Radiofrequency Catheter Ablation of Various Kinds of Arrhythmias Guided by Virtual Electrograms Using a Noncontact, Computerized Mapping System

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Three-dimensional visualization of cardiac activation has become important for providing further insights into the pathophysiological mechanisms of arrhythmias and to increase the efficacy of catheter ablation. The noncontact mapping system enables a single-beat analysis of the reconstructed geometry of the cardiac chamber. In 8 patients with various kinds of arrhythmias (3 with atrial flutter, 2 with right ventricular outflow tract ventricular tachycardia, 1 with idiopathic left ventricular tachycardia, 1 with atrioventricular nodal reentrant tachycardia and 1 with concealed Wolff-Parkinson-White syndrome), non-contact mapping using an EnSite 3000 system was performed for the guidance of catheter ablation. The optimal sites for successful ablation were detected and all of these arrhythmias were successfully eliminated with the radiofrequency energy applications without any adverse effects. The computerized EnSite 3000 mapping system described here computes accurate isopotential maps that are a useful guide for catheter ablation. (*Circ J* 2003; 67: 455–460)

Key Words: Arrhythmia; Catheter ablation; Noncontact mapping system

Multisite cardiac activation mapping with roving diagnostic catheters has provided insight into the mechanism and origin of a number of clinical and experimental arrhythmias.^{1,2} In addition, a nonfluoroscopic electromechanical mapping system that enables the mechanical endoventricular functioning of myocardial tissue has been developed.³ However, endocardial catheter mapping is limited by the number of simultaneous-acquisition sites that are available at a single point in time.⁴ Arrhythmia mapping would be significantly advanced if clinicians had the ability to collect thousands of points in a single beat without the need for point-by-point contact electrograms. An approach using a mathematical inverse solution to estimate the electrical potentials at sites that are not in direct contact with an electrode catheter has been performed^{5,6} and the purpose of the present study was to determine the feasibility and assess the safety of a novel multisite noncontact electrode catheter in mapping the cardiac chamber activation.

Methods

Patient Population

The study was approved by the Ethical Committee of Yokohama Red Cross Hospital. All patients gave informed, written consent to the electrophysiological study and potential ablation procedures. A total of 8 patients (mean

age of 63±11 years) were included and their characteristics are listed in Table 1.

Electrophysiological Study

Antiarrhythmic medications were discontinued for at least 5 half-lives prior to the electrophysiological study (EPS). All patients were anticoagulated with heparin throughout the EPS and ablation procedure. A two-catheter approach through the right femoral vein was used for the diagnostic EPS and ablation, which included a conventional ablation catheter for recording the endocardial signals, pacing, and radiofrequency (RF) ablation, and a 9Fr noncontact mapping catheter.

Noncontact Mapping System

The mapping system (Endocardial Solutions, Inc, St Paul, MN, USA) consisted of a computerized (Silicon

Table 1 Patient Characteristics

Case no.	Age (years)	Sex	Heart disease
1	54	M	Atrial flutter
2	69	M	Atrial flutter
3	73	F	Atrial flutter
4	38	M	Right ventricular outflow tract ventricular tachycardia
5	49	F	Right ventricular outflow tract ventricular tachycardia
6	52	F	Idiopathic left ventricular tachycardia
7	62	M	Atrioventricular nodal reentrant tachycardia
8	65	F	Concealed WPW syndrome

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Fig 1. Fluoroscopic image of the noncontact array in the left ventricle. CS, coronary sinus; RA, right atrium.

Graphics, Mountain View, CA, USA) electrophysiology recording system that, in conjunction with a 64 electrode noncontact balloon catheter, constructed a 3-dimensional (D) model of the endocardium of the cardiac chamber, provided a locator system to identify the position of a conventional electrode catheter within the model and computed 3,360 virtual endocardial electrograms.⁷ The catheter consisted of a 7.5-ml balloon mounted on a 9Fr catheter, around which was woven a braid of 64 insulated 0.003-mm diameter wires. Each wire had a 0.025-mm break in the insulation that served as a noncontact unipolar electrode. The unipolar multielectrode array (MEA) signals were recorded using a ring electrode as a reference, which was located on the shaft of the MEA catheter. Far-field potentials recorded from the surrounding myocardium were amplified, digitized, sampled at 1.2 kHz, and digitally filtered at 0.1–300 Hz. The resulting signals were constructed based on the inverse solution to Laplace's equation by the use of a boundary element method to reconstruct and display virtual electrograms simultaneously from the cardiac chambers surrounding the multielectrode catheter. Activation maps could be reconstructed from a single tachycardia cycle because all the potentials were recorded simultaneously. An electrically based locator signal was also generated by the system to permit nonfluoroscopic navigation of any standard roving contact catheter used for ablation. To position the electrode balloon catheter in the heart, a 0.035-inch guide wire was placed in the central lumen of the electrode balloon catheter. The catheter was advanced over the guide wire from the femoral vein or artery. The balloon was expanded by injection of 7.5 ml of a 50% mixture of a contrast medium and normal saline (Fig 1).

The virtual electrograms could be computed in either a unipolar or bipolar format. The system displayed a color, dynamic 3-D isopotential map derived from the virtual electrograms, based upon the amplitude of the electrograms. The dynamic isopotential map depicted the electrical potential from each virtual electrogram throughout the cardiac cycle, at intervals of 0.83 ms. The leading edge of the depolarization wavefront was a negative potential.⁸ By adjusting the color gain such that the negative potential of the leading edge of depolarization was always white, the advancing edge of a wave of depolarization could be observed (Fig 2). The surface ECG leads and intracardiac electrograms from the conventional electrode catheters were recorded with the computerized recording system. The filter settings for the intracardiac electrograms were 0.1–300 Hz.

Fig 2. (Panel A) Identification of the endocardial activation sites preceding the onset of the QRS complex during ventricular tachycardia. (Left) An open view of a right ventricular reconstruction, with the septum, base and apex as labeled; the inflated noncontact balloon catheter is shown only in the left panel. The numbers 6, 7, 8, and 9 in the right ventricular reconstruction designate the sites at which the virtual electrograms in the left panel were computed. (Panel B) Instantaneous isopotential maps are shown in panels A–D at the time points designated by the vertical lines through the electrograms.

Electrophysiological Study and Catheter Ablation

Atrial Flutter The noncontact multielectrode catheter was centered and inflated under fluoroscopic control in the high right atrium guided by a wire that ended in the superior caval vein. The 3-D contour of the right atrium was constructed using the locator signal. Isthmus conduction was mapped during coronary sinus pacing in patients with sinus rhythm prior to the RF applications.

RF energy was delivered, during atrial flutter or during pacing from the coronary sinus, through the catheter being dragged from the tricuspid annulus to the inferior vena cava. The RF temperature was limited to 60°C. Ablation success was verified by demonstrating complete conduction block in the isthmus region during coronary sinus and latero-inferior right atrial pacing and failure to reinduce atrial flutter after the ablation was completed.

Right Ventricular Outflow Tract Tachycardia The non-contact electrode was advanced by a guide wire that was inserted in advance into the pulmonary artery toward the

Fig 3. Four consecutive isopotential maps indicating the activation sequence of the right atrium (left anterior oblique view) during common atrial flutter (left). Representative virtual electrograms recorded from locations 6–10 in the maps are shown in this panel. Representative virtual electrograms recorded from locations 6–10 in the maps are shown (right).

right ventricular outflow tract. The 3-D contour of the right ventricle was created, and an isopotential map was created while waiting for the spontaneous occurrence of nonsustained ventricular tachycardia or isolated premature contractions originating from the right ventricular outflow tract.

Left Ventricular Tachycardia The noncontact multi-electrode catheter was inserted retrogradely into the left ventricle using the 'over the wire' method through the aortic valve. A comparable procedure to that in the cases with right ventricular tachycardia was performed to delineate the contour of the left ventricle. Ventricular tachycardia was induced during the programmed pacing from the right ventricular apex. Isopotential mapping was performed during sustained ventricular tachycardia.

Supraventricular Tachycardia The noncontact multi-electrode mapping system was also utilized in one case with concealed Wolff-Parkinson-White syndrome and in 1 case with atrioventricular nodal reentrant tachycardia (AVNRT) of the common variety. In both cases, a multi-electrode balloon catheter was inserted into the right atrium. The excitation pattern of the right atrium during constant right ventricular pacing was examined using the noncontact mapping system. In these 2 cases, the safety and the feasibility of the noncontact mapping system were assessed.

Results

Data were collected from all patients during their various kinds of arrhythmias and ablation was completed in all 8 patients. The mean procedure time was $69(\pm 21)$ min, and the mean fluoroscopic time was $38(\pm 13)$ min.

Mapping Procedure

The noncontact mapping balloon catheter was positioned without difficulty in each case, and there were no difficulties with balloon stability or displacement. No surface of the heart chambers was more than 6 cm from the center of the balloon. There were no procedural complications. The noncontact mapping catheter did not cause obstruction of the blood flow or perforation of the cardiac chamber.

There were no thromboembolic episodes and no bleeding complications arising from the anticoagulation.

Fig 4. (A) Four consecutive isopotential maps also showing the activation pattern of the right atrium (left anterior oblique view: LAO) during 'reverse' common atrial flutter in a patient that had previously undergone a conventional ablation procedure. The activation wavefront arrives at the septal entry of the isthmus and moves toward the gap in the ablation line where it narrows significantly. After passing the gap in the ablation line the wavefront widens again and proceeds toward the low lateral wall. (B) Four consecutive isopotential maps indicating the activation sequence of the right atrium (LAO view) during the low lateral RA pacing after successful ablation of common atrial flutter in the same patient in Fig 4A. The conduction block at the ablation line occurs as shown in this panel. The stimulated wavefront is able to move clockwise from the low lateral right atrium next to the ablation line at the isthmus (line of block) toward the high right atrium and the high septal wall, continuing to move to the septal entry of the isthmus, and eventually blocking at the ablation line in the isthmus.

Atrial Flutter Fig 3 shows the activation pattern during typical atrial flutter prior to the ablation procedure. The 3-D model is shown in the left anterior oblique view. In 2 patients who had undergone previous ablation procedures, a gap in the line of block during isthmus conduction was identified and marked on the animation model. Isthmus block in one patient was incomplete, enabling the wavefront to continue in a clock-wise direction through the gap (Fig 4A). The ablation catheter was positioned at this site of the gap and an RF application was able to create complete bi-directional conduction block at the isthmus. In one patient, bi-directional conduction block was constructed at the isthmus by multiple applications of RF current. The complete block was ascertained by the noncontact mapping

Fig5. Display of the virtual electrograms. Multiple virtual electrograms were simultaneously viewed in a linear or grid format after being selected in the area of interest with a computer mouse. The chamber is shown displaying the entire endocardial reconstruction. In each panel, the isopotential map identifies the site of endocardial activation associated with the onset of the QRS complex during nonsustained VT occurring from the right ventricular outflow tract. The maximum negative initial deflection in a reconstructed electrogram representing the leading edge of the wave of depolarization, is shown in white and suggests that the tachycardia originates close to the wavefront's origin on the isopotential map.

system during pacing from the coronary sinus as well as from the low lateral right atrium (Fig 4B). The mean number RF energy applications was 6.1 ± 2.5 . The mean time required to perform the ablation procedure was 37 ± 14 min, and the mean fluoroscopic time was 25 ± 17 min.

Right Ventricular Outflow Tract tachycardia Mapping and ablation was attempted in 2 patients. Only one premature contraction was needed to identify the origin of this arrhythmia using the noncontact multielectrode catheter (Fig5). The ablation catheter was positioned at the site of origin of the arrhythmia using the navigation system, and RF energy was delivered, resulting in the complete elimination of the arrhythmias originating from the right ventricular outflow tract in both patients. The mean number RF energy applications was 4.3 ± 2.2 . The mean time required to perform the ablation procedure was 97 ± 34 min and the mean fluoroscopic time was 47 ± 21 min.

Left Ventricular Tachycardia (VT) Mapping and ablation was attempted in one patient. The mean cycle length of the VT was 331 ± 54 ms. The VT was hemodynamically tolerated allowing conventional mapping, as well as non-

contact mapping, to be performed. The exit site and site of presystolic activation were identified using both mapping methods. The computerized mapping system identified an isolated diastolic potential, which was also recorded with a conventional catheter. The entire reentrant circuit was identified in only 1 VT (Fig6). The RF application site was determined according to the mapping using the conventional catheter where the isolated diastolic potential and Purkinje potential were recorded simultaneously. A single application of RF energy was able to terminate the VT, rendering it non-inducible despite the use of an aggressive stimulation protocol even after the intravenous infusion of isoproterenol. The number of RF energy applications was 3. The time required to perform the ablation procedure was approximately 50 min, and the fluoroscopic time was approximately 25 min.

Supraventricular Tachycardia In one case of concealed WPW syndrome, the accessory pathway was located along the mitral annulus. Therefore, from the retrograde conduction pattern in the right atrium using the noncontact mapping system positioned in the right atrium, we failed to localize the site of the accessory pathway. The RF energy was delivered according to the mapping results obtained from the conventional multielectrode catheter inserted deep into the coronary sinus. A single application of RF current was able to abolish the conduction over the accessory pathway. In 1 patient with AVNRT, the retrograde pattern during the sustained AVNRT was through the antero-superior portion of the right atrial septum, which corresponded to the location of the AV nodal fast pathway. RF energy was applied to the infero-posterior portion of Koch's triangle where the AV nodal slow pathway courses. After the occurrence of accelerated junctional tachycardia during the RF energy application, the conduction over the AV nodal slow pathway was completely eliminated.

No cardiac complications resulted from the noncontact multielectrode catheter system.

Discussion

Major findings

The results of this study demonstrate that the noncontact mapping system was able to accurately compute virtual electrograms of each heart chamber without any complications associated with the procedure. Mapping was facilitated by the ability to view virtual electrograms from any

Fig6. (Left panel) Noncontact map of a ventricular tachycardia in the left ventricle. Sequential panels from a movie depicting arrhythmia propagation are shown (A-F). Purple depicts resting myocardium (with white having the most negative unipolar potential). A right anterior oblique view is demonstrated. The instantaneous isopotential maps are shown in panel A to F at the time points designated by the vertical lines through the electrograms (Right panel). Right panel shows representative 'virtual' electrograms recorded from locations 6-11 in the maps are shown. The numbers 6 to 11 in the left ventricular reconstruction designate the sites at which the virtual electrograms in the left panel were computed.

portion of the 3-D endocardial model without moving a conventional catheter to each area of interest.

Noncontact Electrode Mapping

Evaluation of distant endocardial potentials from an intracavitary electrode represents a specialized case of a solution to the 'inverse problem'.⁹ The accuracy of the electrogram reconstruction was similar to that previously reported in the human left ventricle.¹⁰ So far as this system has been used in clinical and experimental studies, and some limitations were noted. Accurate electrogram reconstruction was obtained only at sites within 4.0 cm of the center of the balloon, which might limit the clinical applicability of this system in patients with large cardiac chambers, or it could require balloon repositioning to the areas of interest.

Clinical Usefulness

As noted earlier, typical atrial flutter usually is readily treated by standard ablation techniques. However, noncontact mapping has been used to confirm the anatomic location of the flutter circuit.¹¹ Because of its ability to record from multiple sites simultaneously, the technique is uniquely suited to the identification of gaps in linear lesions constructed at the isthmus between the tricuspid annulus and the inferior vena cava in cases of atrial flutter ablation of the common variety. Thus, the noncontact mapping system has been used to identify and guide RF ablation to the sites of residual conduction following creation of an incomplete linear lesion at the isthmus. Schumacher et al.¹² demonstrated that noncontact isopotential maps reliably distinguished conduction delays from complete conduction block, and when a gap in a line of block was present, its location was instantaneously identified. Such a gap could be eliminated by an RF application guided by the noncontact system. Although localization of a gap using the virtual electrograms was hampered by the presence of fractionated low-amplitude signals along the ablation line, the gap was readily identified by noting the breakout site of electrical activity across the line on the isopotential map.

Regarding arrhythmias originating from relatively small areas, such as right ventricular outflow tachycardia, the noncontact mapping system was able to identify its origin with almost pin-point accuracy, which is comparable to conventional endocardial mapping,¹³ from the mapping data of only 1 arrhythmic excitation. Using the navigation system, the ablation catheter was easily positioned at the site for successful abolition of this arrhythmia. Conventional catheter-based techniques to map VT have included concealed entrainment, identification of an isolated diastolic potential, identification of the earliest presystolic endocardial activation during VT and pace mapping during sinus rhythm.^{14–16} Each of these techniques, except for pace mapping, requires that VT is present during mapping. Therefore, if the VT is not hemodynamically tolerated, conventional mapping is limited to pace mapping during sinus rhythm. In contrast, the noncontact mapping system is able to identify the arrhythmia circuit or origin with only 1 tachycardia cycle.

The EnSite system is suitable for mapping these kinds of hemodynamically unstable tachyarrhythmias. Moreover, arrhythmias arising from a small focus, such as ventricular premature contractions from either ventricle, may also be good candidates for the EnSite system.

Limitations of the Noncontact Mapping System.

A concern with dilated chambers is the accuracy of the system at sites more than 4.0 cm from the center of the balloon. Although the electrogram morphology may become less accurate, the location of endocardial potentials is not affected. Loss of accuracy is gradual, so that timing differences between adjacent areas of the myocardium are minimal.

Another limitation is that the endocardial geometric model used in this system must be obtained during the baseline rhythm, and the virtual electrograms calculated during other arrhythmias are fit to this model. This limitation might be more important in a vigorously contracting heart chamber than in a poorly functioning ventricle.^{17,18}

Conclusions

Complex arrhythmias necessitate high-density, multisite mapping techniques, such as noncontact mapping, which can provide accurate 3-D maps of the arrhythmia circuits in the heart chambers. The noncontact mapping system is effective in determining an arrhythmia's circuit or its origin, but further advanced ablation technologies are almost certainly required for adequate lesion formation to ablate these circuits.

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