Radiofrequency ablation for cardiac tachyarrhythmias: principles and utility of 3D mapping systems

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Radiofrequency ablation for cardiac tachyarrhythmias is one of the most innovative achievements in cardiology. The ability to 'cure' a potentially fatal condition rather than palliate, as in most chronic diseases, is perhaps the underlying factor that gives it the novelty. The field has grown tremendously within a short span of 25 years. The concept of three-dimensional electro anatomic mapping, wherein a 3D geometry of the chamber(s) is made and then contact mapping done to show the location and electrical activity at the same place is a remarkable advancement. Such three-dimensional mapping can now be integrated to MRI/CT images on which electrical signals can be anatomically marked. This article addresses the technology behind these systems as well as its clinical application. This may interest the basic scientists who after understanding its advantages and limitations can then focus on evolving newer strategies.

Keywords: Arrhythmias, cardiac mapping, electrophysiology, radiofrequency ablation.

Introduction

ADVANCES in electrophysiology and radiofrequency ablation (RFA) have practically 'eradicated' simple arrhythmias like accessory pathways, atrioventricular nodal tachycardia (AVNRT; see Appendix 1) and focal atrial tachycardias in the developed world. Other simple substrates like fascicular ventricular tachycardia (VTs), right ventricular outflow tract tachycardia (RVOT) and typical atrial flutter can now be successfully ablated in over 95–97% with occasional recurrences[1–3]. Several arrhythmias that were never thought to be amenable to ablation have also been shown to have an underlying trigger and substrate that can be modified by ablation. Thus paroxysmal atrial fibrillation (AF) can now be cured by electrically isolating the pulmonary veins and even chronic AF known to be due to multiple small wavelets in the left atrium can be treated to some extent by doing an additional catheter-based or a surgical Maze operation[4–6]. VTs in the presence of ischaemic heart disease or arrhythmogenic right ventricular cardiomyopathy (ARVC) can also be modified by trans-catheter techniques, wherein scars in the ventricles are targetted[7,8]. Idiopathic ventricular fibrillation (VF) and polymorphic VT in long-QT syndrome have been successfully ablated in selected patients who are symptomatic[9,10]. Such therapies are also useful as an adjunct to an implantable cardioverter defibrillator (ICD) for patients getting frequent shocks due to recurrent ventricular tachycardia[11].

An equally important area in which these systems have contributed immensely is in the understanding of arrhythmia mechanisms, the circuits in reentry, mechanism of recurrence and planning of the approach. Macroreentrant arrhythmias in the atrium have now been demonstrated to have several circuits and may not involve the typical cavotricuspid isthmus. Postoperative scar-based reentry may be due to a surgical incision scar or large atrial scars because of chronically elevated atrial pressures in a Fontan circulation[12,13]. Such arrhythmias along with atrial fibrillation, ischaemic VT and some others need a large area of ablation in different 'formats'. Designing lines along the map helps in delivering targetted therapy in these complex arrhythmias. Outlining the pulmonary vein ostium by mapping techniques or intracardiac echocardiography[14] helps in decreasing complications of pulmonary vein ablation by avoiding burns inside the veins. Such clear demarcation of anatomy and physiology was not possible with the conventional systems and these advances have been tremendously useful for clinical, teaching and research work. These recent advances are the focus of this article.

Limitations of conventional mapping

RFA has revolutionized the management of tachyarrhythmias. From being one of the most feared cardiological field, it has become one of the most sought after subspecialty in cardiology. This stems from the fact that it can potentially cure, unlike most other chronic cardiac or extra-cardiac diseases. In addition, the rapidly evolving technology and the huge investments in research are fuelling new opportunities. Conventional mapping techniques have been extremely useful in understanding and

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managing most of the 'relatively' simpler arrhythmias. Even though the fluoroscopic procedure is still used in over 90–95% of simple ablations, its limitation in providing a good 3D geometry is evident while doing complex cases like VT with structural heart disease or designing long continuous lesions in AF ablation. Fluoroscopy provides only a two-dimensional image of the heart, wherein it is difficult to guide your catheter repeatedly to the area of interest.

Need for non-fluoroscopy systems

Non-fluoroscopic systems are useful beyond a mere decrease in radiation exposure. Even though increasing operator experience has decreased the long electrophysiologic procedure times significantly, radiation hazards remain a major issue. Further, radiation is an important issue in infants and children, wherein it may be useful to use the non-fluoroscopic systems even for simple tachycardias. Thus the recent 3D systems which integrate electrophysiologic signals with anatomy to provide a three-dimensional geometry (which was not possible with conventional fluoroscopy) are extremely useful in situations where radiation needs to be limited as much as possible.

During intracardiac mapping it is not unusual to find sites at which the operator feels ablation is likely to succeed. With routine fluoroscopy mapping because of the fear of not being able to come back to such sites, the operator often gives burns in these areas that may be unnecessary. Three-dimensional systems allow the marking of such points and carry on mapping as the stored 3D geometry can guide the operator by allowing the marking of precise points of ablation and also facilitating fixing the reference point if the ablation process has to be repeated. Tagging of points also allows demarcation of ostium of venous structure, His bundle, crista, coronary sinus and valves, which are generally the points of reference and abalation. Failed recurrences can be better targeted as the precise point of breakthrough can be located as in an atrial flutter, wherein isthmus mapping will show the remaining small area of live tissue that is responsible for the continuing conduction. Some tachyarrhythmias and population subsets where arrhythmia control is a major clinical problem and where these systems are promising are listed in Table 1.

What is possible with current systems?

Current systems are able to integrate the location of a point within the heart with the activation time, and unipolar and bipolar voltage at that spot. Ongoing research has also been able to integrate the anatomy with this physiological information. Presently the anatomy is generated offline by a CT/MRI and the image of the appropriate chamber is frozen on the mapping system and provides the chamber geometry over which points are taken while mapping[15–17]. Ongoing research will be able to fuse live ultrasound images with these maps and also sort out other shortcomings of these procedures. Although there are several such mapping systems, this discussion is predominantly focused on two of the most commonly used systems. These are CARTO (Biosense Webster, Inc., CA, USA) and EnSite (EnSite System, St Jude Medical, St Paul, Minnesota, USA).

CARTO has been derived from the word 'cartography' that is the science and art of map-making. Broadly, this system consists of an intracardiac electrophysiologic mapping catheter with miniaturized coils at the tip, a magnetic field generator (emitter) located underneath the patient, a unit which analyses the current generated by the coils in the tip of the catheter and a post-processing graphical display unit (Figure 1).

The fundamentals of the system are based upon a principle in physics, that a metal coil placed in a magnetic field can generate a current. The size of this current is proportional to the strength of the magnetic field and the orientation of the coils in the field. The location pad fixed beneath the patient table has three coils that generate ultra low magnetic fields (1, 2 and 3 kHz; Figure 2). The emitted fields possess well-known temporal and spatial distinguishing characteristics that 'code' the mapping space around the patient's chest. Two location sensors are used, one in a circular reference patch (Refstar) strapped onto

Table 1. Complex tachyarrhythmia/population subsets needing newer technologies

Supraventricular arrhythmias
• Accessory pathways
In infants and children
Pathways close to vital structures like AV node/sinus node/HB/phrenic nerve
Failed Mahaim
Associated structural heart defects
• Intraatrial reentrant tachycardias
Post Fontan, Glenn, atrial switch
• Atrial fibrillation
CHF including CAD, DCM
HCM
RHD
Junctional tachycardias
• Acquired: postoperative, myocarditis
• Congenital
Ventricular tachycardia
• Failed ventricular tachycardia's in normal heart's
• Scar-based
ARVC
Myocardial infarction
Ventricular fibrillation
• Idiopathic
• Recurrent polymorphic VT in long QT and Brugada syndrome

the patient's back, fluoroscopically within the cardiac silhouette in anteroposterior (AP) projection and the other at the tip of the intracardiac mapping catheter (Navistar) inserted into the cardiac chamber/s, as in any normal cardiac catheterization procedure. The location is mapped in three-dimensions with reference to a fixed point. The location of each sensor is determined by its distance from the location pad. Reconstruction is done by calculating the distance between the two sensors. If the patient moves, the distance of each sensor from the location pad is changed, but the distance between the sensors is retained. The three distances determine the location, orientation and rotation of the catheter. Sensing of the magnetic field by the location sensor enables the determination of the location and orientation of the catheter in six degrees of freedom (see later in the article)[18,19].

The activation time is referenced against an ECG lead or an intracardiac catheter. For atrial mapping one of the bipoles of the catheter in the coronary sinus is used since it remains stable in that position. Any movement of the reference bipole will change the activation times of the

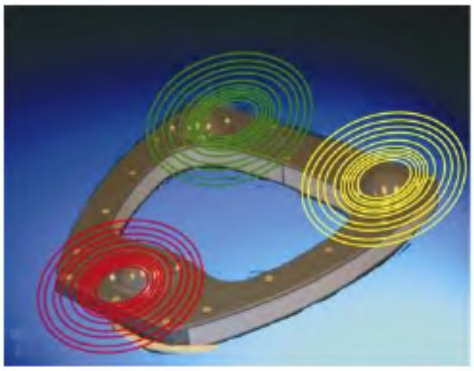

Figure 1. Location pad of CARTO XP system, an external ultra-low magnetic field emitter. The three electromagnetic fields (denoted by different colours) possess temporal and spatial distinguishing characteristics.

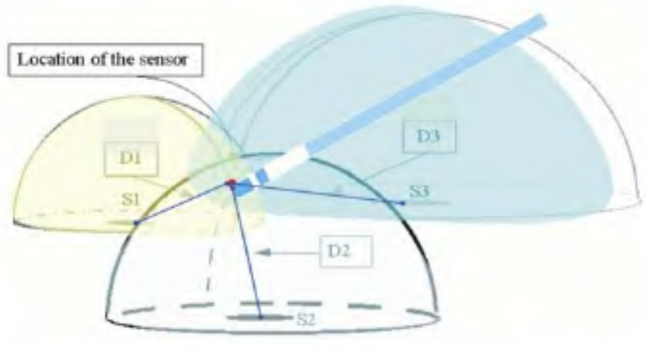

Figure 2. Three electromagnetic fields originating from location pad emitters (S1, S2 and S3). Spatial location of the catheter tip is accurately found by the electromagnetic fields, by determining the distance of the sensor on the catheter tip (blue) from each emitter (D1, D2 and D3). This information is instantly computed using the triangulation principle (see text), to generate the real-time position of the catheter tip. (Images courtesy: Biosense Webster.)

selected points thus invalidating the map. For ventricular mapping, the QRS in a lead showing a good positive or negative deflection with no slurring or notching is used to mark the QRS consistently on the same point in the QRS. It should be ensured that the signals have a clean negative or positive upstroke without any slurring as this can lead to wrong tagging on the reference point that again makes the map uninterpretable. It is important to take the point for location and timing during the same time in every cardiac cycle as this variation would also lead to incorrect markings.

The activation time can be taken during the tachycardia or during sinus/paced rhythms. In general, it is essential to have a nearly fixed heart rate for mapping the activation timings, as a sudden change in the tachycardia cycle length or a new tachycardia coming up during mapping can lead to confusion. It is therefore important to be able to pick up the exact time/point when the tachycardia changes. Editing each point is also an important part of the study wherein the location, activation time and cycle length are checked to be correct. For this, a set deviation in location/cycle length and local activation time (LAT) is acceptable. In CARTO this is done by superimposing the current beat with the previous beat in terms of these three characteristics. At each frozen point during mapping the computer grabs the local electrogram (EGM) of the previous ten beats. The electrophysiologist immediately selects the beat having the best local electrogram out of these and accepts it. However if such a point has to be either deleted or selected, care has to be taken that it does not alter the map radically. The labelling of the intracardiac EGM from the mapping catheter is modifiable later, wherein one can choose to tag either the maximum deflection or onset to keep the map uniform. It is also essential to take surface points, as inner points can cause confusion both in terms of the location, activation time and voltage. The reference catheters on the back and within the heart have to be stable as movement of any of them can change the map contour and render it inaccurate. Alternative processes that can lead to faster mapping are needed; one of these is to use a Kwikmap® catheter that has the capability to take six points at one go because of more active bipoles.

Degrees of freedom

For the uninitiated, this terminology appears somewhat complex, especially when one realizes that the term has different connotations depending on the subject like physics, chemical engineering, or statistics and even robotics. The number of degrees of freedom (DOF) that a manipulator possesses is the number of independent position variables that would have to be specified in order to locate all parts of the mechanism. In effect, the DOF as applied to CARTO mapping imply the number of ways the mapping catheter can be placed on one specific point

or the number of parameters that are needed to specify the exact place the catheter tip is on a point in the 3D space around the patient. To understand the concept one needs to look at the DOF that our shoulder joint enjoys – a human arm is considered to have seven DOF. A shoulder gives pitch, yaw and roll, an elbow allows for pitch, and a wrist allows for pitch, yaw and roll. Tilting up and down is pitch, turning left and right is yaw, and roll is in the anteroposterior direction in the sagittal plane. A point mapped on the heart is thus marked in the X, Y and Z planes, the way in which the catheter tip touches the point from top, side or in the anteroposterior direction.

The EnSite system

The EnSite system has two different techniques for mapping – the no contact mapping by the balloon array (EnSite array) and a contact mapping system (EnSite NavX), wherein points assimilate anatomic and physiologic information in reference to five location patches applied to the skin at different places. For EnSite array studies, the geometry is required for solving signal algorithms and displaying iso-potential maps. For EnSite NavX studies, the geometry is not required.

Hardware and basic functioning

The EnSite multi electrode array (MEA) is a mesh basket of 64 braided surgical-steel wires with a polyimide coating. The unipolar electrodes are created by removing a small area of insulation for each wire.

The MEA is introduced into the body like any other catheter and inflated to 7.5 ml after positioning it in the chamber of interest (Figure 3). The balloon array electrodes make galvanic contact with the blood and sense the electrical potentials induced upon them by the electrical fields generated by myocardial activity. The sensed signals can be of the order of tens of microvolts for non-contact mid-diastolic potentials to several millivolts for contact potentials, if an Ensite electrode happens to come in contact with the endocardium. Two ring electrodes (E1 and E2) used to build the geometry of the chamber are located on the catheter shaft about 1 cm proximal and distal to the MEA. A third ring electrode (E3) meant to serve as a reference for unipolar signals is located on the catheter shaft about 16 cm proximal to the MEA. The EnSite array and a conventional EP catheter (connected to the EnSite system) are placed in the heart in the same chamber. The Patient Interface Unit (PIU) sends a 5.6 kHz signal through an EP catheter electrode 200 times per second. E1 and E2 alternately receive and return the 5.6 kHz signal to the PIU. Each of the 64 electrodes on the EnSite array electrode senses the strength of the 5.6 kHz signal. Using the sensed 5.6 kHz voltages and the respective array electrode locations, the three-dimensional position of the EP catheter electrode is precisely located relative to the position of the EnSite array.

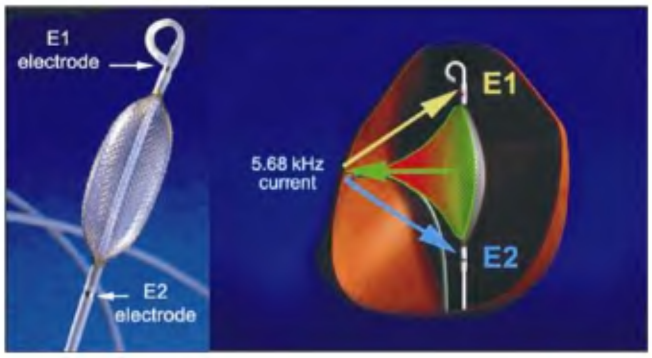

Figure 3. The EnSite balloon array along with the ring electrodes E1 and E2. These ring electrodes are used to build the geometry of the chamber and are located on the catheter shaft about 1 cm proximal and distal to the multi electrode array (MEA). The third ring electrode (E3) meant to serve as a reference for unipolar signals is located on the catheter shaft about 16 cm proximal to the MEA (not shown in the figure). The Patient Interface Unit (PIU) sends a 5.6 kHz signal through an EP catheter electrode 200 times per second. E1 and E2 alternately receive and return the 5.6 kHz signal to the PIU (see text for further details). (Images courtesy: St Jude Medical, Inc.)

For EnSite NavX studies, five patches are applied on the patient's skin in such a way that this placement forms three orthogonal axes with the heart at the centre. The patches are applied front to back, left to right, and inner left thigh to the back of the neck. Conventional EP catheters (connected to the EnSite system) are placed in the heart. The PIU alternately sends a 5.6 kHz signal through each pair of surface electrodes to create a trans-thoracic electrical field. The signal is sensed by all electrodes connected to the EnSite system. Using the sensed 5.6 kHz signal, the three-dimensional position of each conventional catheter electrode is located relative to a user-selected positional reference. The location of EP catheter electrodes appears in the map display as EnGuide locators.

The EnSite array is the only non-contact mapping system that can identify the path of a single atrial/ventricular beat and thus does not need a sustained arrhythmia to be able to map. This is obviously useful in settings where a sustained tachycardia leads to hemodynamic deterioration or when few ectopics are available to be able to create a map. Map points may be added from the active electrode, all electrodes on a specified catheter, or all electrodes in use. Several tools are available to facilitate interpretation, like iso-potential mapping, virtual waveforms, and single-beat isochronal maps, find early activation tool, auto focus colour controls and dynamic substrate mapping (DSM) tool.

EnSite array algorithm

The EnSite system uses the chamber geometry to solve the inverse problem for Laplace's equation at 64 locations on the geometry surface. The process creates an

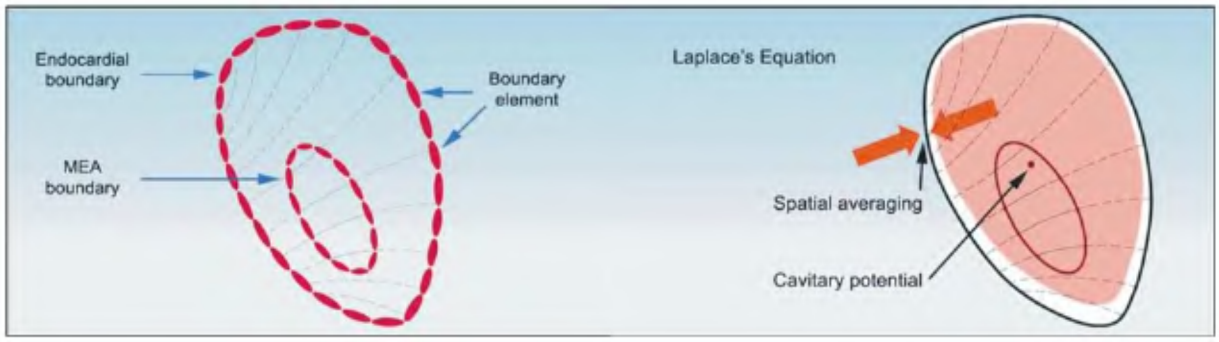

Figure 4. Chamber geometry to solve the inverse problem for Laplace's equation at 64 locations on the geometry surface. The process creates an isopotential map surface with more than 3000 virtual EGMs. The boundary element method for each array electrode divides the boundaries of the chamber geometry and the MEA into narrow elements. Laplace's equation by spatial averaging of voltages on the outer boundary (endocardium), allows us to determine the precise voltages at any point within the cavity. The potential field at any one electrode (point shown) is influenced by electrical potentials from the entire endocardium, with the degree of influence diminishing as distance between the electrode and each endocardial point increases. (Images courtesy: St Jude Medical, Inc.)

isopotential map surface with more than 3000 virtual EGMs (Figure 4). The Laplace equation states that if the voltages measured on an outer boundary (endocardium) are known, voltages everywhere inside the chamber can be calculated. The potential field at any one electrode (point shown) is influenced by electrical potentials from the entire endocardium, with the degree of influence diminishing as distance between the electrode and each endocardial point increases. Using the known information about the MEA, chamber geometry, and position and distance of the MEA relative to the endocardial surface, the EnSite system can construct endocardial EGMs from MEA potentials. To solve the inverse problem for Laplace's equation, the cardiac mapping system uses the boundary element method for each array electrode. This method divides the boundaries of the chamber geometry and the MEA into narrow elements. It then accurately estimates the electrical behaviour within and between each element combining which estimates the endocardial potential. Additional processing allows the cardiac mapping system to calculate the electrical potential at more than 3000 points on the endocardium. This information is collated by means of triangulation.

Triangulation refers to measurements using triangles and is also referred to as cartography, the science of making maps. Triangulation, in advanced geometry, involves the division of the Euclidean plane into triangles, or of a higher-dimensional Euclidean space into simplices. It is the process of finding coordinates and distance to a point by calculating the length of one side of a triangle, given measurements of angles and sides of the triangle formed by that point and two other known reference points, using the law of sines. In 3D mapping acquisition of each point creates a triangle that is seen in the mesh map (Figure 2). The mesh map is able to show the likely degree of extrapolation and also the 3D location of each point.

Combined anatomic and physiological imaging

Over the past 3 years, substantial progress has been made in the integration of anatomic and multisite computer-assisted mapping. This process requires multiple steps, beginning with the acquisition of cross-sectional or 'axial' CT or MRI at sufficient resolution to delineate cardiac structures <1–2 mm in thickness. Achievable slice thickness on CT at present is 0.6 mm, and slice increment is 0.4 mm that lets a significant amount of overlap of images, ensuring high-resolution images. Images at 0.625 mm thickness can be reconstructed from images obtained at 1.25 mm intervals with currently available multirow, helical scanners and dual-source CT scans. This along with a multiplane spatial resolution of 0.4 mm provides a true isotropic resolution of all axes in three-dimensions. ECG gated images on a dual-source CT provide the highest available temporal resolution of 83 ms at a gantry rotation time of 330 ms. A high temporal resolution implies reduction of artefacts due to high heart rates or tachyarrhythmias. MR may directly define the atrial walls, openings of pulmonary or other veins and other structures like appendages, pectinate muscles, crista terminalis and subeustachian sulcus; however, the spatial resolution is inferior to that of currently available multislice CT. An MRI can provide a better temporal resolution of 45–50 ms, but the long acquisition time during which the patient should not move makes it impractical to use. Overall, multislice CT technology with ECG gating and better temporal resolution, along with superior spatial resolution leading to better 3D reconstructions, is probably a better option for anatomical mapping of the cardiac chamber. MRIs are likewise obtainable, although at slightly less spatial resolution.

Rendering a 'volume' or reconstructing any cardiac chamber in three dimensions from the axial images is a straightforward process using any one of a variety of

software packages. The process of 'extracting' that chamber or volume from its surrounding structures or 'segmentation' is not difficult, provided there are sharp contrasts in the image between the chamber or structure of interest and the neighbouring tissue. These segmented volumes can also be viewed from an external perspective or from within the chamber using virtual endoscopic or cardioscopic displays.

Although such segmented structures are highly useful in visualizing the cardiac structures and characteristics of the tissue forming that structure, they do not convey the physiology of an arrhythmia. Integrating that physiology, as captured by electroanatomic or noncontact mapping, with the spatial information contained in the CTs and MRIs requires 'registration' of activation or voltage data to an appropriate location on a three-dimensional representation of a chamber. Global LA activation during sinus rhythm and at the onset of AF, as recorded in non-contact and electroanatomic mapping, has likewise been registered to rendered CT volumes and matched to specific surfaces of the LA. This concept will rapidly expand to include the registration of activation maps, voltage maps, and information from other technologies measuring physiological variables. This is of critical importance in that it establishes the relationship between anatomy and physiology as required for the structure/activity-based understanding of arrhythmias and for enabling image-guided intervention. Both the CARTO and EnSite systems have this merge tool available using different algorithms.

These approaches are limited by the requirement of offline generation of the CT and MRI libraries. Rapidly moving structures in the heart, presence of surgical clips or other materials are prone to interference during CT/MRI. To overcome these limitations, efforts are now underway to fuse real-time intracardiac echocardiographic images with those generated by CT/MRI scans and to provide a more real-time interactive display. In the future, it is anticipated that these real-time ultrasound and offline CTs and MRIs will be fully fused and displayed with registered activation maps.

Practical issues

Although both these systems provide several helpful tools and make the task of mapping and ablation much easier, this technology is still evolving. Two points that need to be stressed are the necessity of the patient to remain still for the procedure duration and need for more than one electro physiologist for these procedures, especially the more complicated ones. In CARTO, even a small movement of the patient can lead to the mapping becoming fallacious in terms of the location of the points and therefore, the need to remap or start a new map. This problem has been solved to some extent by keeping two sensors and also a tool that can show the exact movement in reference to the previous position. The location pad or the patient is then moved to get back to the original point that is in three dimensions and therefore quite accurate. This necessity leads to use of GA for several of these procedures. The second need is of having two qualified personnel for the procedure, one for the catheter manipulation and other at the computer station. This problem may also be gradually overcome by stereotaxis[20], wherein the person on the computer can manipulate the catheters with a joy stick.

Scar resolution

Delineation of scars in the myocardium is one of the most important issues when mapping these re-entrant arrhythmias. Scars do not allow any conduction and therefore are the substrate wherein the re-entry circulates. Often these scars may not be one non-conducting mass, but provide channels in between to lead to slow conduction and re-entry. The border zones of scars, which comprise of partially damaged myocardium also play a critical role in the circuit. Scars may be relatively discrete, as in the case of a surgical incision or more ambiguous, as occurring due to chronic pressure in the atrium in Fontan patients and also in an ARVC or post-myocardial infarction (Figures 5 and 6). During mapping, the myocardial areas that show no EGM and cannot be paced despite high voltages, are marked in grey as definite scars. Different voltage cut-offs are used in atrial and ventricular signals and inability to pace despite very high currents also points to scarred tissue. However, these arbitrary cut-offs may not always allow 'channels' to be seen and targetted for ablation[21,22]. The balloon array may be complimentary in such a patient, wherein its movement through the exact channel may highlight the isthmus within the large scar.

Issue of noise

Understanding the noise interference while using such systems is of vital importance when dealing with such advanced systems wherein very small potentials need to be seen. Most biomedical instruments either measure signals from closely spaced electrodes (bipolar measurements on most EP systems) or drive the patient with a signal that reduces the effects of the mains noise (drive reference on ECG systems). Bipolar measurements reduce mains noise because the measurement dipole is so small that the mains noise induced on both electrodes of the pair is almost the same amplitude and phase, resulting in a very small common-mode output from the sense amplifier. ECG systems handle this a little differently. They actually measure the mains noise on one set of leads and then drive the patient with an out-of-phase replica of this signal to servo out the mains noise contribution.

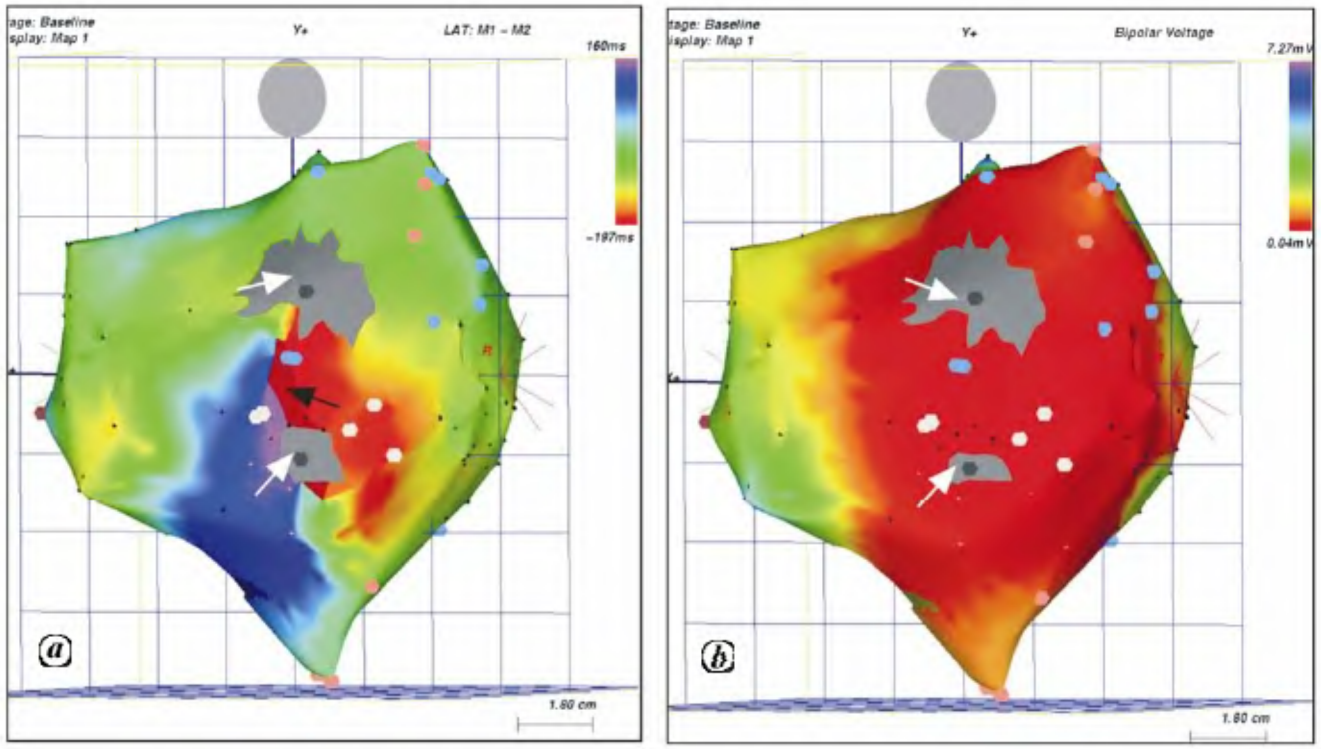

Figure 5. Isochronal activation map (***a***) and bipolar voltage map (***b***) in a patient with Situs ambiguous, right atrial isomerism, single AV valve with TAPVC, malposed great arteries with DORV and PS, who had a bidirectional Glenn shunt done in 1989. The isochronal map shows activation times during one of the tachycardias. The tachycardia cycle length is 390 ms. The bar on the top right shows a covered cycle length of 197 + 180 = 377 ms. The head of the 'patient' does not show the eyes, implying this surface is the posterior part of the huge common atrium. The two grey areas seen in the middle denote scar tissue (white arrow). Blue dots represent double potentials and pink colour shows fragmented signals. The smaller black dots represent activation times at the locations wherein points were mapped. Standard VIBGYOR colour coding depicts late activation as violet, earliest activation as red with intermediate activation depicted by the standard colour spectrum. The place where red meets purple, implies early meeting late (black arrow), a hallmark of re-entry. The re-entry is around the lower scar and not across the upper one as both sides show green, implying same activation times on either side. The bipolar voltage map is colour-coded with red showing very low voltages (manually adjustable, in this map showing <0.1 mV). The large red area denotes scarring because of a volume and pressure-loaded atrium. This tissue is not totally dead and within this area there would be areas that conduct very slowly, do not conduct at all and form the 'inner' loop of one or more tachycardias. Contact mapping within this large area needs very dense mapping and is extremely time-consuming, making studies last more than 5–6 h.

The EnSite balloon array records unipolar signals that have a large measurement dipole and is therefore more easily corrupted by the mains noise. For maintaining uniformity it then becomes important that all EGMs are unipolar. The reconstructed ('virtual') electrograms are small due to lack of direct contact with the tissue and therefore, the noise has to be minimized to be able to get meaningful signals from the majority of the array electrodes. In CARTO special filters have been provided to get clean signals at least on the CARTO system; the attached EP lab may still not be able to provide similar signals.

Ablation

While it is important to gather all the location, voltage and activation data so as to construct the map accurately, it is also essential to understand the complex three-dimensional circuits to be able to plan a strategy of ablation; the 3D system not only provides a road map but also serves as a guide to reach difficult ablation sites. Both these systems have different ways to guide the ablation process. The CARTO system allows the operator to draw a 'design line' on which the ablation can be carried out. During the ablation the tip of the CARTO turns red and the closest proximal 1 cm of the catheter can be seen with different colour coding to allow understanding of the orientation of the electrode in the six DOF. Each burn gets tagged and the signals in that area are monitored till the ablation is completed. The map provides a 3D real-time image of the catheter during ablation and therefore, fluoroscopy is not required at that time.

The EnSite system generates an EnGuide signal that provides the means to manoeuvre the ablation catheter to the correct spot using the triangulation system. The EnGuide signal is also used to monitor the health of the EnSite array electrodes and by identifying the faulty electrode, can disregard the data from that electrode.

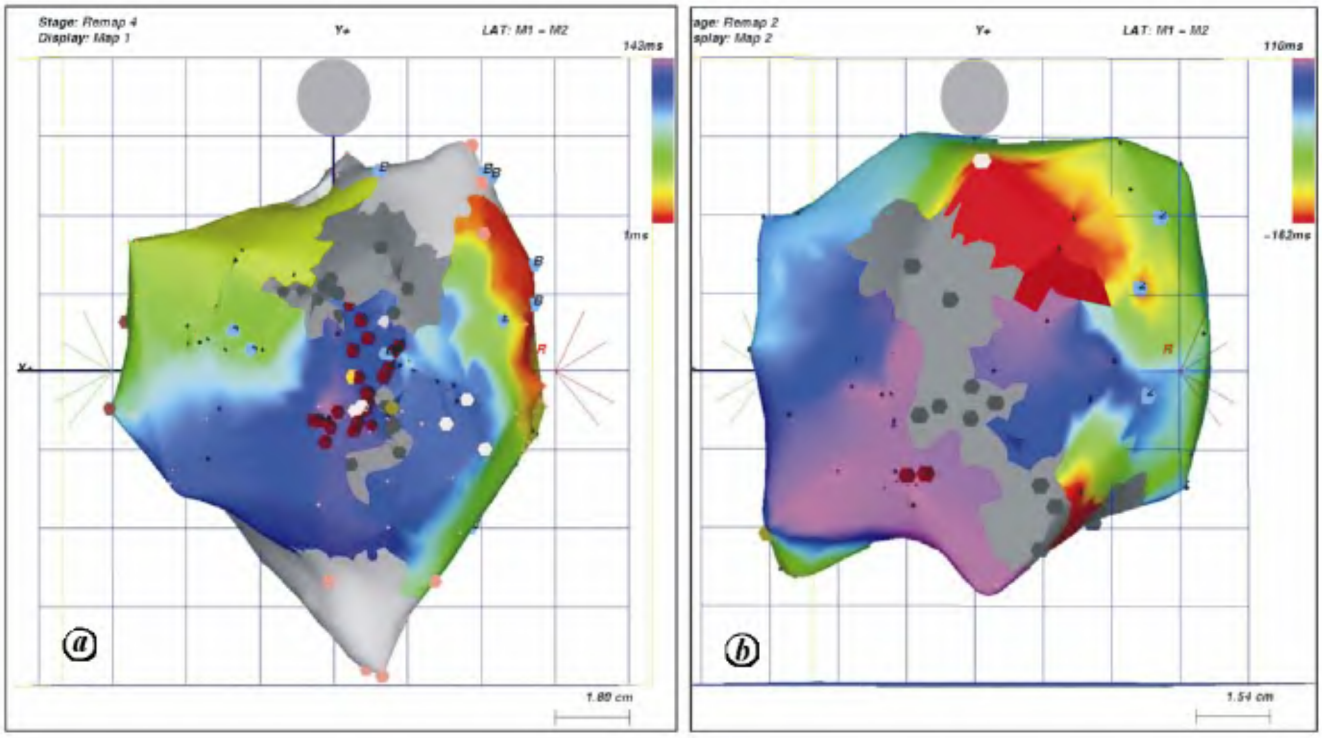

Figure 6. ***a***, Ablation strategy for the tachycardia mapped in Figure 5. Since there are two scars lying close to each other and part of the circuit is going between these scars, this forms the protected isthmus. Connecting the two scars by radiofrequency ablation should interrupt the tachycardia. The red dots on the left are ablation points that can be seen connecting the two scars. ***b***, Mapping after the burn was completed. As can be made out, the entire surface shows a continuous scar breaking the previous circuit. On both sides of the scar are purple areas implying similar activation time. A different tachycardia can now be seen probably going around the double potentials that reflect a line of conduction block. There are not yet enough points to be certain of this circuit. This patient turned out to have eight different tachycardias and despite three attempts could not be made tachycardia-free. In such a patient additional information from the EnSite balloon array may be useful – the path of the current within the large low voltage area can be demonstrated by it. These systems can therefore be complementary to each other, rather than mutually exclusive.

Conclusion

Catheter ablation of tachyarrhythmias is now a standard modality of treatment accepted universally. Within this spectrum, more and more complex tachycardia are now being attempted and the technology continues to expand bringing in more effective and safer tools. Three-dimensional mapping systems are a major step forward in this direction, though cost considerations remain a deterrent towards wider acceptance. This article focuses on some of these tools, predominantly on their application and technological backbone with a twofold intention. It targets basic scientists who with their expertise can refine and improve these systems further, and to clinicians who can develop a deeper understanding of the systems that they use in the management of arrhythmia. First is for the people involved in basic sciences we can refine and improve these systems further to achieve better results. The second goal is to create a deeper understanding of these complex arrhythmias and tools among cardiologists who are the potential users of this technology.

Appendix 1. Alphabetic glossary of terms

AVNRT: Atrioventricular nodal re-entrant tachycardia. It is the commonest SVT in adults and incorporates the AV node and the perinodal atrial tissue.

AVRT: Atrio-ventricular re-entrant tachycardia. This is the usual SVT involving a bypass tract that may be manifest or concealed. It is different from an AVNRT as this has to have participation of the ventricle/s to complete the circuit.

EAT: Ectopic atrial tachycardia. This tachycardia is due to enhanced automaticity of parts of the atrium that then takeover the atrial activity.

VT: Ventricular tachycardia. These can be of several different types and the morbidity/mortality from these is often related to the underlying substrate that may be an infarct, dilated ventricles and uncommonly normal hearts.

Fascicular ventricular tachycardia (ILVT), Right ventricular Outflow tract Tachycardia (RVOT). These two types of ventricular tachycardia occur mostly in patients with normal hearts and are rarely fatal.

Long QT syndrome (LQTS): This purely electrical abnormality that is often congenital or due to drugs may lead to a polymorphic VT also called as Torsades de Pointes. This fatal condition can lead to sudden cardiac death (SCD) of children and young adults with otherwise normal hearts.

Implantable cardioverter defibrillator (ICD): This is a small device weighing less than a 100 gm that is inserted in the thoracic wall like a permanaent pacemaker. The device can recognize fatal arrhythmias and can terminate these episodes by antitachycardia pacing or a DC shock. This device is now one of the most effective weapon to counter SCD and is evolving rapidly because of its role in decreasing mortality in patients with VT/VF.

Arrhythmogenic right ventricular cardiomyopathy (ARVC): This is a type of cardiomyopathy wherein the Right Ventriclular muscle gets replaced by fibrofatty tissue that can lead to fatal ventricular tachycardias. This disease also occurs often in young adults and SCD can be its first manifestation.

3D mapping: 3-dimensional mapping wherein special systems are used to create anatomical maps of the cardiac chambers suspected to be 'housing' the tachycardia. While creating such maps physiological signals like activation time, bipolar voltage, etc. are integrated into the map. This allows understanding of the exact mechanism of the tachycardia and the important areas supporting the tachycardia. This information is then utilized to ablate the tachycardia using minimal fluoroscopy and possibly decreasing the number of burns because of the better localization.

1. Badhwar, N. and Scheinman, M. M., Idiopathic ventricular tachycardia: diagnosis and management. *Curr. Probl. Cardiol.*, 2007, **32**, 7–43.
2. Della, B. P., Carbucicchio, C. and Trevisi, N., Ventricular tachycardia ablation. *Ital. Heart J.*, 2005, **6**, 221–230.
3. Shah, D. C. *et al.*, Simplified electrophysiologically directed catheter ablation of recurrent common atrial flutter. *Circulation*, 1997, **96**, 2505–2508.
4. Oral, H. *et al.*, Pulmonary vein isolation for paroxysmal and persistent atrial fibrillation. *Circulation*, 2002, **105**, 1077.
5. O'Neill, M. D. *et al.*, The stepwise ablation approach for chronic atrial fibrillation – evidence for a cumulative effect. *J. Interv. Cardiol. Electrophysiol.*, 2006, **16**, 153–167.
6. Cox, J. L. *et al.*, Current status of the Maze procedure for the treatment of atrial fibrillation. *Semi. Thorac. Cardiovasc. Surg.*, 2000, **12**, 15–19.
7. Delacreta, E. and Stevenson, W. G., Catheter ablation of ventricular tachycardia in patients with coronary heart disease. Part I: Mapping. *Pacing Clin. Electrophysiol.*, 2001, **24**, 1261–1277.
8. Stevenson, W. G. and Soejima, K., Catheter ablation for ventricular tachycardia. *Circulation*, 2007, **115**, 2750–2760.
9. Haïssaguerre, M. *et al.*, Mapping and ablation of idiopathic ventricular fibrillation. *Circulation*, 2002, **106**, 962–967.
10. Haïssaguerre, M. *et al.*, Mapping and ablation of ventricular fibrillation associated with long-QT and Brugada syndromes. *Circulation*, 2003, **108**, 925–928.
11. Bella, P. D. and Riva, S., Hybrid therapies for ventricular arrhythmias. *Pacing Clin. Electrophysiol.*, 2006, **29**, S40–S47.
12. Markowitz, S. M. and Lerman, B. B., How to interpret electroanatomic maps. *Heart. Rhythm*, 2006, **3**, 240–246.
13. de Groot, N. M., Schalij, M. J., Zeppenfeld, K., Blom, N. A., Van der Velde, E. T. and Van der Wall, E. E., Voltage and activation mapping: how the recording technique affects the outcome of catheter ablation procedures in patients with congenital heart disease. *Circulation*, 2003, **108**, 2099–2106.
14. Rotter, M. *et al.*, Prospective validation of phased array intracardiac echocardiography for the assessment of atrial mechanical function during catheter ablation of atrial fibrillation. *Heart*, 2006, **92**, 407–409.
15. Martinek, M., Nesser, H. J., Aichinger, J., Boehm, G. and Purerfellner, H., Accuracy of integration of multislice computed tomography imaging into three-dimensional electroanatomic mapping for real-time guided radiofrequency ablation of left atrial fibrillation-influence of heart rhythm and radiofrequency lesions. *J. Interv. Cardiol. Electrophysiol.*, 2006, **17**, 85–92.
16. Martinek, M., Nesser, H. J., Aichinger, J., Boehm, G. and Purerfellner, H., Impact of integration of multislice computed tomography imaging into three-dimensional electroanatomic mapping on clinical outcomes, safety, and efficacy using radiofrequency ablation for atrial fibrillation. *Pacing Clin. Electrophysiol.*, 2007, **30**, 1215–1223.
17. Packer, D. L., Three-dimensional mapping in interventional electrophysiology: techniques and technology. *J. Cardiovasc. Electrophysiol.*, 2005, **16**, 1110–1116.
18. Duru, F., CARTO three-dimensional non-fluoroscopic electroanatomic mapping for catheter ablation of arrhythmias: a useful tool or an expensive toy for the electrophysiologist? *Anadolu. Kardiyol. Derg.*, 2002, **2**, 330–337.
19. Gepstein, L., Hayam, G. and Ben-Haim, S. A., A novel method for nonfluoroscopic catheter-based electroanatomical mapping of the heart. *In vitro* and *in vivo* accuracy results. *Circulation*, 1997, **95**, 1611–1622.
20. Pappone, C., Augello, G., Gugliotta, F. and Santinelli, V., Robotic and magnetic navigation for atrial fibrillation ablation. How and why? *Expert Rev. Med. Devices*, 2007, **4**, 885–894.
21. Nakagawa, H. *et al.*, Characterization of reentrant circuit in macroreentrant right atrial tachycardia after surgical repair of congenital heart disease: isolated channels between scars allow 'focal' ablation. *Circulation*, 2001, **103**, 699–709.
22. Deneke, T., Grewe, P. H., Lawo, T., Calcum, B., Mügge, A. and Lemke, B., Substrate-modification using electroanatomical mapping in sinus rhythm to treat ventricular tachycardia in patients with ischemic cardiomyopathy. *Z. Kardiol.*, 2005, **94**, 453–460.
23. Packer, D. L., Evolution of mapping and anatomic imaging of cardiac arrhythmias. *J. Cardiovasc. Electrophysiol.*, 2004, **15**, 839–854.