1 CHAPTER 1

Electroanatomical mapping technologies

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Introduction

Mapping of cardiac arrhythmias is the process of identifying, characterizing, and localizing an arrhythmia. Mapping forms the foundation for guiding ablation therapies and directing intervention. The principles and techniques for mapping have advanced considerably over the past decades. With improved understanding of cardiac arrhythmias including anatomical and structural relationships, the concept of combining the electrical information obtained using mapping catheters to anatomical information guided by catheter position and contact has been crucial in the understanding and success of catheter ablation.

The principle behind electroanatomical mapping involves using mapping catheters that collect electrical information from the tip of the catheter, such as the timing of the electrogram with respect to a stable timing reference as well as the local voltage, and combining this with catheter tip location information, where the electrical information was obtained. In this fashion, a three-dimensional surface geometry that represents the chamber of interest is created. The surface anatomical geometry can be color coded to represent timing or voltage. This allows the operator to examine an activation map of the arrhythmia wave front. In addition, the operator may be able to visualize areas of scar or areas of interest such as fractionated electrograms or anatomical landmarks.

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Current electroanatomical mapping systems utilize either contact or noncontact mapping. Contact mapping relies on the mapping catheter making contact with the endocardial border and sequentially acquiring location data points over many cardiac cycles. Current systems that use this technique include CARTO™, NavX™, and Realtime Position Management. Noncontact mapping is based on a concept of simultaneously acquiring electrogram data of an entire chamber without making physical contact with the endocardial border. The only system that currently uses this technique is the EnSite Array™.

Three-dimensional mapping systems are currently being utilized by the majority of cardiac electrophysiology laboratories in the United States as well as internationally for mapping and ablating a variety of arrhythmias.

Electroanatomical mapping systems

The Biosense CARTO™ system

The first description of the use of nonfluoroscopic electroanatomical mapping *in vivo* by Ben-Haim *et al.* in 1996 heralded the beginning of the use of this technology for catheter ablation [1]. The technology, which became Biosense CARTO™, was the first three-dimensional electroanatomical system. In the initial study, CARTO™ was used to map and navigate the right atrium during both normal sinus rhythm and atrial flutter, proving that nonfluoroscopic electroanatomical mapping techniques were feasible *in vivo*. The Biosense CARTO™ system has been extensively validated and has been used to map a variety of arrhythmias in all cardiac chambers.

The technology can be used for mapping ventricular tachycardias, atrial tachycardias, and identification of scar using voltage map [2–6].

The Biosense CARTO™ system utilizes a magnetic field sensor incorporated in the tip of a deflectable quadripolar mapping catheter (NAVISTAR™) and an external magnetic field emitter located under the patient and the operating table. The external magnetic field emitter utilizes three coils that generate an ultra-low magnetic field (between 5×10^{-6} and 5×10^{-5} T) that codes the mapping space around the patient's chest with both temporal and spatial information [7]. Spatial information is encoded in the decaying magnetic field as a function of distance from the coil. The magnetic field sensor at the tip of the catheter measures the strength of the magnetic field from each coil, this can then be used to calculate the distance from each coil. The location of the catheter in space is computed as the intersection of the distance from the three coils (Figure 1.1). The magnetic field contains the information needed to determine the sensor location in six degrees of freedom, dimensions (x, y, z), and orientation (roll, yaw, pitch).

An electroanatomical map is generated when the mapping catheter is manipulated around the cardiac chamber and data points are sequentially collected. Data collection includes three-dimensional spatial location corresponding to electrical data of local activation time relative to the reference location. By sequentially acquiring data from multiple endocardial points, a detailed three-dimensional electroanatomical map is generated. As more points are acquired, the more detailed the map is.

To correct for minor patient movement, a reference is used, which is located on the patient's back (REF-STAR with QuikPatch). The mapping system subtracts the location of the mapping catheter from the simultaneous location of the reference patch to compensate for any patient motion.

Recently, Biosense CARTO™ has introduced a module that allows for the incorporation of a pre-acquired three-dimensional image obtained using computer tomography (CT) or magnetic resonance imaging (MRI) into the electroanatomical map as a fully registered image. This new software, CARTOMERGE™, merges the CT and MRI data with the electroanatomical map obtained during the procedure (Figure 1.2). This technology is useful for the ablation of atrial fibrillation, where the ablation strategy may often be anatomical and an understanding of each patient's individual variation may be useful [8–10]. Recently, Fahmy *et al.* showed that posterior wall landmarks at the pulmonary vein and left atrium junction are the most accurate landmarks for image registration and integration of cardiac CT data with CARTO™ [11].

Potential limitations to the Biosense CARTO™ system are the sequential mapping on a point-by-point and beat-by-beat basis. This limits the use of this technology for unsustained or unstable rhythms as they are difficult or time consuming to map. Despite this limitation, for some unstable arrhythmias, difficult-to-induce rhythms, or sustain rhythms, generating a voltage map in normal

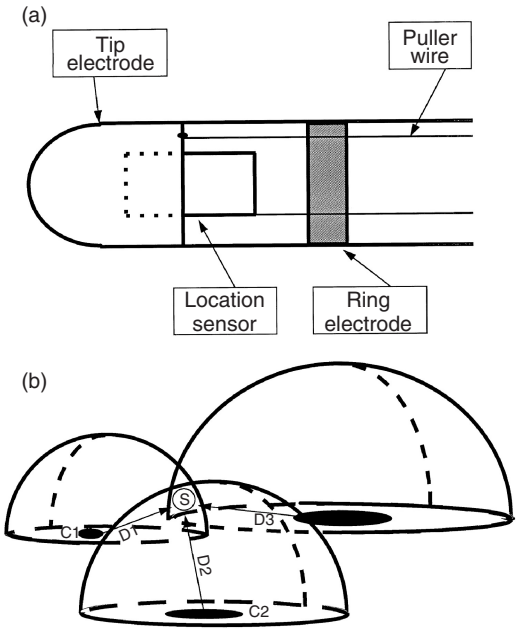

Figure 1.1 The new locatable catheter (a) and the process of location determination (b). (a) The locatable catheter is composed of tip and ring electrodes and a location sensor totally embedded within the catheter. (b) Process of location determination. A location pad is composed of three coils (C1, C2, C3) that generate a magnetic field that decays as a function of distance from that coil. The sensor (S) measures the strength of the field, and the distance from each coil (D1, D2, D3) can be measured. The location of the sensor is determined from the intersection of the theoretical spheres whose radii are the distances measured by the sensor. (Reprinted with permission from Reference 7.)

sinus rhythm may help the operator gain insight on potential arrhythmia circuits in the case of and may result in a successful ablation outcome. Another potential limitation includes the possibility that the system accuracy may be compromised by the presence of any material that may disrupt the magnetic field. As the spatial orientation is calculated from the measured strength of the generated magnetic fields from the coils, any disturbance to the magnetic field or strength may lead to inaccurate distance measurements, although this would be rare in a well-shielded modern electrophysiology laboratory. Additionally, the Biosense CARTO™ system is sensitive to patient motion because of the location of the coils underneath the patient. This necessitates remapping of the arrhythmia if significant patient movement is detected and can be time consuming or lead to inaccuracies if not detected relatively quickly. In addition, significant movement of the internal reference catheter can also lead to map inaccuracies. Finally, the Biosense CARTO™ system requires the use of proprietary single-use catheters made by Biosense Webster and does not support the use of other manufacturer catheters.

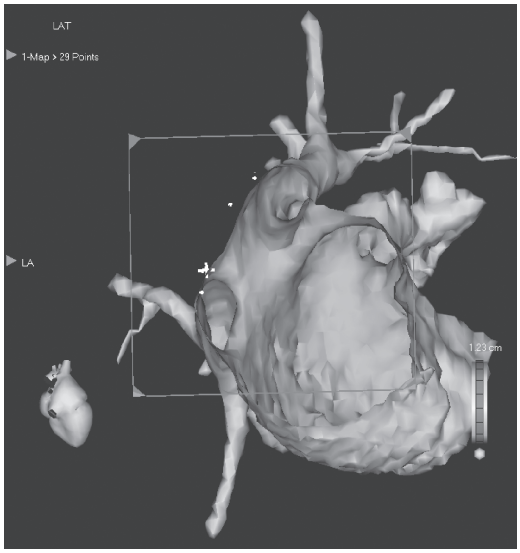

Figure 1.2 Registered three-dimensional left atrial surface reconstruction showing the left pulmonary veins during pulmonary vein isolation for atrial fibrillation using CARTOMERGE™.

St. Jude Medical EnSite Array™ system

In 1998, a second mapping system, EnSite 3000, later renamed EnSite Array, by St. Jude Medical (St. Paul, MN) was described by Schilling *et al.* They compared the left ventricular electroanatomical map of the new noncontact mapping system against a traditional contact map of 13 patients undergoing left ventricular ablation [12]. The EnSite Array™ system is a noncontact mapping system that allows for simultaneous recordings from multiple sites within a single cardiac chamber. In addition to the ability of the system to map sustained atrial or ventricular arrhythmias, the system can be used for mapping of nonsustained or hemodynamically unstable arrhythmias. It can also be used to map multiple cardiac cycles allowing the ability to visualize changes in the electrical map over time. The system can be used in conjunction with the EnSite NavX™ system.

The system utilizes a 9-Fr catheter with a 7.6 mL (18 × 40 mm) ellipsoid balloon surrounded by 64 multielectrode array (MEA) [12] (Figure 1.3). Each of the 64 electrodes is electrically insulated and has a 0.025-in. break in the insulation,

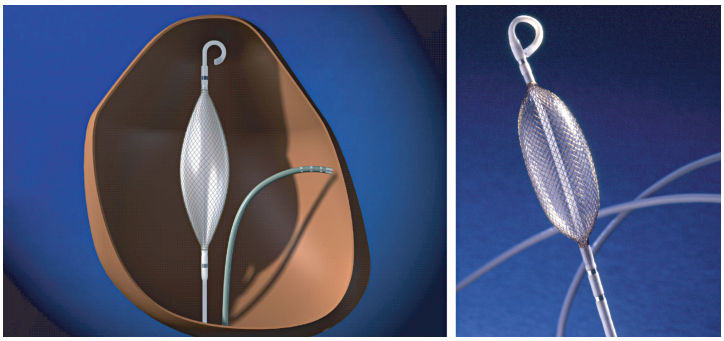

Figure 1.3 EnSite Array™ noncontact system with MEA. (Courtesy of St. Jude Medical.)

allowing it to function as unipolar electrodes. Raw far-field electrogram data generated by the endocardial surface are acquired by the MEA and fed into a multichannel recorder and amplifier system. Laplace's equation with boundary conditions can be used to describe how potentials at the endocardial boundary would appear at a remote location. The solution to the inverse Laplace's equation using the boundary element method would predict how a remotely detected signal by the EnSite Array™ would have appeared at its source, the endocardial border. The solution creates 3360 "virtual" endocardial electrograms making up the endocardial boundary.

The system also has a locater system to locate any conventional catheter in space relative to the EnSite Array™. Location is achieved by using a low-current, 5.68-kHz signal passed between the ablation tip and between the ring electrodes proximal and distal to the EnSite Array™. This is used to generate a more anatomically accurate endocardial model to plot the reconstructed endocardial electrograms. The locator signal is also used to display the position of the mapping catheter on the virtual endocardium during a study.

Limitations to the system include loss of accuracy of virtual electrograms if the endocardial surface is greater than 34 mm away from the balloon surface [12]. Large endocardial borders within a large volume may require MEA repositioning to collect adequate virtual electrogram data. This makes mapping of ventricular tachycardia in a large left ventricle potentially difficult. In addition, the EnSite Array™ has a volume of about 8–10 mL, and positioning of the MEA in small areas may limit the movement of the ablation catheter [13]. Low endocardial voltages may also be missed as it may be too weak to be detected by the time the signal reaches the MEA. And lastly, during a 1:1 tachycardia, mapping in an area with simultaneous atrial and ventricular components such as atrioventricular nodal reentry tachycardia (AVNRT) may be difficult.

St. Jude Medical EnSite NavX™

The latest mapping technology to come to market is EnSite NavX™ by St. Jude Medical, which was first described by Ventura *et al.* in 2004 [14]. In a randomized study of 40 typical atrial flutter ablations comparing NavX™ to traditional fluoroscopy, the NavX™ system significantly reduced fluoroscopy time without significantly increasing procedural time. This mapping system allows the display of exact anatomical position of multiple conventional electrophysiology catheters in real time. In addition, the navigation system can be used with the EnSite Array™ catheter. The system has been used for mapping atrial and ventricular tachycardias [14,15].

The system includes three external orthogonal electrode pairs positioned on the body surface for catheter location [14,16,17] (Figure 1.4). One electrode pair is placed at the back of the neck above C3/4 and the medial upper left leg. The second electrode pair is placed on the left and right lateral thoracic cage close to T5/6. The third electrode pair is placed on the anterior and posterior chest at position T2. The six electrodes form three orthogonal axes with the heart at the center. A maximum of 64 electrodes (maximum 8 catheters) with up to 20 electrodes per catheter can be detected. A 5.68-kHz constant low-current locator signal is multiplexed with each pair of surface electrode to create a transthoracic electrical field. The potential

Figure 1.4 EnSite NavX™ navigation system (left) with external reference pads (right). (Courtesy of St. Jude Medical.)

difference between these electrode pairs and each catheter electrode is measured. A multiplex frequency of 93 Hz allows almost real-time navigation and visualization of catheter position. Any movement of the catheter causes a change in the measured voltage potential and impedance for each electrode. The potentials are defined with respect to a reference electrode. The reference electrode can be a surface electrode or an internally fixed electrode such as a coronary sinus catheter electrode. The position of the electrode can be determined to an accuracy of 0.6 mm. Electroanatomical mapping is obtained by manipulating a conventional mapping catheter throughout the heart cavity to generate a three-dimensional endocardial border. An endocardial surface geometry can be generated in a short period of time.

One potential limitation to the EnSite NavX™ system similar to the CARTO™ system is that it requires a stable rhythm as mapping is done sequentially on a point-by-point and beat-to-beat basis. However, unlike CARTO™, electrograms from multiple poles of a catheter may be recorded simultaneously. The EnSite NavX™ has recently released a software version that allows integration with CT or MRI. Adding this will undoubtedly increase the utility of this mapping system in the ablation of atrial fibrillation and potentially ventricular tachycardia as well.

Boston Scientific RPM™ Realtime Position Management

The RPM™ Realtime Position Management by Boston Scientific (Natick, MA) was first used and described by de Groot *et al.* in 2000 [18]. In that study, 30 patients referred for radiofrequency catheter ablation used the RPM™ system to map and track the position of the ablation catheter relative to two reference catheters with good success. The Boston Scientific RPM™ Realtime Position Management system is the first mapping system to use the technique of ultrasound ranging for mapping. The system uses an internal reference system that removes the need for skin electrodes or patches as well as minimizes the impact of respiratory variations and patient movement. The system has been validated in both atrial and ventricular tachycardia [18,19].

The navigation and mapping system includes an acquisition module and an ultrasound transmitter/receiver unit connected to a SPARC 20 computer (Sun Microsystems, Palo Alto, CA). The system can simultaneously process seven position management catheters, 24 bipolar/48 unipolar electrograms, a 12-lead ECG, and 2 pressure signals. The intracardiac part consists of a series of transmitters and receivers of ultrasound pulses on reference catheters. The time delay between transmitters and receivers is proportional to the distance between the transducers assuming a speed of sound in the blood of 1550 m/s. The time and distance information is transmitted back to the computer for real-time display. The catheter positions are used to reconstruct a three-dimensional endocardial geometry. There are three catheters, two reference catheters, and one mapping/ablation catheter. The reference catheters are 6-Fr multipolar catheters, and the first reference catheter is usually positioned in the right ventricle and the second reference catheter can be positioned in the right appendage, lateral right atrium, or the coronary sinus. For mapping/ablation, a 7-Fr, 4-mm-tip bidirectional steerable ablation catheter is used. The reference catheters are equipped with four ultrasound transducers whereas the ablation catheter only has three. The right atrial reference catheter contains nine 1-mm ring electrodes and one 2-mm tip electrode with 1-mm interelectrode distance. The right ventricular reference catheter contains three 1-mm ring electrodes and one 4-mm tip electrode. The ultrasound transmitter sends a continuous cycle of ultrasound pulses at 558.5 kHz to the transducers of the reference and ablation catheters. The electroanatomic mapping of the heart is generated by manipulation of the mapping catheter along the endocardial surface.

A limitation to this system is the need of at least three catheters to provide internal reference. As the localizing technology uses ultrasound frequency, the use of intracardiac echocardiography may be limited. In addition, the catheters are proprietary single-use catheters made by Boston Scientific.

Future direction of electroanatomic mapping

Electroanatomical mapping is increasingly being used for all kinds of ablation procedures. The technology including better mapping and visualization has improved significantly over the past few years.

In addition, advancements in integration with CT and MRI data sets are improving rapidly. Future advancements may include electroanatomical map integration with intracardiac echocardiogram or three-dimensional fluoroscopy.

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