DynaCT acquisition started and a 200° C-arm rotation was performed over the following 5 s. The resulting rotational projection images were automatically transferred to the Siemens Leonardo 3D workstation and reconstructed to 2D axial CT-like images, which were used for further 3D-processing.

References


