ABSTRACT. Background: Intra-atrial re-entrant tachycardia (IART) occurs frequently in patients after surgery for congenital heart disease. Electroanatomic voltage mapping has been used to identify the channels of conduction for this arrhythmia to propagate. Conventional voltage mapping has demonstrated that these channels occur between areas of scar, which are defined as tissue with bipolar atrial signals of <0.5 mV. To date, there has been limited investigation with other commercially available three-dimensional (3D) electroanatomic mapping systems. We aim to validate the use of electroanatomic voltage mapping to identify channels of conduction in patients with the Ensite NavXTM navigation and visualization technology and determine the optimal low-voltage setting to obtain reliable channels. Methods: All patients with IART after surgical repair of congenital heart disease, excluding the Fontan operation, who underwent catheter ablation and 3D electroanatomic voltage mapping using Ensite NavXTM from January 1 2005 to November 1 2009 were reviewed. The voltages of the bipolar atrial potentials recorded at each site were displayed using a color scale (“scar”, grey; lowest, red; highest, purple) to generate a 3D electroanatomic voltage map to delineate potential channels of conduction between boundaries of dense scar. Based on previously established standards using the CARTO system, the lower threshold to discriminate dense scar was set at 0.5 mV for all procedures. Post hoc analysis to determine the optimal voltage threshold to delineate channels of conduction was performed by generating serial voltage maps with scar defined as a voltage <0.5 mV decrementing by 0.1 mV to 0.1 mV. The critical channel of conduction was confirmed by entrainment of the IART and successful ablation. The optimal voltage threshold was defined as the lowest voltage setting at which the successfully ablated channel was still present. Results: Nine patients were identified: four with tetralogy of Fallot, one with congenitally corrected transposition of the great arteries, one with pulmonary atresia with intact ventricular septum, one with transposition of the great arteries and ventricular septal defect, and two with Ebstein’s anomaly. Electroanatomic atrial voltage maps were obtained with varying map densities (36–1358 pts, median 99). All patients were identified with single circuit atrial flutter with a median cycle length of 250 ms (range 230–460 ms) and successfully ablated. The median low-voltage threshold at which the successful pathway was still present was 0.3 mV (0.1–0.4 m). A low-voltage threshold of 0.5 mV identified only seven of nine pathways. By decreasing the lower threshold, we identified new, merging of old, and loss of existing pathways. The total number
of pathways identified was 19 at 0.5 mV, 18 at 0.4 mV, 19 at 0.3 mV, 15 at 0.2 mV, and eight at 0.1 mV. Of note, four of nine pathways had healthy tissue >1.5 mV in the active channel.

**Conclusions:** The Ensite NavX™ system was effective in delineating scar and channels via conventional electroanatomic voltage mapping, but the optimal threshold to generate these maps may be lower than the conventional low-voltage setting of 0.5 mV.

**KEYWORDS.** electroanatomic mapping, intra-atrial re-entrant tachycardia, heart disease.

**Introduction**

Intra-atrial reentrant tachycardia (IART) is a common finding in patients after congenital heart surgery. The reported incidence of IART ranges from 2% to 50% in patients after the Fontan procedure, the Mustard and Senning operation, and tetralogy of Fallot repair. Inability to control these arrhythmias can result in significant symptoms and ventricular dysfunction over time. Conventional mapping and catheter ablation has resulted in favorable short-term success rates approaching 90%, but with significant recurrence of close to 20% after 1 year. The limitations of conventional mapping include a tedious acquisition process, difficulty in arrhythmia localization due to the complexities of scar anatomy created by congenital surgery, and prolonged procedure times, which can all lead to incomplete success.

The advent of three-dimensional (3D) electroanatomic mapping has provided a modality to identify channels of conduction between boundaries of scar tissue that provide the substrate for IART to occur. Previous work using voltage mapping has been conducted and resulted in defining healthy tissue as a bipolar electrogram voltage signal of >1.5 mV, and scar as a voltage of <0.5 mV. The determination and subsequent clinical use of these threshold values was based on CARTO, an alternative 3D electroanatomic mapping system. We describe the use of Ensite NavX™ (St. Jude Medical, St. Paul, MN) navigation and visualization technology to generate accurate electroanatomic voltage maps which assist in the appropriate identification of channels of conduction in post-surgical congenital heart disease patients and to determine the optimal low-voltage setting for scar and channel identification.

**Methods**

Between January 1 2005 and November 1 2009, all patients with IART after surgical repair of congenital heart disease, excluding the Fontan operation, who underwent electrophysiology study and catheter ablation using Ensite NavX™ navigation and visualization technology were reviewed. Baseline patient data including type of congenital heart disease, age at end of study, age at last comprehensive surgery, age at onset of arrhythmia, age at ablation, presence or absence of recurrence, and time until recurrence of arrhythmia were described. Baseline electrophysiology study data including the type of arrhythmia, location of the circuit, cycle length of the tachycardia, number of mapping points, voltage in the successfully ablated channel, and fluoroscopic time were described.

All procedures utilized the Ensite NavX™ system during the electrophysiology study and catheter ablation. Peak-to-peak amplitude of bipolar atrial potentials were recorded and voltages at each site were used to generate a 3D color-coded endocardial voltage map using a graded color scale (‘‘scar’’, grey; lowest voltage, red; highest voltage, purple) for each patient. By previous convention, healthy tissue was identified as a local electrogram potential of >1.5 mV, and dense scar was identified as a local electrogram potential of <0.5 mV. Based on these standard voltage parameters, endocardial channels of conduction between boundaries of dense scar were identified, and the shortest distance between these boundaries was measured. The critical channel of conduction was confirmed by entrainment of the IART and successful ablation. The entrainment response was defined as a PPI-TCL <30 ms. All arrhythmias were considered macro-re-entrant tachycardia based on activation mapping with confirmation that 90% of the tachycardia cycle length was confined to the chamber of interest and the tachycardia was entrained.

A post hoc analysis of the endocardial voltage maps was undertaken to determine the optimal voltage settings needed to delineate dense scar from active atrial tissue to identify potential channels of conduction for IART to occur. The voltage of the bipolar atrial potential recorded at each site was displayed using a color scale, as mentioned earlier, to generate a 3D electroanatomic voltage map. Dense scar was identified on the map as regions of atrial tissue with voltage less than the set lowest atrial potential. Based on previously established standards, this was initially set at 0.5 mV. Serial voltage maps were subsequently generated to identify scar and channels of conduction for each patient by adjusting the lower voltage threshold from 0.5 mV to 0.1 mV in decrements of 0.1 mV. The channel of conduction was previously demarcated by location entrainment of the IART and the site of successful ablation. The optimal voltage threshold was defined as the lowest voltage setting at which the successfully ablated channel was still present.

**Results**

Nine patients were identified during this time period who had documented IART after surgery for congenital heart disease, excluding patients who underwent the Fontan operation. There were four patients with tetralogy of Fallot status after complete repair, one patient with congenitally corrected transposition status after heart transplantation, one patient with pulmonary
atrial septal defect and intact ventricular septum status after pulmonary valvotomy and the bidirectional Glenn procedure, two patients with Ebstein’s anomaly (one status post bidirectional Glenn and one status post tricuspid valve replacement), and one transposition of the great arteries with ventricular septal defect status after the arterial switch operation. The baseline demographics of the study group are listed in **Table 1**. The median age at the end of the study was 18.8 years (range 13.1–44.4 years); the median age at last major surgery was 6 years (range 0.04–13.6 years); and the median age at onset of arrhythmia was 17.8 years (range 12.2–39 years). All nine patients underwent successful ablation, with one recurrence at 2.8 years after ablation.

Baseline electrophysiologic study results are presented in **Table 2**. The median tachycardia cycle length was 250 ms (range 220–460 ms). The location of the critical channel varied. The median mapping density was 99 points (range 36–1358 points). The median fluoroscopy time was 54.5 min (range 36.2–125 min). The mean voltage of successfully ablated channels was 0.87 ± 0.82 mV (range 0.1–2.57 mV). A relatively high voltage foci (median 1.84 mV, range 1.83–2.53 mV) in the critical endocardial channel was identified at the site of successful ablation in four patients. The mean low-voltage setting used during the procedure was 0.36 mV (range 0.23–0.5 mV).

Post hoc generation of serial endocardial electroanatomic voltage maps was performed as described (**Figure 1**). Based on lowering the optimal low-voltage setting, the number of potential channels identified was 19, 18, 19, 15, and 8 at 0.5, 0.4, 0.3, 0.2, and 0.1 mV respectively (**Figure 2**). As expected, with lowering of the low-voltage threshold we identified new, merging of old, and loss of existing pathways. The mean channel widths were 17.3 ± 12.8 mm, 17.1 ± 7.2 mm, 18.3 ± 7.7 mm, 17.3 ± 8.6 mm, and 19.3 ± 14 mm from 0.5–0.1 mV by 0.1 mV decrements, respectively. The median low-voltage threshold until loss of successful pathway was a 0.3 mV (range 0.1–0.4 mV). The presence of the channel occurred at a median of 0.5 mV (range 0.3–0.5 mV). Based on entrainment of the IART and presence of the channel occurred at a median of 0.5 mV (range 0.3–0.5 mV). The mean channel widths were 17.3 ± 12.8 mm, 17.1 ± 7.2 mm, 18.3 ± 7.7 mm, 17.3 ± 8.6 mm, and 19.3 ± 14 mm from 0.5–0.1 mV by 0.1 mV decrements, respectively.

**Discussion**

We have demonstrated that the Ensite NavX™ navigation and visualization technology was an effective tool used to assist in the ablation of intra-atrial re-entrant tachycardia in patients after surgery for congenital heart disease. The electroanatomic voltage maps generated provided easy identification of the potential channels of conduction, and in conjunction with conventional mapping using entrainment this resulted in a high success rate.

**Acquisition and efficacy of electroanatomic voltage maps**

3D electroanatomic mapping systems have resulted in reduction in the time needed for pathway localization. However, acquisition of the voltage maps can be tedious and time consuming due to the need for point-to-point acquisition of local atrial electrograms. Our practice was to identify the area of interest and aim to acquire a minimum of 100 points. Because of anatomical considerations of the congenital heart disease, acquisition of the set number of points was not always achieved. This can result in significantly varied map densities, as demonstrated here, which are dependent on numerous factors including the operator, anatomic substrate, type of catheter used, and electrode spacing.

The voltage maps generated by utilizing the Ensite NavX™ navigation and visualization technology in this cohort despite the variability in map densities have demonstrated both electroanatomic and clinical efficacy. Seven of nine patients had accurate pathway identification using 3D electroanatomic voltage mapping with a lower bipolar atrial signal threshold of <0.5 mV to delineate scar. The ability to identify pathways by this modality takes on greater importance in situations where the anisotropic properties of the channel may lead to incorrect localization based on entrainment mapping.

**Table 1: Baseline demographics**

<table>
<thead>
<tr>
<th>Patient number</th>
<th>Age at end of study (years)</th>
<th>Congenital heart defect</th>
<th>Age at major surgery (years)</th>
<th>Age at onset of arrhythmias (years)</th>
<th>Age at ablation (years)</th>
<th>Recurrence</th>
<th>Duration arrhythmia free (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38.6</td>
<td>TOF</td>
<td>9.0</td>
<td>30</td>
<td>37.5</td>
<td>No</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>44.4</td>
<td>TOF</td>
<td>3.0</td>
<td>39</td>
<td>40.6</td>
<td>No</td>
<td>3.8</td>
</tr>
<tr>
<td>3</td>
<td>32.4</td>
<td>TOF</td>
<td>0.8</td>
<td>31.8</td>
<td>32.0</td>
<td>No</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>21.0</td>
<td>TOF</td>
<td>1.8</td>
<td>17.8</td>
<td>18.3</td>
<td>No</td>
<td>2.8</td>
</tr>
<tr>
<td>5</td>
<td>14.6</td>
<td>TGA/VSD</td>
<td>0.04</td>
<td>n/a</td>
<td>11.7</td>
<td>No</td>
<td>2.9</td>
</tr>
<tr>
<td>6</td>
<td>17.9</td>
<td>cc-TGA</td>
<td>13.6</td>
<td>14.5</td>
<td>15.3</td>
<td>No</td>
<td>2.6</td>
</tr>
<tr>
<td>7</td>
<td>18.8</td>
<td>Ebstein</td>
<td>13.0</td>
<td>n/a</td>
<td>15.0</td>
<td>Yes</td>
<td>2.8</td>
</tr>
<tr>
<td>8</td>
<td>13.1</td>
<td>Ebstein</td>
<td>12.2</td>
<td>12.2</td>
<td>13.0</td>
<td>No</td>
<td>0.1</td>
</tr>
<tr>
<td>9</td>
<td>16.5</td>
<td>PA/IVS</td>
<td>n/a</td>
<td>16.2</td>
<td>16.3</td>
<td>No</td>
<td>0.2</td>
</tr>
</tbody>
</table>

TOF: tetralogy of Fallot; TGA/VSD: transposition of the great arteries with ventricular septal defect; ccTGA: congenitally corrected transposition of the great arteries; Ebstein: Ebstein’s Anomaly; PA/IVS: pulmonary atresia with intact ventricular septum.
Using both of these modalities in tandem provides optimal results as seen by the 100% short-term success rate in our series. Based on these findings the Ensite NavX system is a useful clinical tool to assist in IART mapping and ablation.

Localization of endocardial circuits

Sites of successful ablation are based on conventional endocardial mapping using activation sequence, potential distribution, and morphology of signals. This is challenging in patients who have undergone surgery for congenital heart disease due to the significant variability in post-surgical anatomy that can result in complex anatomic scar in addition to functional scar boundaries. This results in multiple channels bounded by scar able to potentially propagate the IART with numerous exit and entrance points.30 3D electroanatomic voltage maps illustrate this quite well. Voltage criteria for healthy tissue and scar have been established based on biatrial electrogram signals. By convention, a lower voltage threshold of 0.5 mV is used to discriminate scar during our ablation cases. If 3D electroanatomic voltage maps were used in isolation, the result would be identification of numerous false-positive channels not integral to or a part of the re-entrant circuit. Understanding anatomic correlation as it pertains to potential locations of suture lines and incisions can further help in reducing the number of pathways that need to be evaluated. Ultimately, entrainment mapping was integral to defining the participating circuit in all of these cases.

Determination of the optimal electroanatomic voltage map

By convention, dense scar has been defined as any bipolar atrial electrogram <0.5 mV.24,25 As expected, patients with congenital heart disease can demonstrate significant portions of atrial tissue which meet this criteria.31 However, the importance of bipolar atrial electrogram voltages between 0.1 mV and 0.5 mV is unclear in this setting for identification for scar and potential low-voltage channels of conduction. In our series, two cases demonstrated peak voltages of <0.5 mV in the critical pathway that was successfully ablated. Without the use of entrainment mapping these pathways may have been missed using the conventional lower threshold of <0.5 mV. The impact of mapping density on this finding is unclear. Proper identification of scar-bound channels can be altered by adjusting the lower voltage threshold. This results in unmasking, loss, and merging of channels, which translate to variations in the number, size, and location of channels. In our series the number of channels

Table 2: Baseline electrophysiologic study characteristics of intra-atrial re-entrant tachycardia

<table>
<thead>
<tr>
<th>Patient number</th>
<th>Arrhythmia</th>
<th>CL (ms)</th>
<th>Location</th>
<th>Mapping points</th>
<th>Fluoroscopy time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IART</td>
<td>284</td>
<td>Lateral right atrium/tricuspid valve</td>
<td>99</td>
<td>54.5</td>
</tr>
<tr>
<td>2</td>
<td>IART</td>
<td>460</td>
<td>Superior crista</td>
<td>156</td>
<td>51</td>
</tr>
<tr>
<td>3</td>
<td>AFL</td>
<td>250</td>
<td>Cavotricuspid isthmus</td>
<td>123</td>
<td>100.4</td>
</tr>
<tr>
<td>4</td>
<td>IART</td>
<td>220–250</td>
<td>Lateral right atrium</td>
<td>36</td>
<td>37.5</td>
</tr>
<tr>
<td>5</td>
<td>IART</td>
<td>250–270</td>
<td>High lateral right atrium</td>
<td>151</td>
<td>46.4</td>
</tr>
<tr>
<td>6</td>
<td>IART</td>
<td>230</td>
<td>High right atrium</td>
<td>77</td>
<td>36.2</td>
</tr>
<tr>
<td>7</td>
<td>AFL</td>
<td>280</td>
<td>Cavotricuspid isthmus</td>
<td>68</td>
<td>107.5</td>
</tr>
<tr>
<td>8</td>
<td>IART</td>
<td>290</td>
<td>Superior crista</td>
<td>1358</td>
<td>71</td>
</tr>
<tr>
<td>9</td>
<td>IART</td>
<td>250</td>
<td>Low medial right atrium/inferior vena cava/coronary sinus</td>
<td>91</td>
<td>125</td>
</tr>
</tbody>
</table>

AFL: atrial flutter; CL: tachycardia cycle length; IART: intra-atrial re-entrant tachycardia.

Figure 1: Reconstructed voltage maps at varying thresholds to identify scar areas. (a–c) Illustration of serial three-dimensional endocardial voltage maps with lowering of the voltage to identify scar, which results in identification of new, merging of old, and loss of existing pathways. (a) 0.3 mV; (b) 0.2 mV; (c) 0.1 mV. The graded color scale is “scar”, grey; lowest voltage, red; highest voltage, purple.

The Journal of Innovations in Cardiac Rhythm Management, December 2012
ranged from 8 to 19 and the shortest width ranged between 3 and 56 mm. Lines of conduction block created during ablation can therefore be incomplete or excessive. Based on our series, 0.5–0.3 mV provided acceptable pathway identification without compromising the clarity, size or number of pathways generated on electroanatomic voltage maps which could reduce the risk of recurrence.

**Figure 2**: Endocardial channels identified based on low atrial voltage threshold.

**Figure 3**: Sensitivity of channel identification. The scar voltage threshold of 0.5 mV and 0.3 mV identified seven (77%) and eight (89%) of successfully ablated channels, respectively.
Advantages of alternative mapping systems

Each 3D electroanatomic mapping system has its own merits. The Ensite NavX system provides several unique advantages. First, the system does not require the use of proprietary catheters, which allows utilization of a variety of catheters for mapping. Second, cyroablation can be utilized for ablation of IART circuits near vulnerable conduction tissue. Third, the newer generations of this system allow for simultaneous acquisition of activation and voltage mapping without the need of steady-state point-to-point acquisition. These advantages could result in 1) reduced recurrence by ensuring more precise electroanatomic voltage maps; and 2) reduced procedural times by improving the speed of data acquisition.

Limitations

All of these cases were performed using the conventional lower threshold limit of 0.5 mV to delineate scar. The benefit of optimizing this threshold during the procedures is unclear based on this study design. In addition, the exact anatomic and functional correlation of every individual pathway was unable to be defined. Other methods of identification of the successful site of ablation such as identification of the mid-diastolic isthmus were not assessed.32

Conclusions

Voltage mapping thresholds for assessment of scar may differ between 3D mapping systems. With Ensite NavXTM navigation and visualization technology, a bipolar voltage range of 1.5 mV (high) to 0.3 mV (low) was most effective in unmasking all channels targeted for ablation in our cohort. Additionally, high-voltage foci in abnormal tissue may provide additional information for localization of the critical channel required for successful ablation in these complex patients.

References


