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

Running title: Ernst et al.; Magnetic navigation in congenital heart disease

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Journal Subject Codes: [22] Ablation/ICD/surgery; [30] CT and MRI; [106] 
Electrophysiology; [41] Pediatric and congenital heart disease, including cardiovascular surgery
Abstract:

**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 (MN) in conjunction with 3D image integration in patients with previous intra-atrial baffle procedures.

**Methods and Results** - Thirteen patients (8 m, 30.5 ± 8 yrs) with supraventricular tachycardia (SVT) underwent catheter ablation. Group A had a past medical history of a Mustard or Senning operation, while group B had undergone total cavopulmonary connection (TCPC). 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 in all but 1 patient located in the remainder of the morphological right atrium. Retrograde access via the aorta was performed and led to successful ablation using MN with a very low total radiation exposure (median of 3.8 min in group A versus 5.9 min in group B). Only one out of 13 patients continued to experience short-lasting SVTs despite 3 ablation procedures during a median follow-up time of > 200 days.

**Conclusions** - Remote controlled catheter ablation by MN 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 following intra-atrial baffle procedures (Mustard, Senning or TCPC).

**Key words:** Magnetic navigation, catheter ablation, Mustard/Senning procedure, total cavopulmonary connection
Introduction

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 have to be understood in the presence of complex anatomy which may limit accessibility\(^8\)\(^,\)\(^9\). Since 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 (MN) facilitated by 3D image registration and electroanatomical mapping in patients with previous intra-atrial baffle procedures.

Methods

Patient cohort

From May 2008 a total of 13 patients (8 male, mean age 30.5± 8 yrs) with documented supraventricular tachycardia, either incessant (6) or intermittent (7), underwent catheter ablation procedures using MN via a retrograde arterial access. Patients were classified into group A with a past medical history of a Mustard\(^10\) or Senning\(^11\) 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 technique\(^12\) (in median 26 years previously). Table 1 summarizes the patient’s demographics.
Pre ablation 3D imaging and image processing

All patients underwent pre-ablation imaging studies using non-contrast cardiovascular magnetic resonance (CMR) or, in the presence of an implantable device, cardiac computed tomography (CT) (Table 1). For CMR imaging, a free breathing, diaphragm navigated balanced steady-state free precession (bSSFP) sequence with 3-dimensional (3D) reconstruction performed to image the whole heart (Figure 1). All pre-acquired 3D imaging DICOM data was processed in order to obtain 3D reconstructions to fuse with the 3D mapping information (POLARIS software, Biosense Webster, Brussels, Belgium) (Figure 1 and 2).

Remote controlled electrophysiology study

All procedures were performed in the presence of an experienced cardiac anaesthetist with continuous invasive blood pressure monitoring via either radial or brachial arterial lines. All patients were studied under general anaesthesia (iv. Propofol and Remifentanil) and vascular access (7 and 8 French sheath) was gained via the femoral veins in all patients but one (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 via both subclavian veins. Finally in another patient (patient #8 of group A), the right femoral vein was thrombosed and alternative venous access was gained via a subclavian vein. To allow retrograde access via the aortic valve a single 8 French vascular access was gained via the femoral artery (right or left depending on pre-existing scars from previous operations/procedures).

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

A multipolar steerable diagnostic catheter (6 French, Parahis, Biosense Webster, Brussels, Belgium) was used as the timing reference in the accessible chamber from a venous vascular access (e.g., appendage of the systemic venous atrium in Mustard/Senning patients) in group A or positioned inside the TCPC in group B. A quadripolar non-steerable catheter was positioned in the ventricle in case of reduced AV conduction properties (Biosense Webster, Brussels, Belgium). For patients in sinus rhythm at the beginning of the procedure (n= 7 pts), atrial (and ventricular) stimulation was performed to induce the clinically documented arrhythmia (Figure 3).

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

**Statistical analysis**

Values are expressed either as mean with 1 standard deviation or median with first to third quartile (Q1-3). Due to 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 280 ms (Q1-3, 240 – 350 ms) for the 1st (inducible) tachycardia.

3D 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 electroanatomical maps. In all patients, the first reconstructed atrial chamber was the one reached by venous vascular access (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 (table 2)

Median tachycardia cycle lengths were shorter in group A (250 ms (Q1-3, 230 – 300 ms) and all were located in the pulmonary venous atrium (PVA) with the exception of one patient in whom the location was in the systemic venous atrium (SVA). All PVA ATs consisted of re-entrant 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 out of 8). Interestingly only subsequently induced AT where potentially of focal substrate (3 of 8 subsequently induced AT).

In all patients, the PVA was accessed 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 was also attempted via 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 electrical reconstructions during AT could be achieved in all patients.

**Tachycardia substrates in group B (table 2)**

In all patients, the tachycardia substrate was located in the “native” atria outside the intra-atrial lateral tunnel. The index AT had median cycle length of 320 ms (Q1-3, 285 – 355 ms). As a first step in the diagnostic workflow, entrainment stimulation was performed from the diagnostic catheter positioned within the tunnel as a timing reference for the 3D electroanatomical mapping system. This showed clear bystander activation in all 4 cases. In 3 patients, the critical isthmus of the re-entrant tachycardia was located in the “classical” 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 re-entrant 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 manoeuvres 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 RF 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 min waiting time.

Procedural details

Procedure parameters amounted to a median procedure duration (from puncture to sheath removal) of 222 min (Q1-3, 174 – 258 min) with no relevant difference between group A (median 225 min) and group B (median 235 min). Of note, in both groups total radiation exposure time was very low; all patients 4.3 min (Q1-3, 2.6 – 6.7 min). This differed between the groups; group A 3.8 min (Q1-3, 2.4 – 6.1 min) and group B 5.9 min (Q1-3, 4.5 – 8.9 min). Total radiation dosage was estimated to a median of 251 cGym² in group A and 963 cGym² for group B. Total ablation time was longer in group A with 39.7 min in median (Q1-3, 16.1 – 48.2 min) in comparison to group B with a median of 24.9 min (Q1-3, 18.2 – 30.5 min).
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. Post-ablation recovery was unremarkable apart from one patient who sustained a hemothorax as a consequence of central jugular venous catheter inserted during anaesthesia. Transthoracic echocardiography pre-discharge excluded the presence of any pericardial effusion and re-confirmed no change in valvular function from retrograde access.

**Cross-over to conventional catheter techniques**

Due to the unavailability of irrigated-tip magnetic ablation catheters for the first patients of this series, only solid tip catheters (8mm or 4 mm tip) could be used. In 1 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 re-entrant circuit using entrainment stimulation, no adequate lesion could be deployed using an 8mm tip catheter and the tachycardia persisted. In the light of the proven higher incidence of thrombus formation on 8mm 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 performed, once a magnetic irrigated-tip ablation catheter became available. Due to the need of direct visualisation of the much stiffer conventional catheter, total fluoroscopy duration amounted to 11.3 min (the longest exposure time in this cohort). In one patient of group B (#11, see table 2) only a 4mm 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 other patient) complete lesion deployment was achieved and tachycardia terminated. Again switching to the conventional technique prompted an increase in fluoroscopy exposure (15.4 min).

No other patient required cross-over to a conventional ablation catheter.

**Follow up results**

During a median follow-up time of 201 days (Q1-3, 159 – 399 days), 10 patients remained in sinus rhythm and have not experienced any further sustained palpitations. Two patients were sequentially paced via devices implanted prior to the ablation procedures and had no evidence of atrial arrhythmia burden on device interrogation. One patient from group B, who was on a beta blocker and in stable SR, died aged 47 years, 22 years following 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 anti-arrhythmic therapy with Amiodarone and a beta blocker. There was no evidence of damage to valvular structures due to 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 using 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. Firstly, although the tachycardia substrate is mostly based on scar-related re-entrant 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. Secondly, direct access to the target chamber may be limited after intra-atrial baffle procedures as in all but one patient presented here. 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 using 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 degree 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 dislodgement 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\textsuperscript{14,20,21}, since 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 that there is virtually no risk of perforation\textsuperscript{20}. The versatility of the magnetic catheter compensates even in situations such as total femoral venous occlusion (patient #7 in group A). Thirdly, appropriate energy delivery at the critical site is the essential step of each ablation procedure. Since the contact force at the tip of a magnetically guided ablation catheter is probably never larger than 5-10 grams at maximum, stability and minimization of beat-to-beat changes in local electrograms have to be observed closely\textsuperscript{22}. 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 one patient where an irrigated magnetic ablation catheter was not yet available, the procedure was finally abandoned since 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 8mm solid tip for multiple high energy application on the systemic side was shared by other groups in similar patient cohorts\textsuperscript{20}.

\textit{The role of image integration in complex ablation in ACHD}

Normal cardiac anatomy differs substantially from patient to patient, but these individual differences can be easily understood from positions of catheters eg. 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\textsuperscript{23, 24} and careful pre-procedure planning should include not only details of cardiac anatomy but also the potential sites of vascular access (Figure 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 trans-baffle or trans-hepatic punctures for those rare patients in whom a retrograde arterial access is impossible (eg. Metallic prosthetic valve)\textsuperscript{9, 18, 19, 25}.

Access to target chambers: transbaffle or transhepatic punctures versus the retrograde approach

Various techniques have been reported to overcome the anatomical “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 using various access routes\textsuperscript{26-31}. 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\textsuperscript{32}. As an alternative, a transbaffle puncture from the right jugular vein has been described in conjunction with intracardiac echocardiography (ICE) in a Mustard patient with blocked femoral vein. The procedure duration and the total fluoroscopy time amounted to 278±78 and 20±15 min in mean\textsuperscript{19} when using ICE.
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 hours procedure time and 48.6 min of fluoroscopy. Recently, a percutaneous transhepatic access was described in 2 patients with interruption of the inferior caval vein, which subsequently required cauterization of the hepatic tract in 1 patient and positioning of an Amplatzer vascular plug in the second patient to stop intraabdominal bleeding. In none of our patients conversion to transbaffle or alternative punctures (transthoracic or transhepatic) was necessary.

**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 ACHD patients using magnetic navigation. This effect is the result of the non-fluoroscopic 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 to published reports using the same 3D mapping system but without remote navigation, the reduction in radiation exposure is within a factor of 10. 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.
The 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 one were of a re-entrant 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 re-entrant tachycardia may masquerade as a focal SVA tachycardia (refer to Figure 4 left and middle panel). 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 (e.g., inside the PVA). Due to 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 centre experience that highlights a novel technique to treat atrial arrhythmias in patients after intra-atrial baffle procedures. Although none of our patients experienced any problems using 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 using conventional catheters. Applying this technique to a larger patient cohort might demonstrate disadvantages, which 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, following 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 using an exclusively retrograde approach, resulting in very low radiation exposure despite the complexity of the overall procedure.

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

Conflict of Interest Disclosures: Sabine Ernst: Consultancy for Stereotaxis Inc and Biosense Webster

References:


<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>Gender</td>
<td>5 m/ 4 f</td>
<td>3 m / 1 f</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 (Q1-3) in years</td>
<td>28 (22-33)</td>
<td>17.5 (12-20.3)</td>
</tr>
<tr>
<td>Pre-ablation antiarrhythmic therapy</td>
<td>Rate control in 6 pts, Amiodarone in 3 pts</td>
<td>Sotalol in 1 pt, Amio in 1 pt, Rate control in 2 pts</td>
</tr>
<tr>
<td>Prev. ablation procedures before MN</td>
<td>In 4 pts (median of 2 procedures)</td>
<td>In 1 pt (1 procedure)</td>
</tr>
<tr>
<td>Implantable device</td>
<td>4 DDD (1 epicardial)</td>
<td>1 DDD</td>
</tr>
<tr>
<td>Pre- ablation 3D imaging (CMR vs CT)</td>
<td>5 CMR, 4 CT</td>
<td>3 CMR, 1 CT</td>
</tr>
</tbody>
</table>

Abbreviations: TGA transposition of the great arteries, TCPC total cavopulmonary connection, Q1 - 3 first and third quartiles, DDD dual chamber pacemaker, CMR cardiovascular magnetic resonance, CT computer tomography
<table>
<thead>
<tr>
<th>Pt</th>
<th>Underlying anatomy</th>
<th>Target atrial chamber</th>
<th>Number, (CL of SVT (ms))</th>
<th>Procedure duration (min)</th>
<th>Total fluoroscopy (min)</th>
<th>Trans-baffle access</th>
<th>Procedural success</th>
<th>Switch to conventional</th>
<th>Follow-up rhythm (meds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>TGA, Mustard OP @ age 1 year, re-do surgery @ 9 years, DDD pacemaker 2004, 2 prev. 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</td>
<td>(only 8mm magnetic tip available)</td>
</tr>
<tr>
<td></td>
<td></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 / ApVp, (none)</td>
</tr>
<tr>
<td>#2</td>
<td>TGA, Mustard OP @ age 1.9 years, re-do surgery @ 2.9 years</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 (Bblocker)</td>
</tr>
<tr>
<td>#3</td>
<td>TGA, Mustard OP age 3 months, revision of Mustard aged 2 years</td>
<td>PVA</td>
<td>1 (280)</td>
<td>230</td>
<td>4.31</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>SR (none)</td>
</tr>
<tr>
<td>#4</td>
<td>TGA, Mustard OP @ age 10 months, 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 @ age 4</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></td>
<td></td>
<td>PVA</td>
<td>1 (240)</td>
<td>175</td>
<td>6.1</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>#6</td>
<td>TGA, Mustard OP aged 13 months, 2 prev. ablations</td>
<td>PVA, SVA</td>
<td>2 (240, 250)</td>
<td>225</td>
<td>3.8</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>SR (Bblocker)</td>
</tr>
<tr>
<td>#7</td>
<td>TGA, Senning OP at 2 yrs, DDD pacemaker (epicardial), 3 previous ablation attempts, block both femoral veins</td>
<td>PVA</td>
<td>1 (300)</td>
<td>326</td>
<td>2.1</td>
<td>N</td>
<td>(but baffle leak present)</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>#8</td>
<td>TGA, Mustard OP aged 2 years, DDD pacemaker 2007, 1 prev. 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/ ApVp (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></td>
<td></td>
<td>PVA, SVA</td>
<td>4 (400, 420, 440, 490)</td>
<td>125</td>
<td>2.6</td>
<td>Both ways used</td>
<td>Y</td>
<td>N</td>
<td>Paroxysmal AT/ ectopy (Amio + BB)</td>
</tr>
</tbody>
</table>

| Σ for Group A | Median (Q1-3) | 260 (235 – 335) | 225 (190 – 250) | 3.8 (2.4 – 6.1) | 8 pts in SR, 1 pt with parox AT (Amio) |
### Group B

<table>
<thead>
<tr>
<th>Pt</th>
<th>Underlying anatomy</th>
<th>Target atrial chamber</th>
<th>Number, (CL of AT (ms))</th>
<th>Procedure duration (min)</th>
<th>Total fluoroscopy (min)</th>
<th>Trans-baffle access</th>
<th>Procedural success</th>
<th>Switch to conventional</th>
<th>Follow-up rhythm (meds)</th>
</tr>
</thead>
<tbody>
<tr>
<td># 10</td>
<td>Absent left AV connection, univentricular atrioventricular 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 (Amio, Bblocker)</td>
</tr>
<tr>
<td># 11</td>
<td>Tricuspid atresia, Pulmonary stenosis, VSD, Fontan, TCPC conversion 2005, 1 prev. 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, discoordant 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 (Bblocker) pt died 1 year post-ablation (aged 47)</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 nodes: AV nodal to AV nodal re-entrant 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 B Median (Q1-3) | 320 (285 – 355) | 235 (198.8 – 305) | 5.9 (4.5 – 8.9) | All in SR |

**Abbreviations:** OP operation, CL cycle length, SVT supraventricular tachycardia, SR sinus rhythm, parox paroxysmal, AVSD atrioventricular septal defect, VA ventricular atrial, AT atrial tachycardia, SVA systemic venous atrium, PVA pulmonary venous atrium, ApVp sequentially paced via DDD pacemaker, Bblocker betablocker
Figure Legends:

Figure 1. Three dimensional reconstruction of a CT scan (patient #7 of group A): depiction of the right subclavian vein (Fig. A) which was utilized for cardiac access after blocked femoral venous access bilaterally. Location of the epicardial pacemaker (PM, Fig. B). Arterial retrograde access via aorta, systemic right ventricle (RV) into the pulmonary venous atrium (PVA) in Figure C. Postero-anterior projection depicting a baffle leak between the systemic venous atrium (SVA) and the PVA (Fig. D).

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 via the aorta.

Figure 3. Different access for individual patients: A depicts 2 diagnostic catheters via femoral venous access (left ventricular lead for chronotropic incompetence during general anaesthesia). The magnetic catheter is advanced antegradely via the aorta and systemic right ventricle (RV) in the PVA. B shows a diagnostic catheter as timing reference advanced in the SVA via a superior approach in the presence of complete right femoral venous occlusion. The magnetic catheter is advanced antegradely via a baffle leak in the PVA. C shows both diagnostic catheters advanced via superior access, while the magnetic catheter is advanced retrogradely via 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 via the
aorta and through the double inlet left ventricle. Abbreviations: REF reference catheter, ABL magnetic ablation catheter, Endo endovascular, A atrial, V ventricular.

**Figure 4.** Right panels show a re-entrant tachycardia in the PVA (bottom) while the SVA 3D activation map mimics a focal activation sequence (top). The middle panel depicts bystander activation of the LA (top) in a re-entrant tachycardia in the residual RA (bottom). The left panel depicts the earliest atrial (top) and ventricular (bottom) activation during AV nodal to AV nodal re-entrant tachycardia in the presence of twin AV nodes. During tachycardia the ventricles are activated via the inferior AV node (inf AVN) which results in a narrow QRS complex with superior axis. Retrograde activation during tachycardia is via the superior AV node (sup AVN) that is located at the junction of the ventricular septal defect (VSD) and the common AV valve.
Remote Controlled Magnetic Navigation and Ablation with 3D Image Integration as an Alternative Approach in Patients with Intra-Atrial Baffle Anatomy

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Circ Arrhythm Electrophysiol. published online November 7, 2011;

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

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Print ISSN: 1941-3149. Online ISSN: 1941-3084

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