Electro-anatomic mapping systems in arrhythmias

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Electroanatomic mapping systems have permitted and facilitated difficult interventional ablation procedures for more than a decade. Initially, their use has been in arrhythmias in which the ablation target is difficult to identify, such as ventricular tachycardias in structural heart disease, atypical atrial flutters, or arrhythmias in patients with complex congenital heart defects. In the recent years, electroanatomic mapping systems have also been used to guide catheter-based isolation of the pulmonary veins, an important component of the modern management of atrial fibrillation (AF). Electroanatomic mapping systems integrate three important functionalities, namely (i) non-fluoroscopic localization of electrophysiological catheters in three-dimensional (3D) space; (ii) analysis and 3D display of activation sequences computed from local or calculated electrograms, and 3D display of electrogram voltage (‘scar tissue’); and (iii) integration of this ‘electroanatomic’ information with non-invasive images of the heart (mainly computed tomography or magnetic resonance images).

Although better understanding and ablation of complex arrhythmias mostly relies on the 3D integration of catheter localization and electrogram-based information to illustrate re-entrant circuits or areas of focal initiation of arrhythmias, the use of electroanatomic mapping systems in AF is currently based on integration of anatomic images of the left atrium and non-fluoroscopic visualization of the ablation catheter. Their use in the treatment of AF is mainly driven by safety considerations such as shorter fluoroscopy and procedure times, or visualization of cardiac (pulmonary veins) and extra-cardiac (oesophagus) structures that need to be protected during the procedure. In the future, the use of magnetic resonance images, and potentially of high-quality 3D ultrasound images, could provide anatomic information without ionizing radiation and may be helpful to visualize left atrial scar tissue.

**KEYWORDS**

Electrophysiology; Mapping; Catheter ablation; Atrial fibrillation; Ventricular tachycardia; Image fusion; Echocardiography; Magnetic resonance imaging; Computed tomography

**Function and clinical development of electroanatomic mapping systems**

Electroanatomic mapping systems have been introduced into clinical electrophysiology over a decade ago.¹,² In principle, such a system consists of three different parts: (i) non-fluoroscopic catheter localization, (ii) calculation and three-dimensional (3D) display of electrical activation sequences (‘activation maps’) and voltage information (‘voltage maps’) within the cardiac anatomy, and (iii) 3D display of the anatomy of a heart chamber from serially generated catheter localization information. More recently, the systems also allow to display catheter positions and stored electrograms jointly with anatomic information of the target heart chamber generated through other imaging modalities, mainly computed tomography and magnetic resonance tomography. This additional functionality is often referred to as image fusion.

**Non-fluoroscopic catheter localization reduces radiation exposure during catheter ablation procedures**

Initially, two non-fluoroscopic catheter localization systems were developed, both of which are available today. One system, initially marketed under the name Localita and currently integrated, e.g. into the NavX system, uses three low-amplitude high-frequency current fields that are generated in three axes over the patient’s thorax to compute the position of an electrode in the thorax relative to a reference electrode that can be placed in the heart or on the patient’s thorax.² A similar technique has been implemented in the so-called Ensite system which is now an integral part of the NavX platform.³ The other system (CARTO) uses three magnetic fields that are generated under the patient’s thorax. A magnetosensor that is integrated into the tip of the ablation catheter measures magnetic field strength at the catheter tip and computes the catheter tip position from these measurements.¹ On the basis of these measurements, the systems then display the position of any electrophysiology catheter (NavX or

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of any catheter equipped with a magnetosensor (CARTO®) in 3D space. An example of such a catheter localization display is shown in Figure 1.

Several groups used either of these non-fluoroscopic catheter visualization techniques to reduce radiation exposure during catheter ablation procedures. The capability of both systems to reduce radiation exposure has recently been confirmed in a controlled trial that used both systems head to head. Given the small but potentially hazardous effect of ionizing radiation for patients and catheter personnel, this constitutes an important improvement, especially for time-consuming procedures such as ablation of atrial fibrillation (AF) or ventricular tachycardias.

Analysis of activation sequences by three-dimensional activation maps can guide catheter ablation

The capability of electroanatomic mapping systems to display activation sequences in 3D space has fascinated clinical electrophysiologists. Initially, only the CARTO® system was equipped with a powerful software to analyse and display electrical activation or voltage of local electrograms. Therefore, this system has been used to delineate activation sequences during sinus rhythm or atrial flutter (Figure 2) and has helped to identify critical sites of ventricular and supraventricular arrhythmias in patients with complex congenital heart defects or in patients with ventricular tachycardias in structural heart disease and with idiopathic ventricular tachycardias. Of note, while many users, including the authors, concur that patients with difficult arrhythmia substrates can often only be treated with such a mapping system, the few systematic data that exist do not show a clear effect of electroanatomic mapping systems on ablation success.

Activation sequences can only be mapped and displayed point by point when the arrhythmia is stable over the time required for mapping. Unstable tachycardias or tachycardias with changing arrhythmia circuits can only be mapped when simultaneous multielectrode recordings can be obtained. The so-called ‘non-contact’ (Ensite®) mapping system records 64 non-contact electrograms from a balloon catheter that is inserted into the heart chamber of interest, whereas a catheter localization system is used to obtain detailed information of the endocardial geometry. A complex ‘inverse solution’ mathematical procedure calculates over 3000 simultaneous ‘virtual’ endocardial electrograms from every recorded arrhythmia beat and thereby determines activation sequences. This technique has been used to identify re-entrant circuits in patients with unstable ventricular tachycardias to identify scar tissue (see below), and occasionally in AF.

Three-dimensional low-voltage maps can identify scar tissue during catheter ablation procedures

Similar to activation maps, voltage of local electrograms can be displayed in 3D space by electroanatomic mapping systems. As low local electrogram voltage is a paramount electrical sign of scar tissue, this feature has been used to identify areas of scar tissue during catheter ablation procedures. Deployment of linear ablation lesions in low-voltage scar areas is an important part of ablation procedures for ventricular tachycardias in structural heart disease.

Electroanatomic mapping systems to guide catheter ablation of atrial fibrillation

Focal triggers of AF in the pulmonary veins or at the junctions between the pulmonary veins and the posterior left atrium can be eliminated by catheter-based isolation of the pulmonary veins. It is interesting to note that almost none of the studies published in this century reports on catheter ablation of AF without some form of electroanatomical mapping or catheter visualization system, mainly driven by safety considerations.

Use of catheter localization systems for ‘segmental’ isolation of pulmonary veins

Early during the clinical development of pulmonary vein isolation procedures, ‘segmental’ isolation of the pulmonary veins at their ostia has been facilitated by simultaneous visualization of the ablation catheter and of a lasso catheter in the pulmonary vein ostium by non-fluoroscopic continuous catheter visualization. It was felt that such a system cannot only reduce radiation exposure, but may also help to avoid pulmonary vein stenoses that are associated with ablation deep within the pulmonary veins. The visualization of left
atrial ‘anatomy’ determined through catheter positions at the endocardial surface of the left atrium appears to increase the success rate of the pulmonary vein isolation procedure, albeit at the price of longer procedure durations. More recently (see below), the integration of preprocedural images of the left atrial anatomy into catheter localization systems has facilitated identification of the antral region of the pulmonary veins in the posterior left atrium. Image integration into catheter localization systems appears to be the ‘standard’ approach for catheter-based isolation of the pulmonary veins at present in many specialized centres.

Electrical activation mapping to guide catheter ablation of atrial fibrillation

At present, there are two electrogram- or mapping-based ablation techniques of AF, namely ablation of the so-called ‘continuous fractionated atrial electrograms (CFAE)’ which is advocated by some groups as a first-line treatment for AF, and ablation of focal or macro-re-entrant left atrial tachycardias that may arise after catheter-based isolation of the pulmonary veins or after surgical ablation of AF. These procedures make use of all functionalities of electroanatomical mapping systems, i.e. catheter localization, 3D display of electrical activation and/or voltage of local electrograms, and 3D display of anatomic information including image fusion.

Deployment of linear, continuous lesions in the left atrium

Prior to the identification of focal triggers of AF, electrophysiologists had already begun to reproduce surgical compartmentalization of the left atrium, the so-called ‘Cox-Maze’ procedure, with catheter-based techniques. Linear lesions can be deployed with greater accuracy when electroanatomical mapping systems are used, although the success rate remains low. In patients with recurrent AF after electrical isolation of the pulmonary veins, linear lesions, ideally with an electrophysiologically proven line of block, may be important adjuncts to pulmonary vein isolation in selected patients. Considerable uncertainty exists as to the type of lesion and the long-term effects of such procedures.

Fusion of preprocedural anatomic images with intraprocedural catheter localization and intraprocedural anatomic information

The capability to place electrophysiological catheters within ‘virtual’ anatomic images of the heart appears to reduce unwanted side effects during catheter ablation of AF, such as pulmonary vein stenosis or thromboembolic complications. Both, the CARTO® and the NavX® systems allow to integrate either computed tomography or magnetic resonance images of the left atrium into the catheter display image of the mapping system. Currently available registration techniques rely on preprocedural 3D computed tomography or magnetic resonance imaging (MRI) data sets which are aligned with or superimposed to intraprocedural electroanatomical information. Although a reasonable accuracy and usability can be achieved with these techniques, preprocedural anatomic images carry inherent disadvantages: atrial volumes are variable and may change between the imaging session and AF ablation session. Especially in larger atria, the integration error is considerable. Furthermore, the contact of the ablation catheter may change atrial geometry. In addition, the true catheter
position in relation to the left atrial endocardial surface and changes of the anatomical substrate cannot be visualized and monitored, and lesion formation or development of potential complications cannot be monitored on preprocedural images. Thus, depiction of the ‘real’ anatomy, catheter tissue contact, and lesion formation during the procedure is desirable. However, there are at least two critical requirements for these techniques: at first, excellent soft tissue-contrast is necessary for visualization of the thin atrial walls. Secondly, the imaging system should be compatible with the catheter/mapping system, e.g. there should not be technical interferences between imaging and mapping system. Intracardiac or transoesophageal echocardiography meets these requirements at present. In principle, MRI could also provide such intraprocedural images. Although techniques and concepts for the development of magnetic-resonance compatible catheter systems have been suggested and initiated (see below),46,47 currently, only ultrasound systems are compatible with the available electrophysiology and ablation systems. Intracardiac echocardiography renders comparable image information as MRI.48 Three-dimensional transoesophageal ultrasound systems have already been used to guide catheter-based septal defect closures,49 more recently by the use of a 3D real-time echocardiography system,50 and intracardiac echocardiography images can be reconstructed to yield 3D images of the atria.51 Unfortunately, current 2D or 3D intracardiac or transoesophageal echocardiographic systems only depict partial atrial volumes in real time. Thus, this intraprocedural focused anatomic information will be most useful if integrated with global preprocedural anatomical information of the entire atrium acquired by, for example, computed tomography (Figure 3). Current state of the art is the so-called ‘CARTO® Sound’ system which integrates 2D intracardiac ultrasound information into the CARTO® electroanatomical mapping system.52 Similar developments are under way for the NavX® system.

Rotational angiography offers a 3D anatomic visualization technique that may meet many of the needs of intraprocedural anatomical information, although some limitations with respect to tissue visualization and spatial resolution apply (Figure 4).53

In summary, although image integration is a fascinating and easily adopted addition to electroanatomical mapping, especially in AF, it has to be appreciated that left atrial anatomy is variable and depends, among other factors, on cardiac rhythm, volume status, respiration, and deformation of the left atrium by electrophysiological catheters during the procedure.45 Image fusion and non-fluoroscopic catheter visualization can therefore probably not fully replace fluoroscopy or other forms of direct catheter visualization during catheter ablation procedures.

**Visualization of adjacent anatomical structures**

The shift from segmental ostial to antral isolation of the pulmonary veins has reduced the risk of pulmonary vein stenosis, but caused concerns about the rare but potentially fatal risk of thermal damage to the oesophagus,54 at worst with development of atrio-oesophageal fistula.55 Unfortunately, the oesophagus, which can be easily visualized by computed tomography, can move remarkably within the thorax.56,57

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**Figure 3** The concept of multimodal three-dimensional visualization of the atria. Three-dimensional magnetic resonance or computed tomography visualizes both atria prior to the procedure. Three-dimensional echocardiography (transoesophageal or intracardiac) is readily available during the ablation procedure but depicts only partial volumes of the atria. Both imaging technologies can be aligned in parallel or superimposed by registration techniques. Thus, echocardiography imaging allows to focus on the target volume in which the ablation catheter is operating whereas magnetic resonance imaging/computed tomography visualizes the outer boundaries of the atria. This concept may become clinically available with the integration of ultrasound imaging into current electroanatomical mapping systems. CT, computed tomography; ICE, intracardiac echocardiography; LA, left atrium, LV, left ventricle; RA, right atrium; RV, right ventricle; MRI, magnetic resonance imaging; TEE, transoesophageal echocardiography; PV, pulmonary vein.
Therefore, placement of an electrophysiology catheter or a temperature probe that can be visualized by the electroanatomic mapping system allows to spare the left atrium directly adjacent to the ossephagus during catheter ablation of AF, and may thereby potentially help to prevent oesophageal damage during the procedure.58,59 Other structures that may in the future become of interest for preprocedural imaging include parasympathetic ganglia adjacent to the left atrial wall, which may ultimately become targets for catheter ablation, and the phrenic nerve which can be damaged during catheter ablation near the right-sided pulmonary veins.

Catheter ablation guided by magnetic resonance imaging: a glimpse into the future?

Magnetic resonance imaging of the heart does not require ionizing radiation and poses a reduced risk of renal dysfunction compared with computed tomography; MRI may hence be helpful to minimize radiation exposure during AF ablation procedures that rely on image fusion. Furthermore, ‘delayed contrast media enhancement’ allows to visualize myocardial scars in magnetic resonance images.60–64 If such techniques are applicable to the visualization of atrial myocardial scarring,65 they may in the future become useful to facilitate (re-) ablation procedures.46 This, however, will require substantial efforts in MR compatible catheter design and development.44,66–69 and considerable changes in the work flow of clinical electrophysiology laboratories. Although the technological perspectives of ablation procedures with a view on the cardiac tissue without ionizing radiation are very attractive, current technology, based on radio frequency energy, fluoroscopy, electroanatomic mapping, and image integration works well and may be ‘hard to beat’.

Summary

Electroanatomical mapping systems have three major clinically relevant advantages. They visualize catheter positions in 3D space during the procedure without ionizing radiation. They allow the detailed analysis of arrhythmia mechanisms and to guide ablation procedures in patients with complex arrhythmia substrates. Finally, they allow movement of electrophysiological catheters in a ‘virtual anatomy’ showing the catheter position visualized onto preprocedural and, in the near future, intraprocedural anatomic images (‘image fusion’). Although the first advantage has been demonstrated in controlled trials, the latter two did so far not undergo rigorous clinical testing.

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