Utility of Noninvasive Arrhythmia Mapping in Patients with Adult Congenital Heart Disease

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INTRODUCTION

Arrhythmia management in patients with adult congenital heart disease (ACHD) is a challenge on many levels, as tachycardic episodes may lead to hemodynamic impairment in otherwise compensated patients even if episodes are only transient.1,2 Arrhythmias are in all the different types of congenital cohorts a marker for significant morbidity and mortality.2–6 Owing to the underlying condition, challenges can present in various aspects such as the corrected anatomic situation after surgery, the inherent conduction properties of a potentially abnormally located or otherwise impaired conduction system, and the arrhythmia substrate itself in the form of fibrosis and/or surgically acquired scars.7 This presentation may give rise to a multitude of arrhythmia

KEYWORDS

- Congenital heart disease
- Catheter ablation
- Anatomy
- Three-dimensional mapping
- Noninvasive
- Outcomes

KEY POINTS

- Previous body surface mapping approaches lacked integration of the individual anatomy, and therefore have rarely been used in clinical practice in the last decade.
- A recently introduced noninvasive multielectrode electrocardiographic mapping system (ECVUE; CardioInsight Technologies Inc, Cleveland, OH, USA) combines 3-dimensional (3D) reconstruction of the cardiac anatomy from computed tomography scans with simultaneous recording of the cardiac activation from 252 surface electrocardiographic electrograms.
- The noninvasive nature of the 3D multielectrode mapping system helped to differentiate multiple targets in some patients or rare ectopy over a longer mapping time of several hours.
- Documentation of the location of the critical substrate allowed an informed choice regarding conventional versus remote-controlled navigation techniques, which in turn resulted in limited procedure time and radiation exposure.
- The 3D multielectrode mapping system helped avoid the unnecessary risk of an invasive procedure in patients with palpitations resulting from sinus tachycardia.

The authors have nothing to disclose.

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substrates, which can vary from infrequent atrial or ventricular ectopy to sustained reentrant tachycardias. Some congenital conditions, such as Ebstein anomaly, have a high incidence of multiple accessory pathways, giving rise to atrioventricular (AV) reentrant tachycardia; this may include several accessory pathways or the normal conduction system, resulting in variable AV reentrant circuits, which can confuse the invasive electrophysiologist and increase the complexity of any catheter ablation procedure. However, as ACHD patients are usually young and active members of society, any curative approach to their arrhythmias leads to a dramatic change in their clinical course such that catheter ablation is advocated in preference to lifelong antiarrhythmic medication by many interventional electrophysiologists. Recently several technical advances, including 3-dimensional (3D) image integration, 3D mapping, and remote magnetic navigation, have been introduced to facilitate curatively intended ablation procedures in this special patient cohort. This review attempts to outline the role of a novel technology of simultaneous, noninvasive mapping in this patient cohort, and gives details of the authors’ single-center experience.

SIMULTANEOUS VERSUS SEQUENTIAL MAPPING

To allow successful catheter ablation, a detailed understanding of the arrhythmia and the exact localization of the critical substrate (eg, focal source of the arrhythmia or critical isthmus of a reentry) needs to be identified. Although body surface electrocardiogram (ECG) mapping has been available for a long time, most invasive mapping systems have used a sequential recording approach, which requires a stable arrhythmia. Any infrequent, irregular, or unstable arrhythmia is essentially “nonmappable” using a sequential approach, as the activation pattern is constantly changing. Moreover, infrequently occurring arrhythmias that are difficult to provoke under catheter laboratory conditions pose a challenge in the electrophysiology (EP) laboratory, as the physiologic conditions of the sympathetic drive might be diminished, especially if invasive procedures require sedation of the patient.

Body surface mapping approaches of the past lacked the integration of the individual anatomy, and therefore have been used rarely in clinical practice in the last decade. The recent introduction of the noninvasive multielectrode ECG mapping (ECM) system (ECVUE; CardiolInsight Technologies Inc, Cleveland, OH, USA) has now closed this gap. It combines the 3D reconstruction of the cardiac anatomy from computed tomography (CT) scans with the simultaneous recording of the cardiac activation from 252 surface ECG electrograms. Using an inverse solution, virtual unipolar electrograms are reconstructed on the epicardial surface of either the atrial or ventricular chambers. This panoramic mapping system allows assessment of a global activation sequence from a single beat in a noninvasive fashion. Its use so far has been reported in patients with atrial or ventricular tachycardia, accessory pathway dependent tachycardia, and atrial fibrillation.

METHODS

Patient Population

Of a total cohort of 27 patients undergoing ECM at the authors’ institution from November 2012 to May 2013, 14 had an underlying ACHD condition. Table 1 gives an overview of the detailed conditions. Patients were recruited from the waiting list for invasive EP studies and gave consent for the noninvasive mapping study using the ECM in addition to the invasive EP procedure. In cases of rare

<table>
<thead>
<tr>
<th>No. of patients</th>
<th>14</th>
</tr>
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<tbody>
<tr>
<td>Age (y)</td>
<td>32.8 (24.6–47.4)</td>
</tr>
<tr>
<td>Gender</td>
<td>9 F, 5 M</td>
</tr>
<tr>
<td>Underlying heart disease</td>
<td>1 D-TGA + arterial switch</td>
</tr>
<tr>
<td></td>
<td>2 CCTGA</td>
</tr>
<tr>
<td></td>
<td>1 AVSD</td>
</tr>
<tr>
<td></td>
<td>1 LSVC + mitral valve disease</td>
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<tr>
<td></td>
<td>1 DiGeorge syndrome</td>
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<tr>
<td></td>
<td>2 Coarctation of the aorta</td>
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<td></td>
<td>2 Fontan</td>
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<td>2 Ebstein</td>
</tr>
<tr>
<td></td>
<td>1 Double-chambered RV + VSD repair</td>
</tr>
<tr>
<td></td>
<td>1 ASD repair</td>
</tr>
<tr>
<td>Previous ablation</td>
<td>9 (6 AT/AF, 1 WPW, 2 VE)</td>
</tr>
<tr>
<td>Spontaneous ablation target</td>
<td>9</td>
</tr>
<tr>
<td>Provocation during EP study</td>
<td>12</td>
</tr>
</tbody>
</table>

Abbreviations: ASD, atrial septal defect; AT/AF, atrial tachycardia/atrial fibrillation; AVSD, atrioventricular septal defect; CCTGA, congenitally corrected transposition of the great arteries; D-TGA, dextro-transposition of the great arteries; EP, electrophysiology; LSVC, left superior vena cava; RV, right ventricle; VE, ventricular ectopy; VSD, ventricular septal defect; WPW, Wolff-Parkinson-White syndrome.
or transient arrhythmias, all antiarrhythmic drugs were discontinued for at least 3 times the elimination half-life, whereas patients with persistent arrhythmia were rate-controlled only. If present, oral anticoagulation was paused 1 day before the procedure.

Preacquired Computed Tomography Image Acquisition and 3-Dimensional Reconstruction

A thoracic, noncontrast CT scan (Somatom; Siemens, Forchheim, Germany) was acquired with the multielectrode vest attached to the patient, firstly to exactly locate the surface electrodes and secondly to reconstruct the 3D anatomy of the atrial or ventricular chambers. Landmarks including the atrioventricular valves, left anterior descending artery (LAD), and posterior descending artery (PDA) were added to facilitate orientation for the operator.

For each heart beat the ECM generated 1500 unipolar electrograms on the 3D epicardial reconstruction of the heart, giving rise to color-coded isopotential, voltage, and propagation maps. The maximal negative slope of the local electrograms determined the activation time, allowing the generation of isochronal and directional activation maps.

Arrhythmia Recording Using Noninvasive Electrocardiographic Mapping

In all cases, patients underwent a recording period on the ward to document their clinical arrhythmia outside the catheter laboratory. In case of rare or transient palpitations, several maneuvers were attempted to provoke arrhythmias, including bicycle exercise, vagal stimulation, and hyperventilation. If the patient remained noninducible, pharmacologic provocation was attempted with isoprenaline infusion and/or atropine bolus. One case with previously documented ventricular ectopics was found to be noninducible and was referred to the EP laboratory since a 12-lead ECG of the clinical ventricular ectopic morphology had been documented earlier, and 1 case was excluded from further study because no arrhythmias were observed at baseline and nothing other than sinus tachycardia could be induced by exercise or pharmacologic provocation. The accelerated sinus rhythm correlated well with the clinical symptoms of these patients, who had undergone several ablation procedures previously, such that no further invasive EP approach was pursued.

Noninvasive Multielectrode Mapping Outside the Catheter Laboratory

Half of the patients presented with ongoing or spontaneously occurring arrhythmia (Fig. 1), and 6 of the arrhythmias originated from the ventricular myocardium and 7 from the atrium, respectively. One patient demonstrated overt preexcitation of a posterolateral accessory pathway in the presence of Ebstein anomaly. In 5 patients, additional measures were taken to induce any arrhythmia; these included physiologic maneuvers (hand grip, Valsalva), physical activity (rapid pace walking, riding a stationary bicycle), or pharmacologic provocation with isoprenaline infusion or atropine bolus. One case with previously documented ventricular ectopics was found to be noninducible and was referred to the EP laboratory since a 12-lead ECG of the clinical ventricular ectopic morphology had been documented earlier, and 1 case was excluded from further study because no arrhythmias were observed at baseline and nothing other than sinus tachycardia could be induced by exercise or pharmacologic provocation. The accelerated sinus rhythm correlated well with the clinical symptoms of these patients, who had undergone several ablation procedures previously, such that no further invasive EP approach was pursued.

In Vivo Localization of the Ablation Target

As the ECM is not a navigation system in the classic sense, no depiction of the ablation catheter
localization is available. Navigation toward the ablation target is helped by iterative spike or pace-mapping techniques. In the first case, pacing is required via the mapping catheter and encompasses the epicardial mapping of the pacing spike with the ECVUE.\textsuperscript{21} As only the site of earliest activation is informative for revealing the position of the mapping catheter, only the pacing spike is used for this approach. Moreover, pace match was visually evaluated to compare the isopotential map of the paced beat with that of a spontaneous beat (\textbf{Fig. 2}). The substrate of interest was further confirmed by classic entrainment and pace-mapping maneuvers. The ECM guided the positioning of the mapping catheter while probing for positive entrainment and perfect pace match, and showed great precision as warming up was observed on radiofrequency (RF) application in many of the designated target areas.

\textbf{Combination of Magnetic Navigation and ECVUE}

In many patients with ACHD, the use of the magnetic navigation system has been advantageous in overcoming access problems, as reported recently.\textsuperscript{14,22} In these studies, the authors elected to use the remote magnetic navigation combined with ECVUE-guided mapping in 4 patients. To the best of their knowledge, this is the first report of the combination of remote magnetic navigation with the ECM platform. The advantages to this patient cohort are evident, as the ECM allows fast arrhythmia mapping regardless of accessibility or anatomic complexity together with remote navigation, further reducing radiation exposure and enhancing access to less favorable anatomy such as corrected congenital heart disease. In the authors’ experience, the magnetic field does not

\textbf{Fig. 1.} Example of a 29-year-old female patient with tricuspid and pulmonary atresia. Five different premature atrial contractions (PACs) were mapped and successfully ablated. Red shows earliest breakthrough; blue/purple shows late activation. AP, anteroposterior; CAU, caudal; CRA, cranial; IVC, inferior vena cava; LA, left anterior; LAA, left atrial appendage; LIPV, left inferior pulmonary vein; LSPV, left superior pulmonary vein; MV, mitral valve; PA, posteroanterior; RA, right atrium; RAA, right atrial appendage; RAO, right anterior oblique; RIPV, right inferior pulmonary vein; RL, right lateral; RSPV, right superior pulmonary vein; SVC, superior vena cava.
Potential Maps (RAO view)

1. Bedside 3 beats PVC mapped as same morph simultaneously having epicardial breakthrough at the RV basal and ant side, septally. Presented area is close to the Sinus breakout level. Suspecting the RV septum close to the conducting system.

2. Invasively, PM at the para-HIS location (yellow marker on RAO/LAO projection). Map shows similar simultaneously epicardial breakthrough at the RV basal and ant side, however, not presenting the same inf/sep RV activation/propagation.

3. Invasively, PM at the position of white marker (ref. RAO/LAO projection). Map shows similar simultaneously epicardial breakthrough at the RV basal and ant side, however, not presenting the same inf/sep RV activation/propagation.

4. Best PM just 1cm below the HIS (light blue marker in RAO/LAO). RF on to see the warming up and first time clinical ectopy (mapped to confirm the same morphology)

Fig. 2. Spontaneous ventricular ectopic and iterative pace map to locate the focal origin using the ECM in combination with remote magnetic navigation. Ao, aorta; HIS, His recording electrodes; LAO, left anterior oblique; Mag, magnetic mapping and ablation catheter; PA, pulmonary artery; PM, pace map; PVC, premature ventricular contraction; RAO, right anterior oblique; RF, radiofrequency; RV, right ventricle/ventricular; TV, tricuspid valve.

cause noise after the magnetic vector has moved, or interference that precludes the use of the ECVUE platform.

Outcome of ECVUE-Guided Ablation in Patients with Adult Congenital Heart Disease

All but 1 patient finally were studied invasively, with only 5 patients under general anesthesia and the remainder under assisted sedation by a dedicated cardiac anesthetic team. Procedure duration amounted to a median 188 minutes (interquartile range 164–237 minutes). Median fluoroscopy duration was 14.7 minutes (interquartile range 11.6–21.1 minutes) with a median of 20 RF applications. In 9 patients multiple arrhythmias were the target, which was greatly facilitated by the simultaneous mapping system. At follow-up (median of 18 months), 9 of 14 patients were in sinus rhythm while 3 experienced further arrhythmias despite antiarrhythmic medication. Of the 2 patients who were noninducible (1 on the ward without an invasive EP study and 1 who remained noninducible despite invasive EP study), both reported further nonsustained palpitations.

DISCUSSION

The recently introduced 3D noninvasive ECM system has the potential to overcome some of the limitations that hamper current ablation procedures.\textsuperscript{16–18} The system overcomes several limitations that are currently not addressed by sequential mapping systems. First, this platform allows prolonged bedside monitoring in a noninvasive fashion and in more physiologic conditions. It allows one to challenge the patient with “common life situations” such as exercise or interaction with staff and relatives. This approach is extremely helpful especially during transient events, when patients can identify their typical symptoms. In the absence of any inducible or targetable arrhythmia, ECM was able to document, for example, sinus tachycardia (which for some patients is very symptomatic), thereby negating the need for further invasive procedures.

Furthermore, as the system requires a single beat to create a complete activation map, the ECM platform allows mapping of multiple arrhythmias in a limited time frame. It therefore is especially suitable for patients with congenital heart disease who often present with multiple arrhythmias. Hence in most patients the nature, number, and localization (ie, right- vs left-sided chamber, endo- vs epicardial surface) of the arrhythmia targets was identified even before the patient entered the EP laboratory, which is advantageous to procedural planning and execution, and prevents unnecessary risk of complications.
Despite the complexity of the underlying disease and the multitude of arrhythmias that were present in these patients, an overall acute success of 75% in a congenital heart disease cohort is impressive (excluding the noninducible patients from the analysis). Similar success rates were obtained for both atrial and ventricular arrhythmias. In the authors’ hands, the combination with remote magnetic navigation is feasible and did not interfere with the operation of the ECM platform. In fact, it provided a further opportunity to reduce radiation exposure and allowed the operator to position the catheter in a stabilized fashion without risking dislodgment during the ECM analysis.

LIMITATIONS

The number of patients included in this study is modest; however, complex cases with extensive ACHD and multiple arrhythmias have been addressed here, making this novel technology at least an additional option to be considered in this challenging patient cohort. Better 3D reconstruction algorithms, especially for complex surgically corrected patients, are needed to allow better “road-map” guidance during the invasive part of the study.

SUMMARY

This article reports on the use of the ECM system for patients with ACHD for the treatment of both atrial and ventricular arrhythmias. In particular, the noninvasive nature of the 3D mapping process on the ward helped to differentiate multiple targets in some patients, or rare ectopy over a longer mapping time of several hours. Documentation of the location of the critical substrate then allowed an informed choice on conventional versus remote-controlled navigation techniques, which in turn resulted in limited procedure time and radiation exposure. This approach helped avoid the unnecessary risk of an invasive procedure in patients with palpitations caused by sinus tachycardia.

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REFERENCES