Mapping and ablation of atrial tachyarrhythmias : from signal to substrate

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chapter 9

Three-Dimensional Catheter Positioning During Radiofrequency Catheter Ablation in Patients: First Application of A Real-Time Position Management System

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Abstract

Introduction: Precise localization of target sites for radiofrequency catheter ablation (RFCA) of arrhythmias is hampered by the relative inaccuracy of X-ray localization procedures. This study evaluated the efficacy of a 3 dimensional real-time position management system in guiding RFCA procedures in patients.

Methods and Results: Patients (n = 30, age 59 ± 20 years) referred for ablation of either atrial flutter (n = 10), ventricular tachycardia (VT) (n = 15) or accessory pathways (n = 5) were studied. The real-time position management system uses ultrasound-ranging techniques to track the position of an ablation catheter relative to 2 multi-transducer reference catheters, positioned in the right atrium or coronary sinus and the right ventricle. Each catheter contains 3 or 4 ultrasound transducers. The distance between the transducer(s) is determined by calculating the time necessary for an ultrasound pulse to reach other transducers, assuming the speed of sound in blood is 1550m/s. The proximal His bundle was marked at the beginning and the end of the procedure as an electrical landmark to verify reproducibility. After identification of target sites, the position of each lesion created with the ablation catheter was marked. Successful ablation was achieved in 94% of the patients. The distance between the location of the proximal His bundle as marked at the beginning and at the end of the procedure was 2.0 ± 1.2mm (1.5-3.5mm).

Conclusions: The new 3-D real-time position management system facilitated RFCA procedures as it allowed accurate and reproducible 3-D tracking of the mapping and ablation catheter.

Introduction

Radiofrequency catheter ablation procedures of tachyarrhythmias are guided by endocardial mapping.[1-4] Endocardial mapping is aimed at identifying target sites for ablation which are characterized by either abnormal electrograms, indicating arrhythmogenic areas or by fast A-V or V-A conduction in the presence of an accessory pathway.[3-9] The accurate 3-dimensional localization of abnormal electrograms and sites ablated at the endocardial surface is of importance for the outcome of RFCA procedures as it will allow repeated repositioning of catheters at specific endocardial sites.[8] Successful ablation of typical atrial flutter, for example, defined as the assessment of a bi-directional conduction block over the lateral or septal isthmus depends on the creation of a complete line of block.[10-14] However, precise positioning of the ablation catheter by fluoroscopy only is difficult, time-consuming, and results in long fluoroscopy times.[8] RFCA procedures may be facilitated using additional endocardial mapping techniques however, current available techniques are limited.[5,15,16] Single-electrode mapping or the use of multiple catheters, is time consuming and geometrical reconstruction is difficult.[15,16] To circumvent some of these problems, 3-D mapping systems such as the electro-anatomical CARTO system have been developed.[17-21] The CARTO system allows real-time positioning of the tip of the ablation catheter relative to a reference patch and the reconstruction of high density 3-dimensional endocardial activation maps.[8,17-19] Although the use of this system may overcome some of the disadvantages of the other techniques, it is still a time consuming procedure and an expensive system. Another system enabling 3-D real-time, non-fluoroscopic visualization of intra-cardiac electrodes is the recently presented LocaLisa system.[21] Both CARTO and LocaLisa depend on a stable position of the reference catheters, because there is no possibility to reposition them when dislocated.[19,21]

The objective of this study was to evaluate the efficacy of a newly developed 3-dimensional real-time position management system in guiding RFCA procedures. The system uses ultrasound-ranging techniques to 1) construct a 3-D representation of catheters (including electrodes and transducers), anatomical structures and ablation sites and 2) display the real-time movement of the tip and the shaft of the catheters.

Methods

Thirty patients were studied. Prior to the mapping and ablation procedure, patients underwent cardiac examination, including 24 hour Holter monitoring, echocardiography (either transthoracic or transesophageal) and coronary plus bi-plane left ventricular (LV) angiography (VT patients only). Patients underwent an electrophysiological study prior to the ablation procedure. During the procedure, heparin was given intravenously (ACT value: 2.5-3 times the baseline value). This study was approved by the institutional ethics committee and informed consent was obtained from all patients

Reference and ablation catheters

Two reference catheters and 1 mapping/ablation catheter were introduced percutaneously using either the femoral or subclavian approach. One reference catheter was positioned in either the right atrial (RA) appendage or the coronary sinus, and one reference catheter was positioned in the right ventricular (RV) apex. For ablation purposes, either

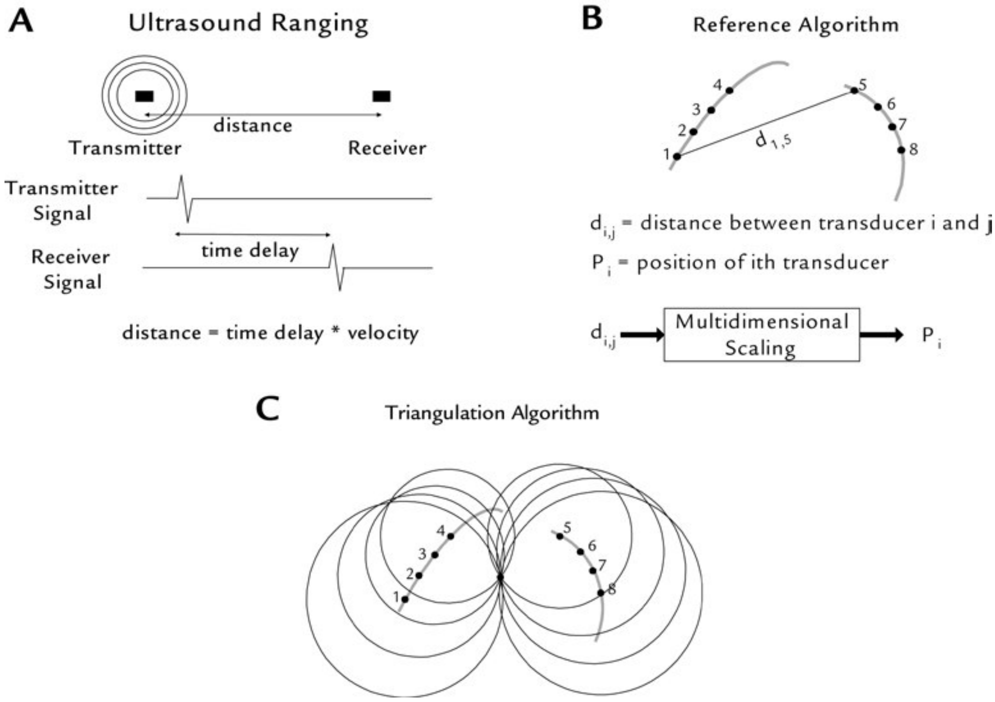

Figure 1.
Ultrasound ranging, basic principles (panel A). The reference algorithm is shown in panel B. By measuring the time delay between the departure of a transmitted ultrasound pulse and the reception of this pulse by the other transducers, the distance between the individual transducers can be calculated (panel B). Once the 3D reference frame is established triangulation can be used to track the position of additional transducers (panel C).

a 7F 4mm tip bi-directional steerable cooled ablation catheter (Cardiac Pathways, USA) or a non-cooled version was used. The reference catheters (Cardiac Pathways, USA) have a 6F fixed curve distal shaft. The shaft of the atrial reference catheter contains nine 1mm ring electrodes and one 2mm tip electrode (interelectrode distance 1mm), whereas the RV reference and the ablation catheter contain three 1mm ring electrodes and one 4mm tip electrode (interelectrode distance 1mm). The reference catheters are equipped with 4 ultrasound transducers; the ablation catheter contains 3 ultrasound transducers. The ultrasound transmit and receiver device sends a continuous cycle of ultrasound pulses (558.5 kHz) to the transducers of the reference and ablation catheters. By measuring the time delay from the departure of a transmitted ultrasound pulse and the reception of this pulse at the other transducers, assuming a speed of sound in blood of 1550 m/s, the distance between the individual transducers can be calculated (**Figure 1**, panel A). These data are subsequently transferred to the computer and used to define the location of the catheter(s) within the reference frame. Once the 3-D reference frame is established, triangulation can be used to track the position of additional transducers (**Figure 1**, panels B, C).

Benchtop validation studies were performed by Cardiac Pathways. Three separate sets of reference and tracking catheters were used. The system tracks the position of the catheter when the catheter was placed in one of 6 holes of a test jig. The holes were in a rectangular grid with 15mm spacing. For each set of catheters 5 cycles through 6 holes were made for a total of 5 points per hole (450 data points). The overall accuracy was –0.6 to 0.3mm with a correlation of 0.99 and an error standard deviation of 0.4 mm.

Because dimensional and structural characteristics of the catheters are known, it is possible to construct a real-time 3-D graphical representation of the catheters, including the position of the electrodes and the transducers. As one of the transducers is positioned distal to the deflection point of the shaft of the catheter it is possible to display the curve of the catheter as well. Furthermore, the real-time position management system graphically displays the beat-to beat movement of the tip of the catheters.

Real-time Position Management and Mapping system

The 3-D real-time position management and mapping system (Cardiac Pathways, USA) uses ultrasound ranging techniques to determine the position of a mapping/ablation catheter relative to 2 reference catheters (**Figure 2**). The mapping system consists of an acquisition module, an ultrasound transmitter and receiver unit, both connected to a SPARC 20 computer (Sun Computers, USA). The system is capable of simultaneously processing: 1) 7 position management catheters; 2) 24 bipolar/ 48 unipolar electrogram signals; 3) 12 lead ECG; and 4) 2 pressure signals. Signals are sampled at 3 kHz/channel with a resolution of 14 bit. The high pass filters are set at 30 Hz, and the low pass filters at 500 Hz. Electrograms and catheter positions are displayed on a computer monitor. Signals and catheter positions are stored on optical disc. The original position of the

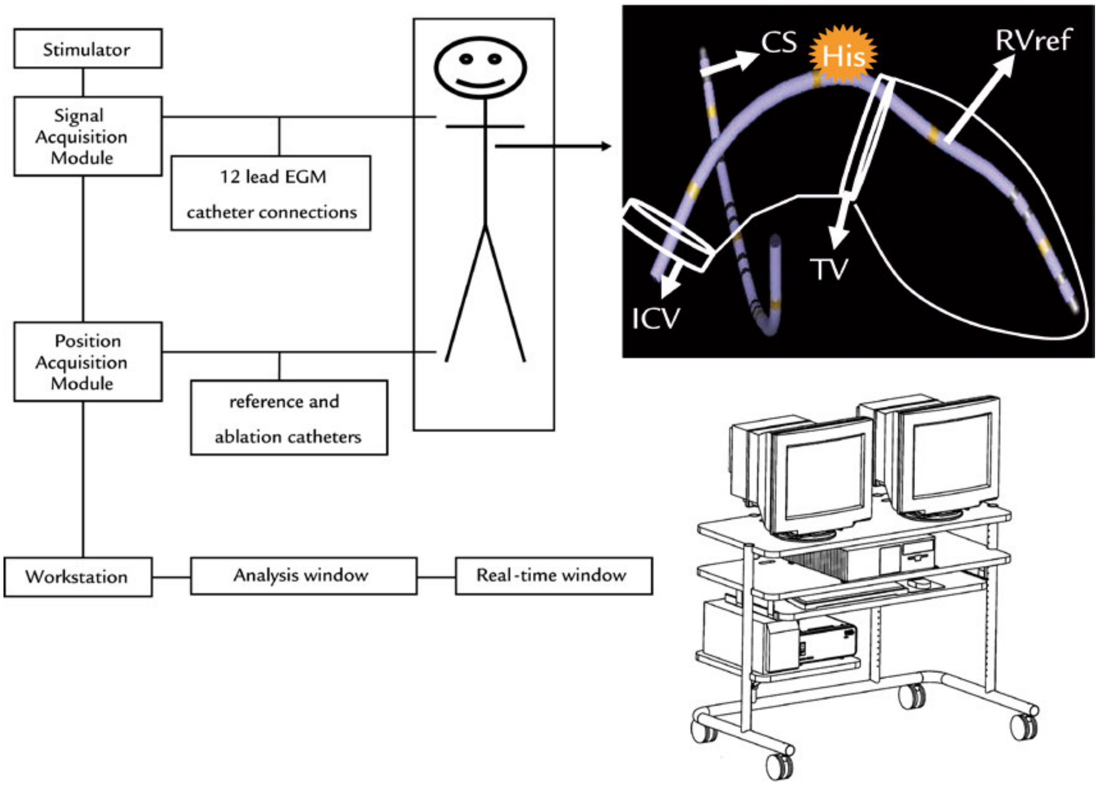

Figure 2.

The real-time position management system. Two multi-transducer reference catheters connected to an ultrasound transmitter and receiver device are positioned in the coronary sinus and the RV apex. The transducer and electrode positions on the catheters are represented by respectively the yellow and white rings. Signals are filtered by the signal acquisition module and transferred to the workstation.
RV ref = RV reference catheter, ICV = inferior caval vein, TV = tricuspid valve.

reference catheters can be displayed on the real-time window (**Figure 3**, green lines) thereby allowing repositioning of catheters after displacement.

Programmed electrical stimulation

The hearts were stimulated with a pulse width of 2ms, using a constant current stimulator (Medtronic, USA). The output of the stimulator could be directed to any of the electrode pairs. Programmed electrical stimulation applying up to three extrastimuli, at 2 times diastolic threshold, was used to induce the clinical arrhythmia.

Radiofrequency ablation procedure

A RFCA procedure was performed immediately following the diagnostic evaluation. A 7F 4mm tip steerable cooled ablation catheter connected to a RF generator (Cardiac Pathways) was used in patients with atrial flutter or VT. The catheter tip was pre-cooled to 23°C and the output of the generator was set at 30-40 Watt. During cooling, radiofrequency current was delivered for 60 seconds and repeated until the target tachycardia was no longer inducible or bi-directional isthmus block was established (atrial flutter patients). A standard 7F 4mm steerable ablation catheter connected to the same ablation unit was used in patients with accessory pathways. Radiofrequency current (the maximum tip temperature was set at 70°C) was delivered for 60 seconds and repeated until conduction over the accessory pathway was terminated.

Atrial Flutter

A decapolar HALO catheter was inserted with its distal electrodes positioned at the cavo-tricuspid isthmus. The procedure started by marking the tricuspid valve and the inferior caval vein. The ablation catheter was used to create a linear lesion between these two structures (lateral isthmus block[10-14]). Successive lesions were marked to ascertain the creation of a complete line of block. Successful ablation of atrial flutter was defined as the assessment of a bi-directional isthmus block, verified by pacing laterally and septally of the ablation line.

Ventricular Tachycardia

Detailed localization included the reconstruction of pacemaps, stimulation during tachycardia to reveal concealed entrainment, and the characterization of locally recorded electrograms.[4,6-8] Successful ablation of VT was defined as termination of VT during ablation and non-inducibility of the clinical VT after ablation.

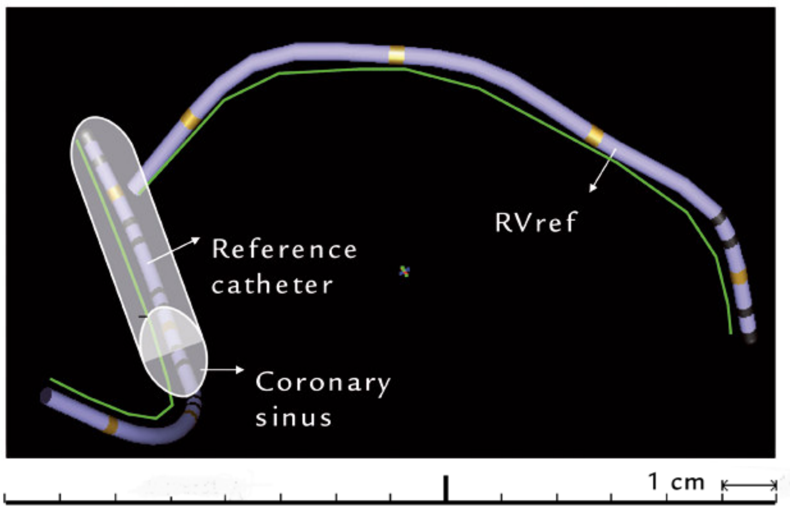

Figure 3.
The position of the coronary sinus reference catheter and RV reference catheters at the end of an ablation procedure. As demonstrated, a small displacement occurred during the procedure (original position = green lines).

Accessory Pathway

RFCA was performed during either sinus rhythm or ventricular pacing via the right ventricular apex reference catheter. Sites showing the shortest atrial to ventricular or ventricular to atrial conduction time were ablated. Successful ablation was defined as the disappearance of the delta wave and/or disappearance of V-A conduction.[1]

Validation protocol

The accuracy and reproducibility of the system was validated.

Protocol I was used to assess the relative stability of both reference catheters throughout the procedure. Herefore, the 3-D construction of both reference catheters representing the position was saved at the beginning of the ablation procedure. This was repeated at the end of the ablation procedure. Then, the distance between the position of the tip and the shaft of the 3-D constructions of both reference catheters at the beginning and at the end of the ablation procedure was measured.

Protocol II studied the possibility to navigate back to a previously marked site.

For this purpose, in each patient, the procedure started with the marking of the proximal His bundle,(identified as a bipolar His bundle deflection smaller than 50 μm and only a negative deflection on the distal unipolar electrogram) using intracardiac signals and fluoroscopy only.

After covering the first marking, the proximal His bundle was again marked in the same way at the end of the ablation procedure, since the reference catheters might have been displaced during the procedure.

Post procedure

The venous and arterial sheath were removed 4-6 hours after the procedure. Patients were then heparinized for at least 6 hours. An echocardiogram and a chest x-ray were obtained <24hours after the procedure. Patients were discharged 24hours after the procedure.

Data Analysis

Data are expressed as mean ± SD.

Results

Thirty patients (25 male, 5 female, age 59 ± 20 years old) referred for RFCA of either atrial flutter (n = 10), VT (n = 15) or an accessory pathway (n = 5) were studied.

The steerability of the mapping/ablation catheter was not affected by the presence of a reference catheter in the heart chamber mapped. Although during the procedure some ultrasound transducers failed, accurate positioning was still possible in all patients. No thrombus formation could be detected on any of the catheters. Complications were not observed.

The mean procedure and fluoroscopy time are shown in **Table 1**.

Stability of reference catheters

Stability of the atrial and ventricular reference catheters throughout the procedures was measured in all patients. **Table 2** gives the displacement of the reference catheters during atrial flutter ablation procedures. Both RV and RA reference catheters shifted ± 5mm (1.6-8.4mm) throughout the procedure. During RF ablation of VT, reference displacement was somewhat larger in 2 patients. This was caused by DC-shock cardioversion/defibrillation because of hemodynamic deterioration in these patients. In the other patients (n = 13) the displacement was ± 5mm (0.9-6.7mm, **Table 3**). During ablation of an accessory pathway the reference shift was minimal (± 1.5mm, **Table 4**).

To evaluate the optimal position of the atrial reference catheter, this catheter was positioned in either the coronary sinus (n = 14) or the RA appendage (n = 16). The corresponding values are shown in **Table 5**. When a stable position was obtained in the RA appendage only a minimal displacement occurred (± 1.7mm), whereas this shift was somewhat larger when positioned in the coronary sinus (± 8mm).

To test the possibility to navigate back to a marked position, the position of the most proximal part of the His bundle was marked at the beginning and at the end of the procedure. Despite small displacements of the reference catheters during the procedure, the distance between the pre-ablation and post-ablation His bundle mark was only 2.0 ± 1.2mm (1.5-3.5 mm).

Atrial Flutter

Patients with atrial flutter (CL = 299 ± 43ms) were ablated during sinus rhythm (n = 4) or during atrial flutter (n = 6). The length and width of the linear lesions created during ablation was respectively 36 ± 8mm and 14 ± 12mm. The number of lesions required to construct a line of conduction block was 28 ± 11. A bi-directional isthmus block was achieved in all patients. An example of the construction of a linear lesion and the subsequent assessment of bi-directional conduction block is demonstrated in **Figure 4**. In the upper panel the position of the coronary sinus and the RV reference catheters are shown. The red line shows the predetermined lateral isthmus, located between the inferior caval

Table 1. **Mean fluoroscopy and procedure time**		
	fluoroscopy time	**procedure time**
	minutes (mean/SD)	
atrial flutter	10 ± 3	28 ± 6
ventricular tachycardia	17 ± 8	42 ± 10
accessory pathway	8 ± 3	19 ± 6

Table 2. **Displacement of the reference catheters during RFCA of atrial flutter.**				
	mean (mm)	**SD (mm)**	**minimum (mm)**	**maximum (mm)**
RV reference catheter	5.4	3.0	2.1	8.0
Tip RV ref catheter	4.7	2.9	1.6	7.5
RA reference catheter	6.0	1.5	5.4	8.4
Tip RA ref catheter	5.6	1.3	4.6	7.5

Table 3. **Displacement of the reference catheters during RFCA of an accessory pathway.**				
	mean (mm)	**SD (mm)**	**minimum (mm)**	**maximum (mm)**
RV reference catheter	2.1	1.6	0.3	1.7
Tip RV ref catheter	1.9	1.6	0.2	3.4
RA reference catheter	1.2	0.6	0.6	1.6
Tip RA ref catheter	1.2	0.6	0.5	3.6

Table 4. **Displacement of the reference catheters during RFCA of VT.**				
	mean (mm)	**SD (mm)**	**minimum (mm)**	**maximum (mm)**
RV reference catheter	6.7	4.1	2.1	12.5
Tip RV ref catheter	6.6	3.9	2.0	11.8
RA reference catheter	4.4	2.6	0.9	6.9
Tip RA ref catheter	4.2	2.4	1.2	6.7

Table 5. **Right atrium / coronary sinus reference position.**		
Location reference catheter	**mean (mm)**	**SD (mm)**
coronary sinus-tip	7.5	4.6
coronary sinus-catheter	8.4	4.8
RA appendage-tip	1.7	0.6
RA appendage-catheter	1.6	0.6

vein and tricuspid valve. Ablation sites are marked with white dots. After creating a line of block this was tested by stimulating laterally and septally from the line of block (lower panels). By using the RPM system, it is possible to accurately determine the pacing site in relation to ablation line.

During pacing from the coronary sinus, the lateral wall is activated in a craniocaudal direction (H1-H5) with double potentials at H1, indicating isthmus block. During pacing from the low lateral wall, a caudocranial activation of the lateral wall with double potentials at H1 is seen, again indicating a conduction block over the isthmus.

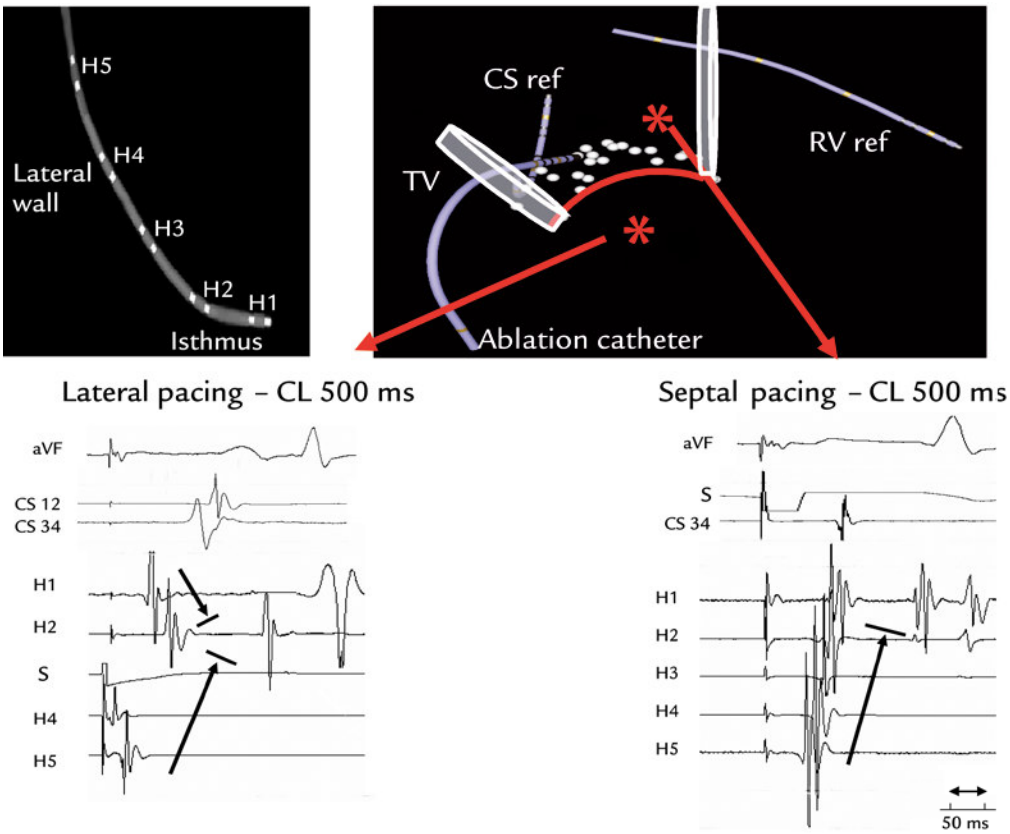

Figure 4.

RFCA of atrial flutter (RAO view).In the upper panel the position of the coronary sinus and the RV reference catheters are shown. The red line shows the predetermined lateral isthmus, located between the inferior caval vein (ICV) and tricuspid valve (TV). Ablation sites are marked with white dots. CS12 = the distal site of the coronary sinus, CS34 = proximal site of the coronary sinus. H1-5 denote the bipoles of a decopolar (HALO) catheter with its distal electrodes positioned at the cavo-tricuspid isthmus. See text for further explanation.

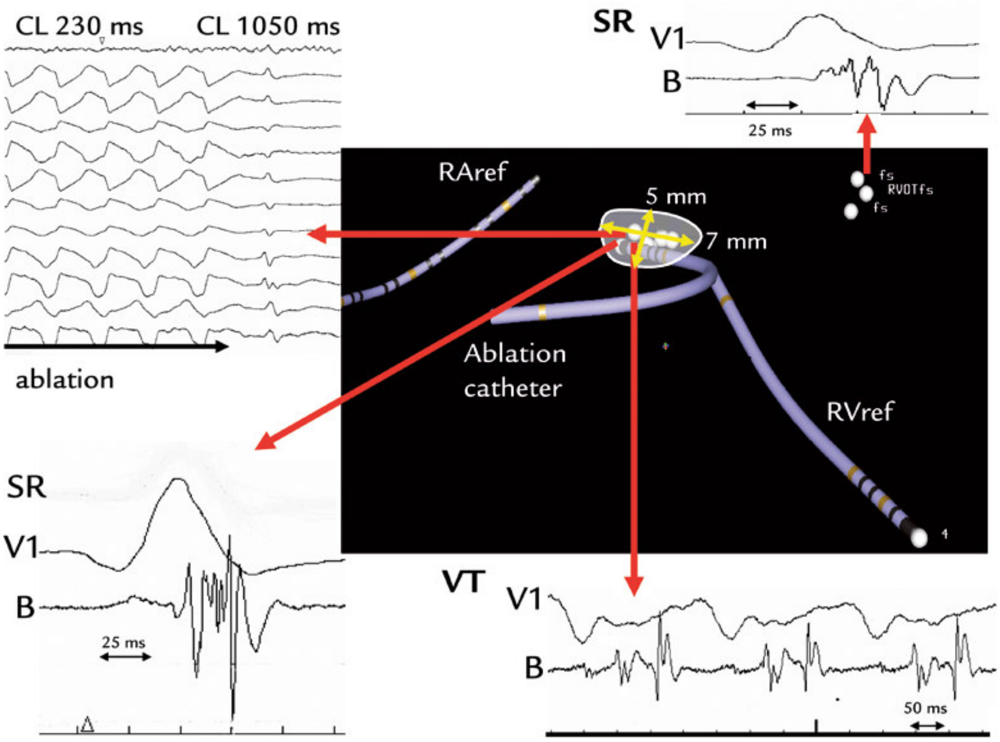

Figure 5.
VT ablation in a patient with an arrhythmogenic RV dysplasia (RAO view). See text for explanation.

Ventricular Tachycardia

Fifteen patients with drug-refractory VT (CL = 391 ± 69ms) were studied. Twelve patients with post myocardial infarction LV VT and 3 patients with RV VT in the presence of an arrhythmogenic right ventricular dysplasia (as confirmed with MRI imaging). RF ablation was successful in 9/12 patients with post-myocardial infarction VT and in 3/3 patients with arrhythmogenic right ventricular dysplasia (defined as non-inducibility of the clinical VT after RF ablation).

Selection of target sites for ablation was based on identification of fragmented early-activated endocardial sites during VT, concealed entrainment or pacemapping.

An example of an ablation procedure in a patient with an arrhythmogenic RV dysplasia is shown in **Figure 5**. The position of the reference catheters is shown in the colored panel (RAO view). The ablation catheter is positioned in the RV just above the tricuspid annulus; stimulation at this site produced a pacemap identical to the clinical tachycardia. During VT, fractionated endocardial activity was recorded ± 110 ms before the onset of

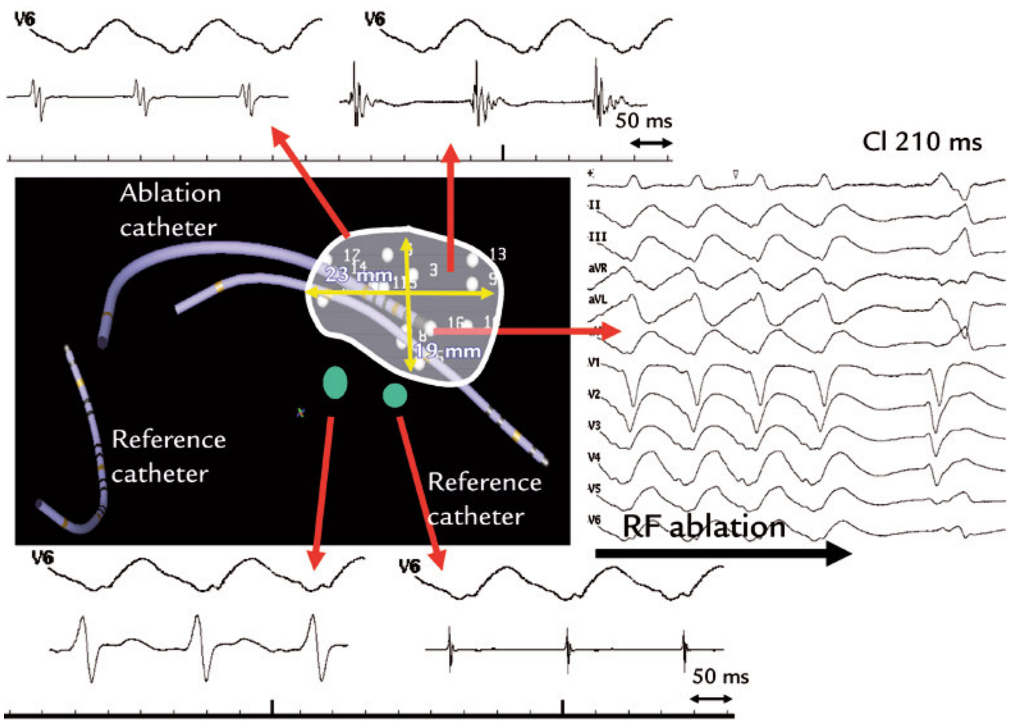

Figure 6.
RFCA in a patient with a post-myocardial infarction VT. It again gives the position of both reference catheters (colored panel). The ablation catheter is positioned in the LV at a site showing mid-diastolic potentials preceding the myocardial activation (upper panels). During ablation at this site, tachycardia stopped and was no longer inducible (right panel). The region around this site was ablated (encircled).

the surface ECG (lower tracing). During sinus rhythm, this area also showed fractionated endocardial activity (lower left tracing). The white dots within the encircled area represent the different ablation sites. During ablation, tachycardia was terminated and no longer inducible (upper left panel). Fractionated endocardial activity was also recorded in the RV outflow tract (upper right panel).
An example of an ablation procedure in a patient with a post-myocardial infarction VT is shown in **Figure 6**. It again gives the position of both reference catheters (colored panel). The ablation catheter is positioned in the LV at a site showing mid-diastolic potentials preceding the myocardial activation (upper panels). During ablation at this site, tachycardia stopped and was no longer inducible (right panel). The region around this site was ablated (white dots, 23 x 19 mm). After ablation VT was not inducible anymore.

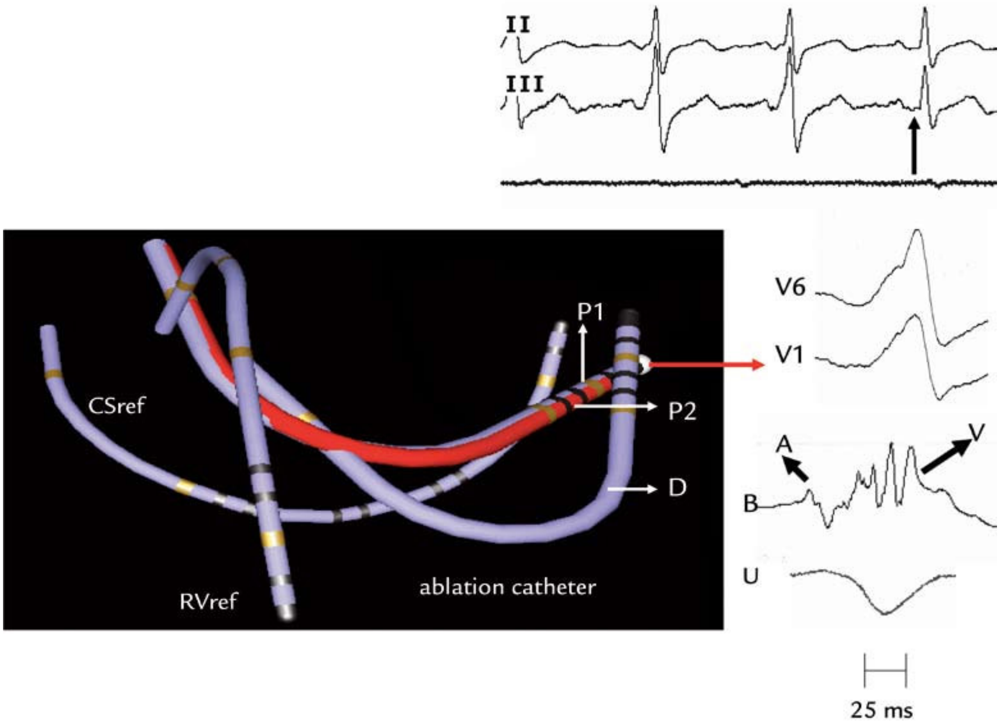

Figure 7.
RFCA of a left lateral accessory pathway (RAO view). The reference catheters in the coronary sinus and the RV apex are shown. The site of successful ablation is marked with a white dot. During ablation the delta-wave disappeared (upper tracing). The corresponding unipolar (U) and bipolar (B) electrograms just prior to ablation are shown in the lower right recording.

Accessory pathways

Five patients with an accessory pathway were studied. The ablation procedure was successful in all. Figure 7 gives an example of a RFCA in a patient with a left-sided accessory pathway. The position of the reference catheters and the ablation catheter is shown (color panel). When the ablation catheter was positioned at the target site, the ablation catheter dislocated (D). Due to the possibility of recalling previous positions of catheters (P1), the catheter was repositioned (P2).

At the site marked with the white dot, the delta wave disappeared during RF ablation (upper right panel). The local electrogram at the ablation site is shown in the lower right panel.

Discussion

Percutaneous endocardial activation mapping during RFCA using the new real-time position management system is feasible and reliable. The use of this system enables reproducible positioning and tracking of catheters.

During the last decade, RFCA has become an established and effective treatment modality for both supraventricular and ventricular arrhythmias.[1,2,8,12,22,23] Until recently, endocardial mapping guided by fluoroscopy only was difficult, inaccurate and time-consuming.[1,2,7] Therefore, non-fluoroscopic, 3-D mapping systems like the CARTO and LocaLisa system were developed.[17-21]

The electro-anatomical CARTO system enables real-time detection of both location and orientation of the tip of the mapping catheter. The position of the mapping catheter is recorded relative to an external reference patch.[17] The signal from an internal reference catheter is used as time reference. Thus a stable position of the reference catheter and a monomorphic and stable tachycardia are prerequisites for successful mapping.[8,19] When the cycle length of the tachycardia changes or when the reference catheter is dislocated, the activation map constructed becomes useless and a new activation map must be constructed resulting in a prolongation of the procedure time.[17] Another limitation of the CARTO system is the fact that only 2 electrograms can be displayed simultaneously. Furthermore, it is not possible to display unipolar and bipolar electrograms simultaneously, which may be desirable during ablation.[1,2] However the 3-D graphical representation of endocardial activation is, at this time, superior to all other available systems.[17]

The accuracy of the LocaLisa system also depends on a stable position of a reference catheter without the possibility of repositioning this catheter when dislocated.[21] At this time, only 2 catheters can be tracked simultaneously.

The 3-D real-time position management system presented in this study uses ultrasound ranging techniques to determine the position of an ablation catheter. Because the original position of the reference catheters can be recalled, it is possible to continue mapping in case of displacement of one of the catheters. The results of this study demonstrates that the system can be used in a variety of different clinical circumstances and that it results in a relative short procedure and fluoroscopy time.

Stability and Reproducibility

As the position of the ablation catheter is determined relative to internal reference catheters positioned in the RA or coronary sinus and the RV, the accuracy depends on the stability of these reference catheters. The results of Protocol I showed that displacement of reference catheters was relatively small during the different procedures. Only in case of DC shock cardioversion or defibrillation dislocation occurred, but due to the possibility to retrieve the original position it was possible to continue the procedures.

On the other hand, the results of Protocol II demonstrated, that even in case of displacement of the reference catheters, it was possible to navigate back to previously marked sites with an accuracy of ± 2mm which is comparable to the results obtained with the CARTO system and the LocaLisa system.[21]

Clinical Implications

The real-time display of the catheter's tip and the possibility of on-line retrieving previous positions and curves of a catheter facilitate repositioning of a catheter at previously marked sites. So far, no mapping system offered these features which facilitate catheter positioning. The use of this system will result in a reduction of the X-ray exposure. Routine application of the real-time position management system requires only the use of special catheters, no additional catheters or skin electrodes are needed. As any type of catheter containing ultrasound transducers can be "tracked" within the reference frame and used to locate positions it is possible to position for example 2 catheters simultaneously in the right and left atria to create lesions using this guidance system. This may be useful in case of the creation of linear lesions in atrial fibrillation patients.[24] The possibility to create lesions within a defined area will ease the systematical ablation of endocardial zones of slow conduction critical for the perpetuation of reentrant ventricular tachycardia or the treatment of AV nodal reentrant tachycardia.[5,8,25,26,27]

System limitations

At this time, limited graphic features are available, and it is not possible to display endocardial activation maps. To enhance the graphic representation, 3-D reconstruction of endocardial activation would be advantageous. Catheter integrity was good although failure of single ultrasound transducers occurred during some procedures. Inspite of that, reliable positioning could be performed in all patients (because each catheter contains 3 or 4 transducers).

Conclusions

The real-time position management system used in this study allow accurate and reproducible 3-D positioning of reference and ablation catheters, marking of anatomical structures and ablation sites. Routine use of this system will result in a limitation of both fluoroscopy and procedure time.

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