Remote-Controlled Magnetic Navigation and Ablation With 3D Image Integration as an Alternative Approach in Patients With Intra-Atrial Baffle Anatomy

Sabine Ernst, MD, PhD, FESC; Sonya V. Babu-Narayan, MB, BS, BSc, MRCP, PhD; Jennifer Keegan, PhD; Irina Horduna, MD; Jonathan Lyne, MB, BChir, BSc, MRCP; Janice Till, MD; Philip J. Kilner, MD, PhD; Dudley Pennell, MD, FRCP, FACC, FESC; Michael L. Rigby, MD, FRCP; Michael A. Gatzoulis, MD, PhD

Background—Improvement in outcome of infants born with congenital heart defects has been accompanied by an increasing frequency of late arrhythmias. Ablation is difficult because of multiple tachycardias in the presence of complex anatomy with limited accessibility. We report on remote-controlled ablation using magnetic navigation in conjunction with 3D image integration in patients with previous intra-atrial baffle procedures.

Methods and Results—Thirteen patients (8 male; age, 30.5±8 years) with supraventricular tachycardia (SVT) underwent catheter ablation. Group A had a medical history of a Mustard or Senning operation, whereas group B had undergone total cavopulmonary connection. A total of 26 tachycardias were treated in 17 procedures (median cycle length of 280 ms). Group A patients had more inducible SVTs than group B, and all index SVTs were located in the remainder of the morphological right atrium in all but 1 patient. Retrograde access through the aorta was performed and led to successful ablation, using magnetic navigation with a very low total radiation exposure (median of 3.8 minutes in group A versus 5.9 minutes in group B). Only 1 of 13 patients continued to have short-lasting SVTs despite 3 ablation procedures during a median follow-up time of >200 days.

Conclusions—Remote-controlled catheter ablation by magnetic navigation in combination with accurate 3D image integration allowed safe and successful elimination of SVTs, using an exclusively retrograde approach, resulting in low radiation exposure for patients after intra-atrial baffle procedures (Mustard, Senning, or total cavopulmonary connection). (Circ Arrhythm Electrophysiol. 2012;5:131-139.)

Key Words: magnetic navigation ■ catheter ablation ■ Mustard/Senning procedure ■ total cavopulmonary connection

Various methods have been devised for surgically repairing or palliating congenital cardiac malformations. As a result, most infants born with congenital heart disease now survive into adulthood.1–5 Improvement in outcome and survival, however, has been accompanied by an increasing frequency of arrhythmias in long-term follow-up.5–7 Ablation in these patients can be especially difficult because of the multitude of potential tachycardia substrates that must be understood in the presence of complex anatomy, which may limit accessibility.5,6 Because cardiac function may already be impaired during sinus rhythm, sustained arrhythmias are likely to lead to clinical deterioration. We report remote-controlled mapping and ablation for atrial tachycardia, using magnetic navigation facilitated by 3D image registration and electroanatomic mapping in patients with previous intra-atrial baffle procedures.

Clinical Perspective on p 139

Methods

Patient Cohort
From May 2008, a total of 13 patients (8 male; mean age, 30.5±8 years) with documented supraventricular tachycardia, either incessant (n=6) or intermittent (n=7), underwent catheter ablation procedures using magnetic navigation through a retrograde arterial access. Patients were classified into group A, with a medical history of a Mustard10 or Senning11 operation for complete transposition of the great arteries (TGA) in early childhood, or group B, who underwent total cavopulmonary connection (TCPC), using a lateral tunnel technique12 (in median 26 years previously). Table 1 summarizes patient demographics.

Preablation 3D Imaging and Image Processing
All patients underwent preablation imaging studies, using noncontrast cardiovascular magnetic resonance, or, in the presence of an implantable...
device, cardiac computed tomography (Table 1). For cardiovascular magnetic resonance imaging, a free-breathing, diaphragm-navigated, balanced steady-state free precession sequence with 3D reconstruction was performed to image the whole heart (Figure 1). All preacquired 3D imaging DICOM data were processed to obtain 3D reconstructions to fuse with the 3D mapping information (POLARIS software, Biosense Webster, Brussels, Belgium) (Figures 1 and 2).

**Remote-Controlled Electrophysiology Study**

All procedures were performed in the presence of an experienced cardiac anesthetist with continuous invasive blood pressure monitoring through either radial or brachial arterial lines. All patients were studied under general anesthesia (intravenous propofol and remifentanil) and vascular access (7F and 8F sheaths) was gained through the femoral veins in all but 1 patient (patient 7 of group A). In this patient, the femoral veins were thrombosed (as a consequence of previous procedures) and therefore venous access was gained through alternative venous access was gained through a subclavian vein. To allow retrograde access through the aortic valve, a single 8F vascular access was gained through the femoral artery (right or left, depending on preexisting scars from previous operations/procedures).

All patients, the electroanatomic mapping system CARTO RMT (Biosense Webster) was used in conjunction with either a solid tip (4 mm or 8 mm) or an irrigated-tip, magnetically enabled catheter (Navistar RMT, Navistar RMT DS or ThermoCool RMT, Biosense Webster, Brussels, Belgium).13,14

**Table 1. Patient Demographics**

<table>
<thead>
<tr>
<th></th>
<th>Group A, TGA Group</th>
<th>Group B, TCPC Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>Sex</td>
<td>5 Male/4 female</td>
<td>3 Male/1 female</td>
</tr>
<tr>
<td>Median age</td>
<td>31.1 ± 6.6</td>
<td>29.2 ± 11.7</td>
</tr>
<tr>
<td>Median time since last surgery (Q1 to Q3) in years</td>
<td>28 (22–33)</td>
<td>17.5 (12–20.3)</td>
</tr>
<tr>
<td>Preablation antiarrhythmic therapy</td>
<td>Rate control in 6 patients, amiodarone in 3 patients</td>
<td>Sotalol in 1 patient, amiodarone in 1 patient, rate control in 2 patients</td>
</tr>
<tr>
<td>Previous ablation procedures before MN</td>
<td>In 4 patients (median of 2 procedures)</td>
<td>In 1 patient (1 procedure)</td>
</tr>
<tr>
<td>Implantable device</td>
<td>4 DDD (1 epicardial)</td>
<td>1 DDD</td>
</tr>
<tr>
<td>Preablation 3D imaging, CMR vs CT</td>
<td>5 CMR, 4 CT</td>
<td>3 CMR, 1 CT</td>
</tr>
</tbody>
</table>

TGA indicates transposition of the great arteries; TCPC, total cavopulmonary connection; Q1 to Q3, first to third quartiles; MN, magnetic navigation; DDD, dual-chamber pacemaker; CMR, cardiovascular magnetic resonance; and CT, computer tomography.

**Figure 1.** Three-dimensional reconstruction of a CT scan (patient 7 of group A): depiction of the right subclavian vein (A), which was used for cardiac access after blocked femoral venous access bilaterally. Location of the epicardial pacemaker (PM, B) is shown. Arterial retrograde access through aorta, systemic right ventricle (RV) into the pulmonary venous atrium (PVA) is shown in C. Postero-anterior projection depicting a baffle leak between the systemic venous atrium (SVA) and the PVA is shown (D).
A multipolar, steerable diagnostic catheter (6F, Parahis, Biosense Webster, Brussels, Belgium) was used as the timing reference in the accessible chamber from a venous vascular access (eg, appendage of the systemic venous atrium in Mustard/Senning patients) in group A or positioned inside the TCPC in group B. A quadripolar, nonsteerable catheter was positioned in the ventricle in case of reduced atrioventricular (AV) conduction properties (Biosense Webster, Brussels, Belgium). For patients in sinus rhythm at the beginning of the procedure (n = 11005 patients), atrial (and ventricular) stimulation was performed to induce the clinically documented arrhythmia (Figure 3).

All intracardiac signals were recorded on an AXIOM Sensis recording system (Siemens AG, Forchheim, Germany), and all signals and mapping information were displayed on the Odyssey platform (Stereotaxis Inc, St Louis, MO). Remote-controlled mapping and ablation was performed with the use of the magnetic navigation system (Niobe II, Stereotaxis Inc, St Louis, MO) in conjunction with the cardio drive system. A detailed description of this system has been published previously.15,16

**Statistical Analysis**

Values are expressed either as mean with 1 standard deviation or median with first to third quartiles (Q1 to Q3). Because of the small number of patients, no comparative statistical analysis was performed.

**Results**

A total of 26 atrial tachycardias (AT) were treated in a total of 17 ablation procedures with a median atrial cycle length of

![Figure 2](image-url)

**Figure 2.** Three-dimensional reconstruction of a cardiovascular magnetic resonance scan (patient 12 of group B) in right anterior (RAO), left anterior oblique (LAO), and postero-antero projection: The total cavo-pulmonary connection (TCPC) is shown in light blue, the left atrium (LA) in darker blue, and the residual right atrium (RA) in orange. Access to the native atria was gained retrogradely through the aorta.

![Figure 3](image-url)

**Figure 3.** Different access for individual patients: A depicts 2 diagnostic catheters through femoral venous access (left ventricular [LV] lead for chronotropic incompetence during general anesthesia). The magnetic catheter is advanced antegradely through the aorta and systemic right ventricle (RV) in the pulmonary venous atrium (PVA). B shows a diagnostic catheter as timing reference advanced in the systemic venous atrium (SVA) through a superior approach in the presence of complete right femoral venous occlusion. The magnetic catheter is advanced antegradely through a baffle leak in the PVA. C shows both diagnostic catheters advanced through superior access, whereas the magnetic catheter is advanced retrogradely through the aorta and RV into the PVA. D depicts the inversion of the magnetic ablation catheter inside the residual RA of a patient of group B after retrograde access through the aorta and through the double-inlet left ventricle. REF indicates reference catheter; ABL, magnetic ablation catheter; Endo, endovascular; A, atrial; and V, ventricular.
280 ms (Q1 to Q3, 240–350 ms) for the 1st (inducible) tachycardia.

**Three-Dimensional Image Registration**

Image registration was achieved initially by manual alignment of the 3D reconstructions on the 2 fluoroscopic reference images on the magnetic navigation system. Careful positioning in both right and left anterior oblique projections, aligning the 3D reconstructions to the cardiac silhouette, allowed a “first step” registration for the subsequent 3D electroanatomic maps. In all patients, the first reconstructed atrial chamber was the one reached by venous vascular access (systemic venous atrium [SVA] in group A, TCPC in group B). Once bystander activation was confirmed for these chambers, a second step of image registration was performed by 3D reconstructing the aorta (arch and root) followed by surface registration.

**Tachycardia Substrates in Group A**

Median tachycardia cycle lengths were shorter in group A (250 ms (Q1 to Q3, 230–300 ms), and all were located in the pulmonary venous atrium (PVA), with the exception of 1 patient in whom the location was in the SVA (Table 2). All PVA ATs consisted of reentrant circuits with a critical isthmus around the tricuspid annulus or around a scar in the superior part of the PVA (Figure 4, left panel). Five patients in group A had a single inducible tachycardia, whereas the remaining 4 had multiple inducible ATs. When the clinical/presenting tachycardia was treated, the sites of origin of subsequently induced tachycardia were more likely to be located in the SVA (6 of 8). Interestingly, only subsequently induced AT were potentially of focal substrate (3 of 8 subsequently induced AT).

In all patients, the PVA was accessed by using a retrograde arterial approach and the magnetic navigation system to advance the soft magnetic ablation catheter across the aortic valve and subsequently across the tricuspid annulus in a remote-controlled fashion. If present, mapping and ablation were also attempted through a baffle leak (Figures 1D and 3B). By taking advantage of the image fusion option of CARTO and also the magnetic navigation system with picture-in-picture display of the acquired map and real-time depiction of the mapping catheter, full 3D electric reconstructions during AT could be achieved in all patients.

**Tachycardia Substrates in Group B**

In all patients, the tachycardia substrate was located in the “native” atria outside the intra-atrial lateral tunnel (Table 2). The index AT had median cycle length of 320 ms (Q1 to Q3, 285–355 ms). As a first step in the diagnostic work flow, entrainment stimulation was performed from the diagnostic catheter positioned within the tunnel as a timing reference for the 3D electroanatomic mapping system. This showed clear bystander activation in all 4 cases. In 3 patients, the critical isthmus of the reentran tachycardia was located in the “classic” isthmus between the right AV valve annulus and the scar at the posterior wall of the remaining part of the original right-sided atrium (Figure 4, middle panel). In 1 patient with right atrial isomerism and twin AV nodes, an AV nodal–to–AV nodal reentrant tachycardia was reproducibly inducible and was abolished by ablation of the inferior AV node (Figure 4, right panel). No additional ATs other than the index AT were inducible in the patients in group B.

**Catheter Ablation**

After conventional electrophysiology maneuvers had confirmed the underlying tachycardia substrate suggested by the 3D mapping information, sequential point-by-point catheter ablation was performed. If necessary, “inversion” of the ablation tip was performed to enhance catheter tissue contact, with a large loop in the target chamber to allow the ablation catheter tip to achieve perpendicular rather than parallel tissue contact (Figure 3D). This was attempted especially at the ventricular aspect of a linear lesion.

To verify successful ablation after termination of the AT during radiofrequency delivery, completeness of the deployed linear lesion was assessed by 3D remapping during constant pacing from an electrode closely located to the ablation line. Widely split double potentials along the deployed ablation line were documented. Additionally, all patients underwent a burst pacing protocol starting at 400 ms with stepwise reduction (by 20 ms) until atrial refractoriness was reached or a tachycardia was induced. This protocol was repeated at the end of the 20-minute waiting time.

**Procedural Details**

Procedure parameters amounted to a median procedure duration (from puncture to sheath removal) of 222 minutes (Q1 to Q3, 174–258 minutes), with no relevant difference between group A (median, 225 minutes) and group B (median, 235 minutes). Of note, in both groups, total radiation exposure time was very low—4.3 minutes in all patients (Q1 to Q3, 2.6–6.7 minutes). This differed between the groups: group A, 3.8 minutes (Q1 to Q3, 2.4 – 6.1 minute), and group B, 5.9 minutes (Q1 to Q3, 4.5–8.9 minutes). Total radiation dosage was estimated to a median of 251 cGy2 in group A and 963 cGy2 for group B. Total ablation time was longer in group A, with 39.7 minutes in median (Q1 to Q3, 16.1–48.2 minutes) in comparison to group B, with a median of 24.9 minutes (Q1 to Q3, 18.2–30.5 minutes).

Conversion to transbaffle or transhepatic puncture was not necessary, and no patient was exposed to iodinated contrast.

All patients were extubated immediately after the ablation procedure. Postablation recovery was unremarkable apart from 1 patient who sustained a hemothorax as a consequence of central jugular venous catheter inserted during anesthesia. Transthoracic echocardiography before discharge excluded the presence of any pericardial effusion and reconfirmed no change in valvular function from retrograde access.

**Crossover to Conventional Catheter Techniques**

Because of the unavailability of irrigated-tip magnetic ablation catheters for the first patients of this series, only solid-tip catheters (8-mm or 4-mm tip) could be used. In 1 patient (patient 1 of group A), after having reconstructed the whole activation sequence during tachycardia in the PVA using magnetic navigation and confirmation of the critical isthmus of the reentrant circuit using entrainment stimulation, no

Downloaded from http://circarrhy.chirg.org by guest on Jul 5, 2017
adequate lesion could be deployed by using an 8-mm-tip catheter, and the tachycardia persisted. In the light of the proven higher incidence of thrombus formation on 8-mm, solid-tip catheters, the ablation catheter was exchanged with a conventional irrigated-tip ablation catheter (Navistar ThermoCool, Biosense Webster). Using the same retrograde approach, positioning of this catheter along the incomplete ablation line in the PVA proved to be technically very challenging. The procedure was finally abandoned, and a further procedure was performed once a magnetic irrigated-tip ablation catheter became available. Because of the need of direct visualization of the much stiffer conventional catheter, total fluoroscopy duration amounted to 11.3 minutes (the longest exposure time in this cohort). In 1 patient of group B (patient 11, see Table 2) only a 4-mm, solid-tip catheter was available, and again, despite complete mapping information and positive entrainment, no adequate lesion formation was possible. Changing to a conventional irrigated-tip ablation catheter (same as in the other patient), complete lesion deployment was achieved and tachycardia was terminated. Again, switching to the conventional technique prompted an increase in fluoroscopy exposure (15.4 minutes).

### Table 2. Procedure Parameters for Group A and Group B Patients

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Underlying Anatomy</th>
<th>Target Atrial Chamber</th>
<th>CL of SVT, ms</th>
<th>Procedure Duration, min</th>
<th>Total Fluoroscopy, min</th>
<th>Transbaffle Access</th>
<th>Procedural Success</th>
<th>Switch to Conventional</th>
<th>Follow-Up Rhythm (Meds)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>TGA, Mustard OP at age 1 y, re-do surgery at 5 y, DDD pacemaker 2004, 2 previous ablation attempts</td>
<td>PVA</td>
<td>1 (370)</td>
<td>210</td>
<td>11.3</td>
<td>N</td>
<td>N</td>
<td>Y (only 8-mm magnetic tip available)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>TGA, Mustard OP at age 1.9 y, re-do surgery at 2.9 y</td>
<td>PVA, SVA</td>
<td>3 (260, 320, 400)</td>
<td>315</td>
<td>3.5</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>SR/Aplp (none)</td>
</tr>
<tr>
<td>3</td>
<td>TGA, Mustard OP at age 3 mo, revision of Mustard at age 2 y</td>
<td>PVA</td>
<td>1 (250)</td>
<td>240</td>
<td>7.5</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>SR (β-blocker)</td>
</tr>
<tr>
<td>4</td>
<td>TGA, Mustard OP at age 10 mo, small residual VSD</td>
<td>SVA</td>
<td>1 (220)</td>
<td>115</td>
<td>2.37</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>SR (none)</td>
</tr>
<tr>
<td>5</td>
<td>TGA with VSD, Mustard OP at age 4 y</td>
<td>PVA</td>
<td>1 (220)</td>
<td>190</td>
<td>5.4</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>TGA, Mustard OP at age 13 mo, 2 previous ablations</td>
<td>PVA, SVA</td>
<td>2 (240, 250)</td>
<td>175</td>
<td>6.1</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>TGA, Senning OP at 2 y, DDD pacemaker 2007, 1 previous ablation</td>
<td>PVA</td>
<td>1 (300)</td>
<td>326</td>
<td>2.1</td>
<td>N (but baffle leak present)</td>
<td>Y</td>
<td>N</td>
<td>SR/Aplp (none)</td>
</tr>
<tr>
<td>8</td>
<td>TGA, Mustard OP at age 2 y, DDD pacemaker 2007, 1 previous ablation</td>
<td>PVA, SVA</td>
<td>2 (280, 300)</td>
<td>219</td>
<td>1.6</td>
<td>Y (through baffle leak)</td>
<td>Y</td>
<td>N</td>
<td>SR/Aplp (none)</td>
</tr>
<tr>
<td>9</td>
<td>TGA, Mustard OP, baffle leak</td>
<td>PVA, SVA</td>
<td>2 (400, 490)</td>
<td>250</td>
<td>2.1</td>
<td>Y (through baffle leak)</td>
<td>Y</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td><strong>Group B</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Absent left AV connection, univentricular AV connection, fenestrated TCPC, interventional closure of fenestration</td>
<td>Residual RA</td>
<td>1 (270)</td>
<td>260</td>
<td>6.7</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>SR (amiodarone, β-blocker)</td>
</tr>
<tr>
<td>11</td>
<td>Tricuspid atresia, pulmonary stenosis, VSD, Fontan, TCPC conversion 2005, 1 previous ablation</td>
<td>Residual RA</td>
<td>1 (370)</td>
<td>210</td>
<td>15.4</td>
<td>N</td>
<td>Y</td>
<td>Y (only 4-mm solid-tip magnetic)</td>
<td>SR (none)</td>
</tr>
<tr>
<td>12</td>
<td>Double-inlet left ventricle, discordant VA connections, Fontan, TCPC 1988</td>
<td>Residual RA</td>
<td>1 (290)</td>
<td>165</td>
<td>5.0</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>SR (β-blocker) patient died 1 y after ablation (age 47 y)</td>
</tr>
<tr>
<td>13</td>
<td>RA isomerism, common AV, AVSD, TCPC 1995, Amplatzer device between SVC and RA junction</td>
<td>Twin AV nodal-to-AV nodal reentrant tachycardia</td>
<td>1 (350)</td>
<td>440</td>
<td>2.9</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>SR (none)</td>
</tr>
</tbody>
</table>

Σ for group A median (Q1 to Q3) 260 (235–355) 225 (190–250) 3.8 (2.4–6.1)

Σ for group B median (Q1 to Q3) 320 (265–355) 235 (198.8–365) 5.9 (4.5–8.9)

OP indicates operation; DDD, dual-chamber pacemaker; CL, cycle length; SVT, supraventricular tachycardia; SR, sinus rhythm; parox, paroxysmal; AVSD, atrioventricular septal defect; VA, ventricular atrial; AV, atrioventricular; AT, atrial tachycardia; SVA, systemic venous atrium; SVC, superior vena cava; RA, right atrium; PVA, pulmonary venous atrium; ApVp, sequentially paced through DDD pacemaker; and TCPC, total cavopulmonary connection.
No other patient required crossover to a conventional ablation catheter.

**Follow-Up Results**

During a median follow-up time of 201 days (Q1 to Q3, 159–399 days), 10 patients remained in sinus rhythm and have not had any further sustained palpitations. Two patients were sequentially paced through devices implanted before the ablation procedures and had no evidence of atrial arrhythmia burden on device interrogation. One patient from group B, who was taking a β-blocker and in stable sinus rhythm, died at age 47 years, 22 years after conversion of an atrio-pulmonary Fontan operation to TCPC and more than 1 year after the ablation procedure. Finally, 1 patient from group A, who initially presented with permanent AT, had recurrent short-lasting focal ATs despite antiarrhythmic therapy with amiodarone and a β-blocker. There was no evidence of damage to valvular structures caused by the retrograde access for any of the patients demonstrated by transthoracic echocardiography during follow-up.

**Discussion**

The majority of index arrhythmias in our study originated from atrial chambers that were no longer accessible by a transvenous approach. Remote-controlled catheter ablation by magnetic navigation in combination with accurate 3D image integration allowed safe and successful elimination of these arrhythmias through the use of an exclusively retrograde approach and resulted in very low radiation exposure despite the complexity of the overall procedure.

Arrhythmia mechanisms in adults after intra-atrial baffle procedures vary according to the underlying anatomic defect and method of surgical repair or palliation but focus mainly on surgically acquired scars combined with chamber enlargement as a consequence of abnormal pressure and volume loading. Catheter ablation of atrial arrhythmia in these patient cohorts poses a number of technical challenges. First, although the tachycardia substrate is mostly based on scar-related reentrant circuits, some patients can present with focal AT. Identification of a focal substrate in the presence of scarred atria with significant conduction delay may be difficult and hence an accurate diagnosis using all conventional techniques in combination with the 3D mapping information is of paramount importance. Second, direct access to the target chamber may be limited after intra-atrial baffle procedures as in all but 1 patient presented in this report. One option is a transvenous approach with perforation of the baffle either under fluoroscopic or intracardiac echocardiographic guidance. However, the rigidity of the baffle material adds to the difficulty of this method. Similarly, gaining access to the functional PVA in a retrograde arterial fashion is also technically challenging when performed with the use of conventional catheters. This is because of the limitation of the curve radius of pull-wire–equipped catheters. Furthermore, crossing 2 cardiac valves in addition to a 180° turn in the aortic arch reaches the limit of steerability of any conventional catheter. Even with correct orientation and appropriate manipulation of the mapping catheter, expert manual and 3D visualization skills are required. However,
there is always a risk of dislodgment and perforation, even in the most experienced hands. Magnetic navigation, with its soft catheter shaft and head-on navigation, allows all sites to be reached even within the most complex anatomy because there is no limitation to curve radius or reach (Figure 3). The floppy distal end of the magnetic catheter allows free alignment of the embedded magnets in the outer magnetic field, so there is virtually no risk of perforation. The versatility of the magnetic catheter compensates even in situations such as total femoral venous occlusion (patient 7 in group A). Third, appropriate energy delivery at the critical site is the essential step of each ablation procedure. Because the contact force at the tip of a magnetically guided ablation catheter is probably never larger than 5–10 g at maximum, stability and minimization of beat-to-beat changes in local electrograms must be observed closely. Inversion of the catheter tip, leaning the shaft of the catheter along the wall, may help to improve stability and complete lesion deployment (Figure 3D). Irrigated-tip technology allows an increase in the amount of delivered energy without the risk of thrombus formation, which larger electrodes might predispose to. In 1 patient, when an irrigated magnetic ablation catheter was not yet available, the procedure was finally abandoned because a conventional ablation catheter could not be positioned stable enough at the ablation target and ablation failed to terminate the arrhythmia. The reluctance to use an 8-mm solid tip for multiple high-energy application on the systemic side was shared by other groups in similar patient cohorts.

The Role of Image Integration in Complex Ablation in Adult Congenital Heart Disease

Normal cardiac anatomy differs substantially from patient to patient, but these individual differences can be easily understood from positions of catheters, for example, inside the coronary sinus, at the free wall of the right atrium, and the His bundle region. The spatial relationship of these catheters depicted in (several) standard projections allows the operator to mentally “envisage” the individual cardiac structures. After intra-atrial baffle procedures, however, orientation and spatial relationships are often difficult to understand; distortion, cardiac dilatation, and progressive fibrosis can result from growth and advancing age. Accurate 3D image information is key to understanding the complex nature of the underlying cardiac morphology, and careful preprocedure planning should include not only details of cardiac anatomy but also the potential sites of vascular access (Figures 2 and 3). Potential limitations such as baffle obstruction, the location of key structures such as the ostium of the coronary sinus, and sites of baffle leaks can easily be understood. Study of 3D reconstruction allows choosing the best approach for an individual patient, reserving potentially more challenging procedures such as transbaffle or transhepatic punctures for those rare patients in whom a retrograde arterial access is impossible (eg, metallic prosthetic valve).

Access to Target Chambers: Transbaffle or Transhepatic Punctures Versus the Retrograde Approach

Various techniques have been reported to overcome the anatomic “hurdles” when attempting to access the PVA in patients after Mustard or Senning procedures when using conventional ablation catheters. Several groups have reported on their experience treating patients with intra-atrial baffle procedures in the past by using various access routes. Transbaffle punctures can be safely performed in experienced hands, although some authors prefer the retrograde over a transbaffle approach or vice versa, especially when using a bidirectional catheter. As an alternative, a transbaffle puncture from the right jugular vein has been described in conjunction with intracardiac echocardiography in a Mustard patient with blocked femoral vein. The procedure duration and the total fluoroscopy time amounted to 278±78 and 20±15 minutes, respectively, when using intracardiac echocardiography.

Khairy et al reported on a sternotomy approach to access the atria of a patient with univentricular heart as an alternative technique. A direct transthoracic puncture technique was described by Nehgme et al in 5 patients (6 procedures) after lateral tunnel Fontan operation that required a mean 4.1-hour procedure time and 48.6 minutes of fluoroscopy. Recently, a percutaneous transhepatic access was described in 2 patients with interruption of the inferior caval vein, which subsequently required catherization of the hepatic tract in 1 patient and positioning of an Amplatzer vascular plug in the second patient to stop intra-abdominal bleeding. Conversion to transbaffle or alternative punctures (transhacric or transhepatic) was necessary in none of our patients.

Reduced Radiation Exposure With Remote Navigation

Our experience of very low fluoroscopic exposure is similar to that reported by others during mapping and/or ablation of atrial arrhythmias in adult congenital heart disease patients, using magnetic navigation. This effect is the result of the nonfluoroscopic real-time 3D depiction of the tip of the ablation catheter on the 2 reference screens of the magnetic navigation system, thereby reducing the need to locate the ablation catheter by fluoroscopy. Compared with published reports using the same 3D mapping system but without remote navigation, the reduction in radiation exposure is within a factor of 10. Khairy et al reported on a sternotomy approach to access the atria of a patient with univentricular heart as an alternative technique. We believe this is particularly important in these young patients with complex congenital heart disease who are likely to have had significant cumulative radiation exposure from previous investigations and will need to undergo further diagnostic and therapeutic procedures over their lifetime. The importance of image integration for the overall low radiation exposure of our patients is further emphasized by the fact that none of our patients received contrast injections to delineate their intracardiac anatomy.

Location of Arrhythmia Substrates After Intra-Atrial Baffle Procedures

In our preliminary experience in a small number of patients, all index arrhythmia originated in the former right atrium and all but 1 were of a reentrant mechanism. Only subsequently induced arrhythmias were located in the SVA and/or of focal origin. Magnetic navigation facilitates access to all sites in complex congenital anatomy and thereby allows a complete 3D reconstruction of the cardiac activation during ongoing
tachycardia. For example, without complete mapping of the PVA, a reentrant tachycardia may masquerade as a focal SVA tachycardia (Figure 4, left and middle panels). By reaching all sites using magnetic navigation, this information is more complete than with conventional 3D mapping, which is limited in its ability to reach certain areas (eg, inside the PVA). Because of the flexible catheter shaft, all positions can be reached without fear of causing perforation, which again is reflected by the reduced fluoroscopy exposure.

Limitations
This is a single-center experience that highlights a novel technique to treat atrial arrhythmias in patients after intra-atrial baffle procedures. Although none of our patients had any problems with the use of the retrograde approach with the remote navigation system, damage to the semilunar or AV valves could be potentially inflicted, although this risk is low even in children when conventional catheters are used. Applying this technique to a larger patient cohort might demonstrate disadvantages that cannot be anticipated at this stage.

The alternative technique of a transbaffle approach in group A has not been compared in a head-to-head fashion with our technique and therefore no claim of superiority can be made.

Conclusions
In our patients, after intra-atrial baffle procedures (Mustard, Senning, or intracardiac lateral tunnel total cavo-pulmonary connection), almost all index arrhythmias originated from atrial chambers that were no longer accessible by a transvenous approach. Remote-controlled catheter ablation by magnetic navigation in combination with accurate 3D image integration allowed safe and successful elimination of these arrhythmias through the use of an exclusively retrograde approach, resulting in very low radiation exposure despite the complexity of the overall procedure.

Sources of Funding
This study was supported by the NIHR Cardiovascular Biomedical Research Unit at the Royal Brompton and Harefield NHS Foundation Trust and Imperial College London.

Disclosures
Dr Ernst is a consultant for Stereotaxis Inc and Biosense Webster.

References
20. Deleted in proof.
26. Kanter RJ, Papagiannis J, Carboni MP, Ungerleider RM, Sanders WE, Wharton JM. Radiofrequency catheter ablation of supraventricular tachycardia substrates after Mustard and Senning operations for


CLINICAL PERSPECTIVE

Atrial arrhythmias are a significant contributor to morbidity in adult congenital heart disease patients and may be a marker of adverse outcome. They may be poorly tolerated hemodynamically and or superimpose a tachycardia-mediated cardiomyopathy on already impaired ventricular mechanics. Catheter ablation in the presence of complex congenital heart disease is technically challenging, but exploiting the advantages of novel technologies might further improve success rates and reduce potential procedural risks. Integration of 3D images provides an anatomic roadmap to allow planning of first-line and alternative access routes to specific cardiac regions. Magnetic navigation, due to the flexible tip of the mapping and ablation catheter, can reach even difficult to reach regions in these complex patients. By combining image integration and remote navigation, total procedure duration and total fluoroscopy exposure were shortened. Applying the same strategy for patients after intra-atrial baffle operations to other complex congenital heart disease patients (in particular those in whom direct access to the cardiac chamber of interest is no longer available) will test the readiness of this method for broader groups. Although this method is not necessarily available in many centers, larger collaborative groups with expertise in electrophysiology and congenital heart disease have the opportunity to join forces to enable optimal treatment.
Remote-Controlled Magnetic Navigation and Ablation With 3D Image Integration as an Alternative Approach in Patients With Intra-Atrial Baffle Anatomy

Sabine Ernst, Sonya V. Babu-Narayan, Jennifer Keegan, Irina Horduna, Jonathan Lyne, Janice Till, Philip J. Kilner, Dudley Pennell, Michael L. Rigby and Michael A. Gatzoulis

_Circ Arrhythm Electrophysiol._ 2012;5:131-139; originally published online November 7, 2011; doi: 10.1161/CIRCEP.111.962993

_Circulation: Arrhythmia and Electrophysiology_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231

Copyright © 2011 American Heart Association, Inc. All rights reserved.
Print ISSN: 1941-3149. Online ISSN: 1941-3084

The online version of this article, along with updated information and services, is located on the World Wide Web at:

http://circep.ahajournals.org/content/5/1/131

**Permissions:** Requests for permissions to reproduce figures, tables, or portions of articles originally published in _Circulation: Arrhythmia and Electrophysiology_ can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

**Reprints:** Information about reprints can be found online at:
http://www.lww.com/reprints

**Subscriptions:** Information about subscribing to _Circulation: Arrhythmia and Electrophysiology_ is online at:
http://circep.ahajournals.org//subscriptions/