Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/crvasa

Review article – *Special issue: Imaging in Coronary Artery Disease*

Electromechanical mapping in electrophysiology and beyond

Tomáš Skála [a,*], *Miloš Táborský* [b]

[a] *Department of Internal Medicine I – Cardiology, University Hospital Olomouc, Czech Republic*
[b] *Czech Society of Cardiology, Head of Department of Internal Medicine I – Cardiology, University Hospital Olomouc, Czech Republic*

ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form
2 October 2015
Accepted 5 October 2015
Available online 3 November 2015

Keywords:
Electroanatomic mapping
Catheter ablation
Atrial fibrillation
CARTO
NavX
Image integration
Fluoroscopy

ABSTRACT

In this review, we outline contemporary and upcoming electroanatomic technologies focusing on new mapping tools especially in catheter ablation for atrial fibrillation. The number of catheter ablations has been increasing exponentially in the last few years due to technological advancements enabling complex ablation strategies. The quality of the contemporary systems of electroanatomic mapping is sufficiently high in terms of both standard ablations, such as isolation of pulmonary veins, and evaluation and elimination of complex arrhythmias. New instruments and devices are coming out to facilitate the process of understanding arrhythmias and thus simplify their elimination. The trend shows a deflection from fluoroscopy towards more advanced technologies.

Contents

* *Corresponding author.*
E-mail address: tomasskala@gmail.com (T. Skála).
http://dx.doi.org/10.1016/j.crvasa.2015.10.002

Introduction

In the last decade electroanatomical mapping systems have noted a steep development. Currently they enable to generate a 3D reconstruction of any part of heart without the need for a fluoroscopic navigation. Fluoroscopy is still a fundamental instrument for displaying mapping and ablation catheters, however, for a precise imaging of those structures that are critical for eliminating complex arrhythmias it can be used only in a limited scope [1] (Fig. 1). These systems, apart from precise imaging of cardiac anatomy, position and movements of catheters, are also valuable in terms of understanding the mechanisms of arrhythmia. Thanks to integration of anatomic and electrocardiographic (ECG) data they are very useful in choosing an optimal location for ablation. Use of mapping systems contributes to reducing the time of operation, fluoroscopy and radiofrequency delivery time [2].

Nowadays there are two mapping systems available for performing catheter ablations: CARTO system (Biosense Webster, Inc., Diamond Bar, CA) and EnSite Velocity cardiac mapping system (St. Jude Medical, Inc., St. Paul, MN). In both aforementioned cases the concept is based on a 3D reconstruction of the heart chamber being examined together with imaging of mapping and ablation catheters.

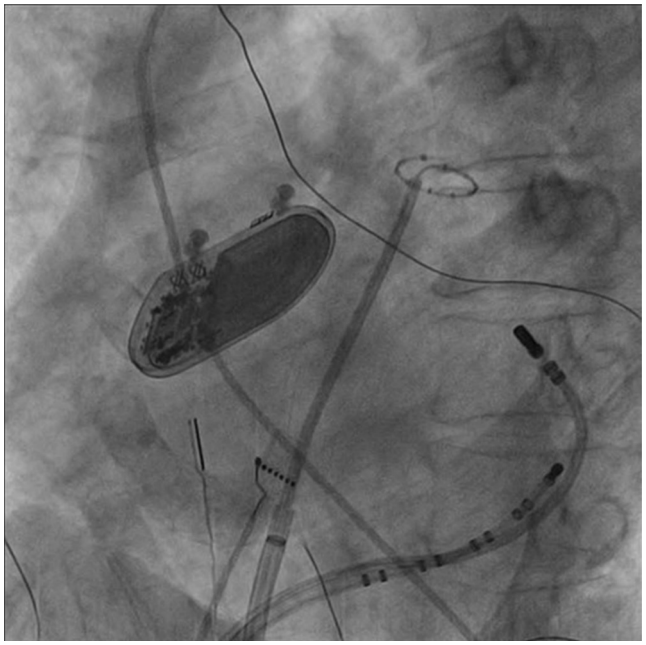

Fig. 1 – Fluoroscopy. Transseptal sheath with circular mapping Lasso catheter in pulmonary vein. Decapolar mapping catheter and ablation catheter in coronary sinus. Biomonitor (implantable ECG recorder).

CARTO

The CARTO mapping system uses low energy electromagnetic fields. The coils emitting nonhomogenous magnetic field (3 coils with different weak magnetic fields – 5×10^{-6} to 5×10^{-5} Tesla) are located in a triangle (location pad) that is placed under the table on which the patient lies during ablation procedure. A magnetic sensor is in the catheter tip. The evaluation of the magnetic field strength and orientation enables to localize catheter in space accurately. Patient's motions cause inaccuracies in the already generated map, thus previous generations of the CARTO system included a reference pad placed on a patient's back within the range of the electromagnetic field. The last generation of the CARTO system (CARTO3) combines the technology of magnetic and impedance based catheters localization. Six electrode patches, 3 on patient's chest and 3 on the back, screen the current emitted at a unique frequency from different catheter electrodes (Figs. 2 and 3). Data from magnetic sensors are rectified by impedance data to overcome distortions from non-uniform intrathoracic resistances. Furthermore, this hybrid method enhances the CARTO system accuracy and mainly enables to display more catheters at a time. A 3D reconstruction of cardiac chambers can be generated by moving a catheter in space (Fig. 4). Patient's movement or dislocation of the location pad may lead to significant map shifts that may be uncorrectable. Space maps of the heart chambers are obtained through an acquisition of points when a catheter is in touch with endocardium (or epicardium in epicardial ablations), and the greater the number of points acquired, the better the anatomical detail obtained. The new CARTO system generation is capable of creating space maps using the so-called *fast anatomical mapping (FAM)*, continuous acquisition of points by a simple movement of a catheter in individual heart chambers. A drawback of the CARTO system is seen in its closed architecture necessitating use of the original ablation catheter with the magnetic sensor (e.g. Navistar, Biosense Webster, Inc., Diamond Bar, CA, USA), since no map can be generated by a catheter other than original.

EnSite NavX

EnSite NavX (the last version entitled *EnSite Velocity*) system is based on use of body-surface patch electrodes. A high-frequency (8 kHz) alternating current electrical signal is delivered between pairs of patch electrodes. Intracardiac

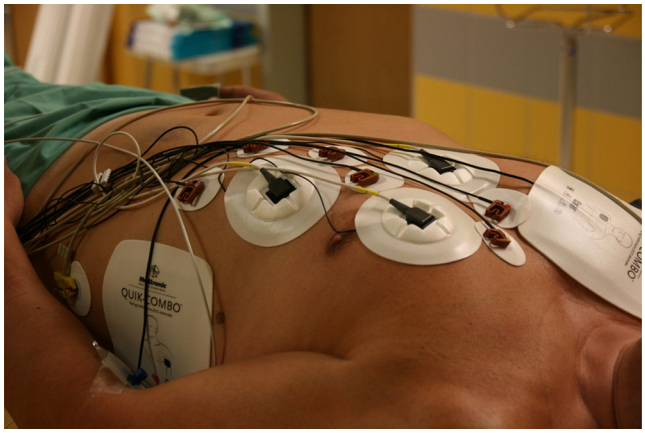

Fig. 2 – CARTO electroanatomical system. Electrode patches (3 on patient's chest).

Fig. 4 – Workspace of technician operating electroanatomical mapping system (CARTO3).

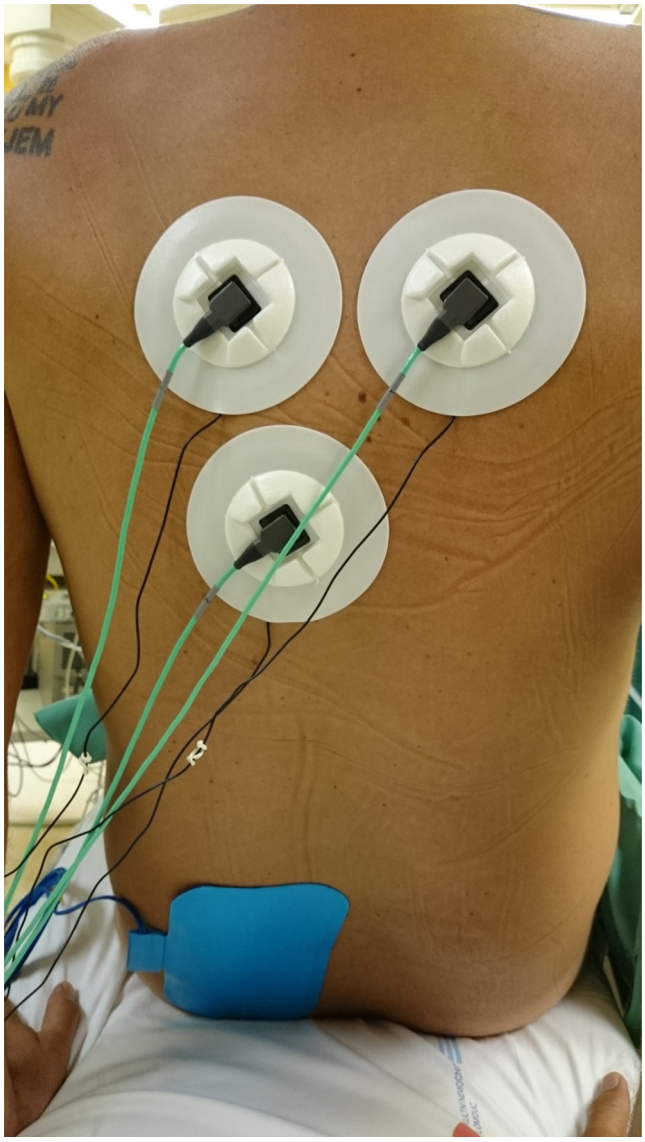

Fig. 3 – CARTO electroanatomical system. Electrode patches (3 on patient's back).

catheters are equipped with sensing electrodes. The electrodes on the catheters read relative voltages with respect to a reference electrode and send the data to the computer for a further processing. The position of the electrode, and thus the catheter in space, is identified upon the analysis of voltages [3]. This makes a big difference in comparison with the CARTO system (in CARTO specific patches see unique current from electrodes in catheters, whereas in EnSite electrodes in catheters see current delivered between patch electrode pairs). The localization of catheters is calculated based on an impedance gradient in relation to a reference electrode. These calculations are often complicated by a non-linear impedance of human body (impedance can alter during an operation). This obstacle might be to some extent corrected by a process called *field scaling*. This adjusts for the non-linearity of the geometry and takes into account the measured inter-electrode spacing for all the locations within the geometry.

The Main advantage of the EnSite system over CARTO rests in a visualization of multiple catheters from different manufacturers, thanks to the open configuration of the system. All displayed catheters may be used for generating a map. By moving a catheter in space we can create a 3D reconstruction of cardiac chambers. The process of obtaining anatomical data from all electrodes on any catheter can be simultaneously connected with receiving electrophysiological data. A 3D map is generated from individual points in space and the electrocardiographic signals can be integrated into this map (Fig. 5). In contrast to the CARTO system, EnSite usually prefers a catheter placed at coronary sinus, which is relatively stable, instead of extra-cardiac reference electrode. Use of this intra-cardiac reference catheter improves the compensation for cardiac and respiratory motion artefacts. A problem occurs in the event of dislocation of the reference catheter, which leads to uncorrectable map shifts.

Small single-centre studies comparing the two systems head to head in atrial fibrillation (AF) ablation therapy directly demonstrated advantages of CARTO over EnSite NavX in terms of fluoroscopy use and procedure durations but with similar clinical results [4,5].

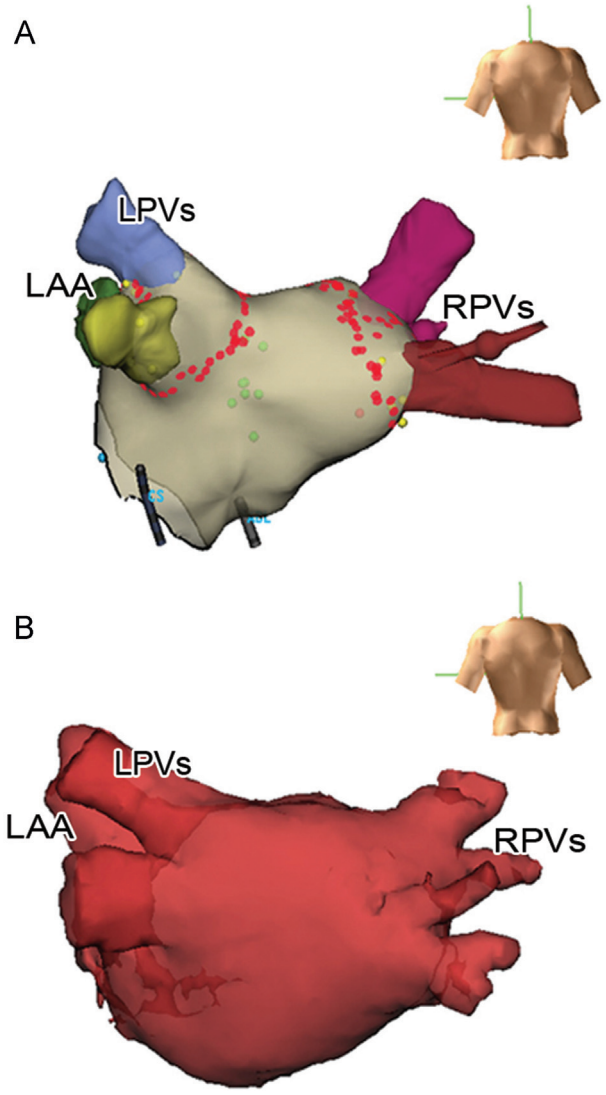

Fig. 5 – EnSite NavX. 3D reconstruction of left atrium. (A) Ablation for paroxysmal atrial fibrillation. Red dots – ablation points. (B) CT image integration.
Pictures courtesy of MUDr. Petr Peichl, Ph.D., IKEM, Prague.

Image integration

In most cases anatomical data from *cardiac computed tomography* (CT), and (less frequently) *magnetic resonance imaging (MRI)*, acquired prior to performing the ablation, are used. These data are processed and a 3D virtual CT map is made. The map shows accurately individual structures and partial details such as the pulmonary vein-atrial junction and the ridge between left pulmonary veins and left atrial appendage with potential anatomical variations. The 3D CT model serves at first just as a tool for orientation and anatomy assessment in order to generate an electromagnetic map on which specific points are subsequently defined (e.g. the ridge between left pulmonary veins, etc.) that are anchored to the relevant spot on the CT map (Figs. 6 and 7). Both the CT and anatomical maps are then either merged or fused together (for the CARTO system the

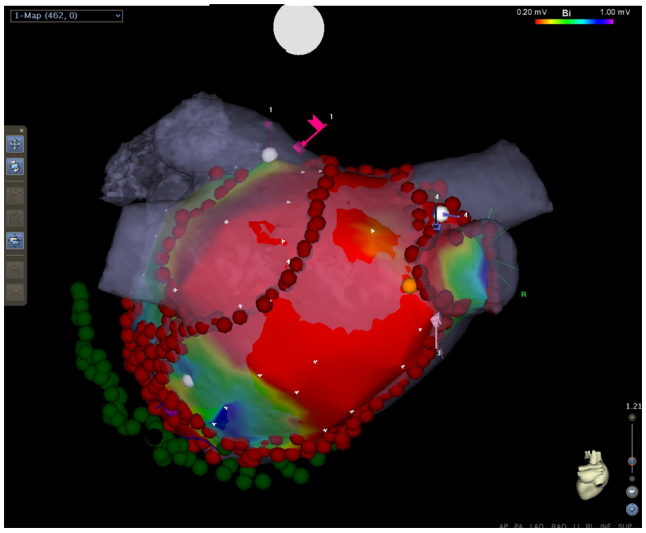

Fig. 6 – CARTO electroanatomical mapping system. CARTO-Merge – image integration (electroanatomical voltage map and CT 3D-reconstruction of left atrium). Catheter ablation for persistent atrial fibrillation. Red dots – ablation points. Green dots – ablation points in coronary sinus. Orange dot – oesophagus in close proximity with posterior wall of left atrium.

module is entitled *CARTO-Merge*). Hence ablation can be carried out either on the map, which results from the fusion of the CT and generated anatomical map, or only in the 3D CT map that is precisely anchored in space. This integrating enables us to increase the understanding of a patient's complex atrial anatomy even more. For generating a detailed

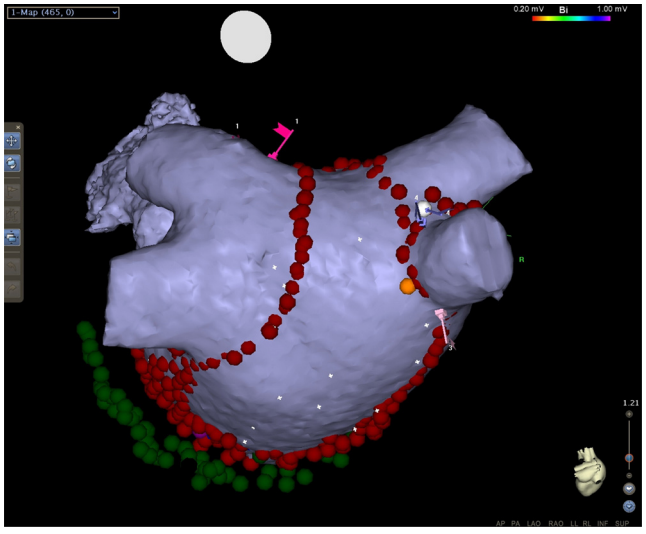

Fig. 7 – CARTO electroanatomical mapping system. 3D reconstruction of left atrium – CT image integration (CT map only) Catheter ablation for persistent atrial fibrillation. Red dots – ablation points. Green dots – ablation points in coronary sinus. Orange dot – oesophagus in close proximity with posterior wall of left atrium.

3D anatomical map we can also use *intracardiac echocardiography (ICE)*. The CARTO system entails an option for using the *CARTO-Sound* module which can be applied, by means of ICE, for creating a 3D map through the combination of multiple 2D ultrasound cross sections generated by the transducer.

However, the image integration has not proven any unambiguous benefit. The retrospective comparative studies have documented reduced fluoroscopy times, lower complication rates and even improved success rates [6]. Nonetheless, these results have not been confirmed in prospective studies [7]. The great advantage of integrating an image with a precise imaging method lies in displaying specific details of the cardiac section accurately, showing anatomical variants with a feasibility of an improved catheter contact in relatively difficult spots such as the ridge of the left pulmonary vein and left atrial appendage. The setback is undoubtedly the price for conducting the imaging method, its eventual radiation load (CT) and potential complications caused by an allergic reaction to the contrast medium being applied. Another fact to be taken into consideration is that a virtual 3D reconstruction, same as the point by point generated anatomical map, is just a static representation of a moving organ. Not always are both maps perfectly integrated, mainly due to different volumes during CT and during the procedure. Nevertheless, many electro physiologists use the image integration method in their routine clinical practice just for its accuracy in anatomical imaging.

Intracardiac echocardiography

Together with the electroanatomical mapping, ICE represents an imaging modality having probably the biggest impact on the procedure accuracy. Fluoroscopy is unable to display a precise detail of a contact between a catheter and myocardium (Fig. 8). A CT image, even though being accurate, is not always perfectly integrated into the map for the reason of different volumes of the specific cardiac section during CT and during the ablation because of the patient's movements or inspiration motions. Nor electrograms are deemed perfectly reliable for assessing an accuracy of the catheter contact. ICE will always localize the catheter precisely and reveal its relations to the surrounding structures, so the method is in the high extent capable to replace the CT reconstruction with its integration with the anatomical map, as it enables us to carry out non-fluoroscopic real-time imaging of all important anatomical structures and their potential anatomical variations. In real time we can see all catheters and their contact with tissue as well as their relation to a supporting sheath. Furthermore, we are able to monitor the dangerous potentiality of a tissue overheating accompanied by microbubbles and potentially perilous steam pop that may be completely prevented by a timely termination of ablation to avoid cardiac tamponade. Having displayed the oesophagus, we can also avoid excessive ablation in its vicinity and thus prevent atrio-oesophageal fistula formation but also the necessity of monitoring the temperature in oesophagus during operation. By imagining of antrum and ostia of pulmonary veins, we can avoid too deep ablation and hence avoid the danger of pulmonary veins stenosis completely. An ICE image clearly shows even small thrombi that may be drained out, treated by coagulation and thus thromboembolic complications can be prevented. An eventual pericardial effusion can be noticed already in its early stage when the volume of fluid in pericardium is very low. Last but not least, we have to highlight the fact that ICE enables us to perform a safe transseptal puncture [8]. From the perspective of performing safe and effective ablations, ICE is probably the most important imaging method. In spite of its high price that may be viewed as a drawback, we are convinced that a regular use of ICE, for its undisputed contribution to safety, effectiveness and minimizing fluoroscopy, shall be fully justified.

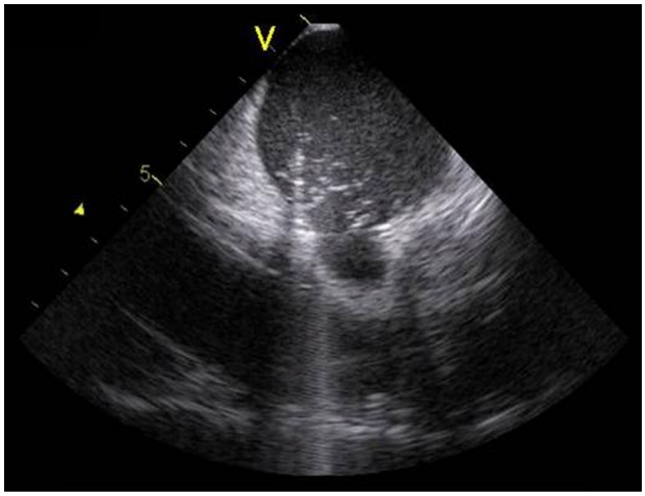

Fig. 8 – Intracardiac echocardiography. Contact of ablation catheter. Bubbles from catheter irrigation.

Arrhythmia mapping with use of the electroanatomical mapping system

The process is based on generating a 3D shell map of the heart chamber in which the ablation shall be performed. The map is created either manually point by point or simply by moving a catheter without acquiring individual point (FAM) (Fig. 9). The acquisition of points in any heart rhythm such as sinus rhythm, atrial fibrillation or other arrhythmias is connected with automatic measurement of their voltages.

This *voltage map* enables us to assess eventual endocardial and epicardial scars both primary, when the structure of myocardium is afflicted (fibrotic atrial remodelling, scar after myocardial infarction, scar after cardiac surgery, myocardium areas damaged by cardiomyopathy, etc.) or secondary, following the already performed ablation. It is important to mention that voltage mapping is influenced by heart rhythm and tachycardia rate. The range of normal voltage for a bipolar voltage map is most commonly selected from 0.3 to 1.0 mV for atria and from 0.5 to 1.5 mV for ventricles (Fig. 10). The areas indicating lower voltage will be shown in red and are deemed to correspond to scar tissue. These areas enable us to define those spots that are potentially significant in terms of arising and sustaining an arrhythmia even in its absence. The atrial fibrosis propensity is associated with a worse post-ablation prognosis and can be also assessed from a

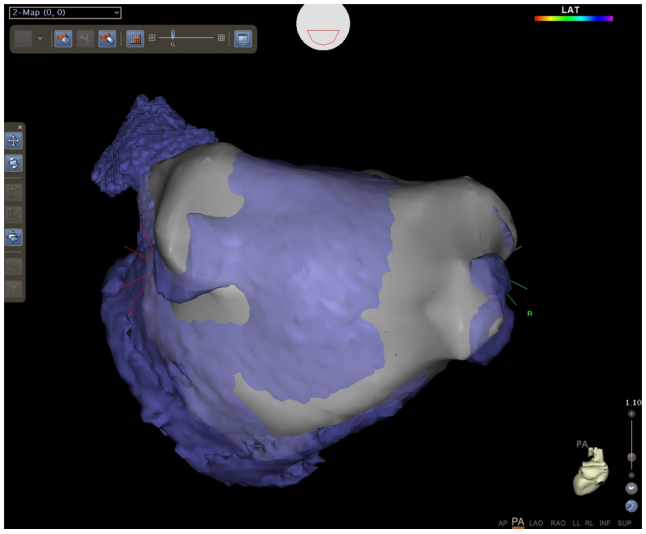

Fig. 9 – CARTO electroanatomical mapping system. FAM map (3D reconstruction of left atrium) + CT image integration.

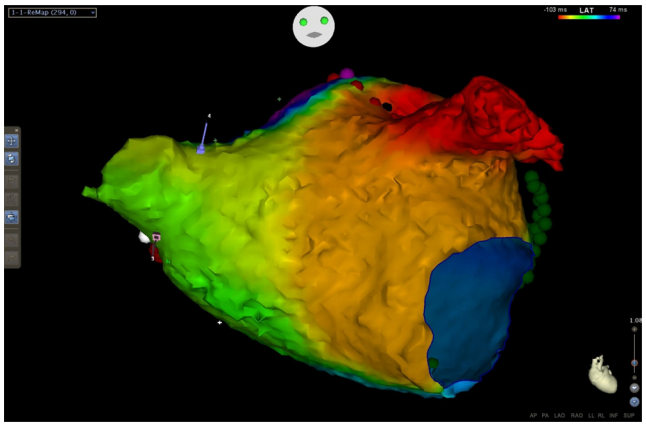

Fig. 11 – Activation map (CARTO). Map of left atrium after pulmonary veins isolation, roof line and posterior mitral line. Focal atrial tachycardia from left atrial appendage. Red colour – earliest activation of left atrium, target for ablation. Centrifugal activation, conduction block on ablation lines.

pre-ablation perspective. The DECAAF study demonstrated that atrial tissue fibrosis evaluated using *late gadolinium enhancement (LGE) MRI before ablation* was in patients ablated for AF an independent arrhythmia recurrence factor. The extent of LGE predicted arrhythmia recurrence (15% for stage 1 fibrosis (<10% of the atrial wall) to 69% for stage 4 fibrosis (≥30% of the atrial wall)) after 1–2 years [9]. Nonetheless the MRI resolution values are still limiting for a real clinical practice, yet we can expect in the future that the advances in the field of MR spatial resolution will facilitate using this method in clinical practice to define myocardial scarring even prior to performing ablation, which could contribute to selecting right patients for ablation, precise ablation targeting, or choosing the correct range of ablation for each patient. For the time being, MRI is used only before ablations of ventricular tachycardias (regarding the bigger thickness of ventricular walls in comparison with atrial) so as to define the myocardial scar. Bearing in mind its low spatial resolution, this method has not been hitherto used in practice prior to conducting ablation of atrial fibrillation. The future outlook promises the integration of data from MRI (LGE) into an electroanatomical map for a further imaging of areas, apart from voltage, aimed potentially at the substrate modification [10]. The LGE method should be capable of revealing eventual gaps in the previous ablation lines, albeit, regarding the capacity of contemporary mapping methods (such as Lasso circular mapping catheter in a pulmonary vein), this task is not very difficult [11].

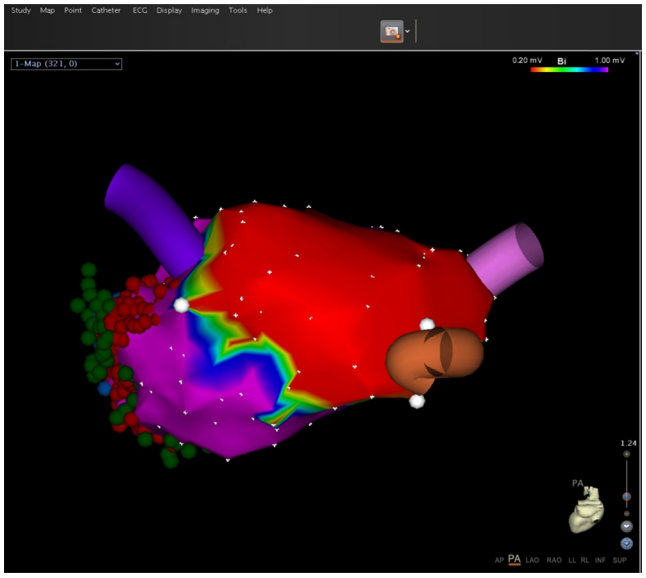

Fig. 10 – Voltage map (CARTO). Map of left atrium after pulmonary veins isolation and a box lesion (exclusion of posterior wall of left atrium). Red colour – areas indicating low voltage (deemed to correspond to scar tissue). Violet colour – areas with normal voltage (supposedly healthy myocardium). Other colours – transient zone, areas with lower voltage (possibly impaired myocardium).

Activation mapping enables us to assess relative activation time in a specific point in comparison with the reference while tachycardia is in progress. As a reference for atrial tachyarrhythmia (AT) is used the signal from a stable catheter (most frequently catheter in the coronary sinus) and the map of the right or left atrium is being reconstructed point by point while the activation time is measured precisely in each individual point to calculate time difference in each point against the stable reference (Fig. 11). Used as a reference in mapping ventricular tachyarrhythmias is a QRS complex of surface ECG (the complex with sharp R or S deflection is selected). The character of signal propagation (i.e. activation of atria) helps us to specify the mechanism of arrhythmia. The centrifugal pattern is registered in case of focal tachycardia when ablation in the earliest point enables us to terminate the arrhythmia and eliminate its focal source. The wavefront activation with circuit-like propagation pattern around an anatomical structure or a scar can be found in the case of macroreentry

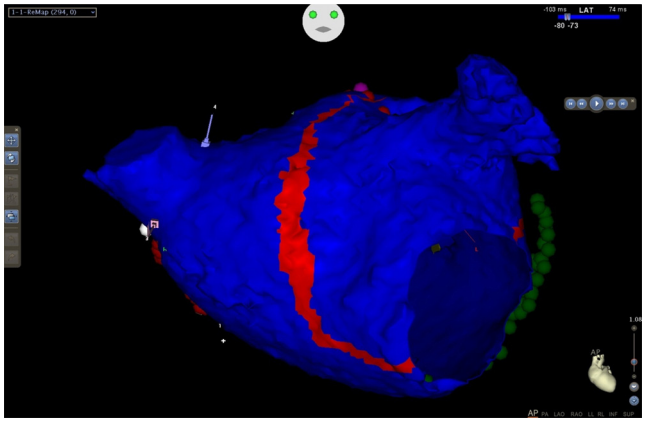

Fig. 12 – Propagation map (CARTO). Map of left atrium after pulmonary veins isolation, roof line and posterior mitral line. Focal atrial tachycardia from left atrial appendage. Red colour – activation of left atrium in one moment of time. Centrifugal activation from left atrial appendage, conduction block on ablation lines.

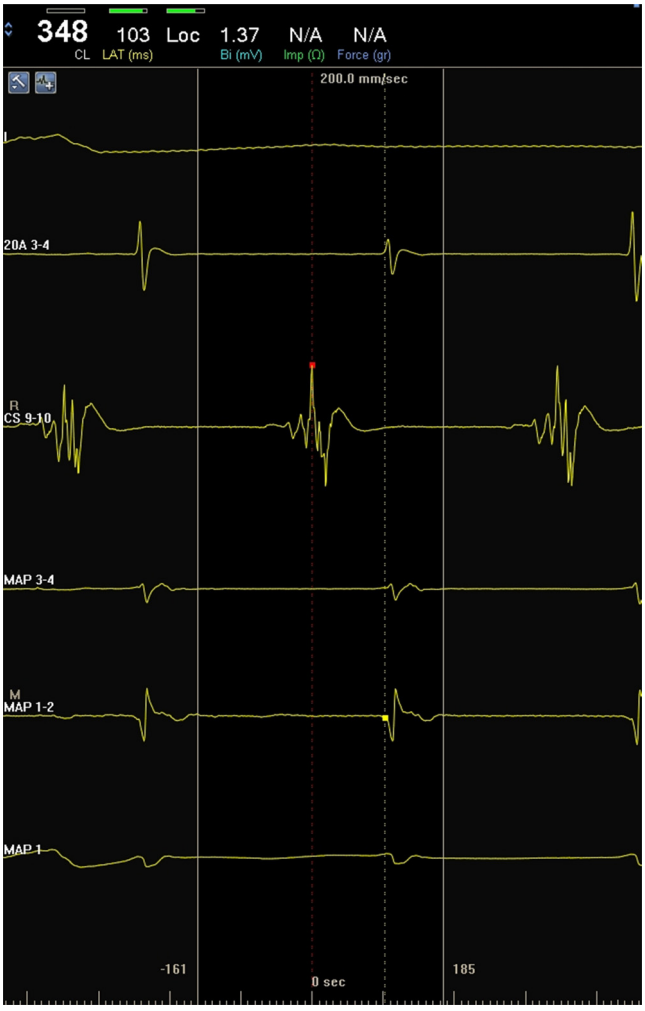

Fig. 13 – Window of interest settings. Annotation of signal at a point being examined (ablation catheter, MAP 1–2). Reference signal in proximal coronary sinus (CS 9–10). WOI (vertical lines) spans the whole tachycardia cycle.

tachycardia. The arrhythmia can be terminated and its recurrence prevented through ablation in the point of critical isthmus of arrhythmia, i.e. the area of a slow-pathway conduction between 2 anatomical barriers. The ablation can be visualized as a barrier put in a gorge between two mountains to block any pathway that may lead through this area deemed critical for sustaining arrhythmia. Relative time (i.e. time difference between the activation time in a specific point and in the reference signal) can be expressed in a variety of colours so as to render a better view of each activated point in the relevant heart chamber. A spread of electrical activation on the two-coloured animated *propagation map* can be displayed as soon as the activation map is completed (Fig. 12). Use of activation mapping is difficult in unstable arrhythmias with a changing cycle length.

A necessary condition for generating an activation map that can be evaluated and understood is setting the *window of interest (WOI)* correctly (Fig. 13). The setting is different for atrial and ventricular arrhythmias, and for focal and macroreentry tachycardias. Should the WOI be set incorrectly in assessing a ventricular tachycardia, the operator can become totally perplexed and thus misunderstand the aetiology of arrhythmia.

For the focal AT the WOI is set so as to commence before the beginning of P wave (ca 100 ms in advance). The most frequent spot (red colour, ''hot spot'') represents the source of tachycardia from which the signals propagate omnidirectionally in centrifugal pattern. The WOI does not need to contain the entire length of a tachycardia cycle. In contrast, macroreentry tachycardias necessitates mapping of the whole length cycle. The electrical wavefront circulates around an obstacle. There is no site of earliest activation. The colours smoothly and progressively change around the central obstacle from the earliest to the latest activation. Most operators set the WOI as simply as possible so that 50% of tachyarrhythmia length cycle begins before the reference signal (mostly the signal from the proximal CS) and 50% of TCL length ends after the reference (TCL is simply divided into 2 halves with the reference signal in the middle). The WOI, if set randomly, shows indeed a fluent change of colours, but the points of the earliest and latest signal collisions will not make any deeper sense. This spot (head meets tail) should ideally coincide with the propagation of the activation wavefront throughout the zone of slow conduction. According to Di Ponti this *optimal WOI setting* (onset of the window is fixed in mid-diastole) for macroreentry tachycardias can be attained based on this formula [12]:

> Backward interval = (TCL − duration of P wave)/2 + Interval from onset of P wave to reference signal (which has a negative value when the reference signal precedes the P wave onset)
>
> Forward interval = (TCL − Backward interval) × 0.9

The activation map, even though the setting seems at first glance a bit complicated (but in practice it takes several tens of

seconds), not only shows the activation sequence, but also directly indicates the critical area of the mid-diastolic narrow isthmus (the place of the earliest and latest activation points, red and purple). If turned out to be a focal arrhythmia, instead of macroreentry, applying this formula does not lead to a major mistake, since the centrifugal activation from the focal point is clearly visible.

Nevertheless, in creating activation map it is indispensable to avoid the sole reliance on annotation of signals. The key principle rests in trying to understand the arrhythmia mechanism through creation of a detailed voltage map indicating fractionated and double potentials to enable us to identify the zone of slow conduction and local lines of the blockage. In many cases it is needless to create an activation map if the operator is able to visualize mentally the signal propagation (caudocranial, clockwise direction) in the largest areas of the relevant heart chamber. This effort exerted for understanding an arrhythmia without the toilsome process of annotating each specific signal can still save a great deal of time, in spite of all advanced imaging technologies (Fig. 14).

An enormously useful instrument to facilitate understanding the distance of a specific point from an arrhythmia critical spot is the *entrainment mapping*. Entrainment is simply a suprathreshold pacing to the point whose distance from the arrhythmia circuit shall be calculated by pacing with a little higher speed than speed of arrhythmia (i.e. shorter cycle length by 30–50 ms). If the pacing site lies within the arrhythmia circuit, pacing speeds up the circulation without changing the morphology of the P-waves or QRS complexes and other intracardiac signals. In the event of an uninterrupted arrhythmia, we will measure the interval from the last stimulus to the first following signal in the stimulated spot. This interval is called *post pacing interval (PPI)*. PPI should be identical in the cycle length to that of the tachycardia. The longer PPI is in reference to the TCL, the farther the calculated spot is found from the arrhythmia circuit. So by means of the entrainment method we can localize an approximate position of the arrhythmia circuit in few steps and, consequently, the spot that is needed for its

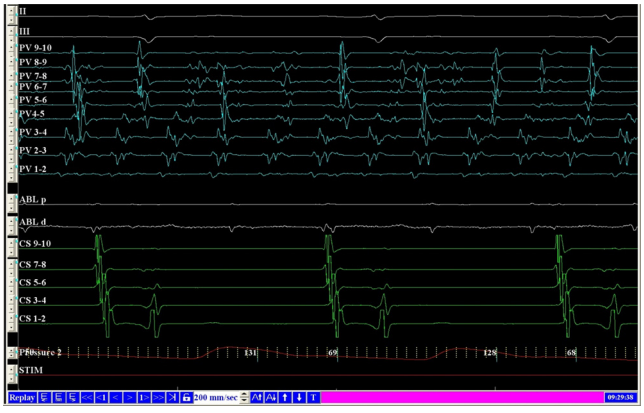

Fig. 14 – Intracardiac ECG. Atrial fibrillation in left superior pulmonary vein antrum after isolation of all pulmonary veins. Normal sinus rhythm, arrhythmia is entrapped in isolated vein and is dissociated from the rest of the heart. Blue – signals from circular Lasso catheter in pulmonary vein. Green – atrial and ventricular signals from coronary sinus.

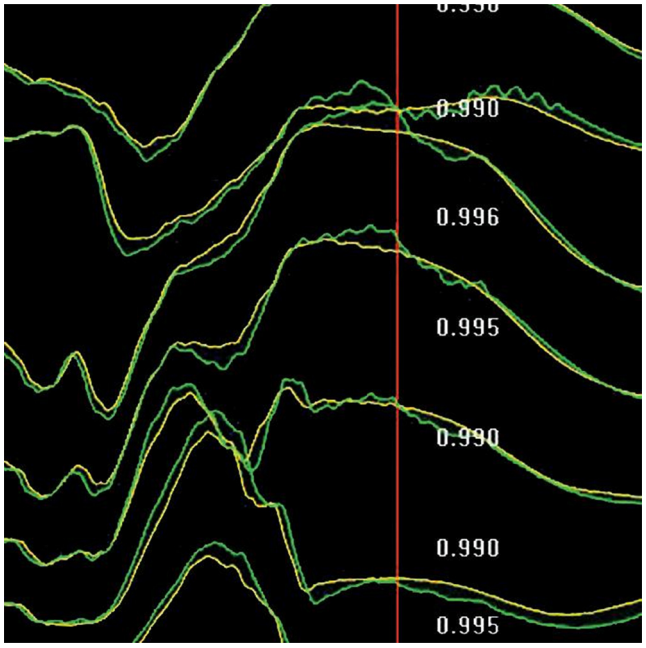

Fig. 15 – CARTO-PASO. Automatic comparison of QRS complex morphology in a tachyarrhythmia/extrasystole with the QRS complex during stimulation at any point in the heart chamber being examined (Biosense Webster).

sustainment. The entrainment mapping can be also used in case of focal tachyarrhythmias. However, systematic use of entrainment mapping to define the reentry course and the ablation target has several limitations. Stimulation may terminate arrhythmia or cause degeneration into atrial fibrillation. In regions with lower voltage it often cannot be performed because of the lack of electrical capture. To prevent the termination of an arrhythmia during entrainment pacing, regions with fractionated signals should be annotated first. The operator should already have a vision of activation in the examined heart chamber. In the process of generating an activation map, it should already be completed.

When a traditional activation map is being generated, each point is attributed time corresponding to the activation time difference between the local point and the reference signal. The values of individual points (and their colour representation) will continuously change in the arrhythmia circuit. However, if the PPI measurement is carried out in more points, the PPI value can be allotted manually to the point whose stimulation brought about the acquired PPI value. The process thus gives rise to the *map of post pacing intervals* when all points in the circuit have the same colour (WOI start is set to 0 because, if PPI-TCL = 0, we are in the arrhythmia circuit).

A novelty in the field of *pace mapping* is the capability of the CARTO system to use the *CARTO-PASO* technology (Fig. 15). The PASO is used for ablation of ventricular tachyarrhythmias, including simple ventricular extrasystoles. The principle lies in automatic comparison of QRS complex morphology in a tachyarrhythmia/extrasystole with the QRS complex during stimulation at any point in the heart chamber being examined. This comparison is automatic and results not only in a

comprehensive view of even small differences in the local and targeted QRS complex, but also in general percentage concordance. The QRS complex when stimulated in the optimum point for ablation reaches the closest match with the QRS in arrhythmias.

Pace mapping is also used to define *channels of slow conduction*. Ventricular tachycardia late after myocardial infarction is usually due to reentry and is dependent on these channels. Pace mapping in sinus rhythm provides a measure of slow conduction, indicated by a long interval between the stimulus and the onset of QRS complex (S-QRS).

Bearing in mind the effort aimed at understanding an arrhythmia in activation mapping, the acquisition of points through manual point-by-point annotation (when the signal beginning is precisely indicated) is probably more accurate than automatic algorithms, but the method is far from flawless and an eventual error in annotation cannot be excluded either, especially in low voltage fragmented signals (that inundate the atria in long-persistent atrial fibrillation). In the event of annotating a fragmented or double signal, only one concrete signal beginning is annotated, so part of important information is lost while generating an activation map for complex signals. The new CARTO system technique, capable of imaging the electrogram time-voltage data simultaneously as dynamic bars on CARTO surface shells, was named *Ripple mapping* [13].

When this mapping technique is used, the electrograms are displayed in the spatial map of a heart chamber as attached 3D colour bars, instead of a simple point. In addition to localizing a point on the map, the information on voltage–time relationship can be added thanks to changing colours and dimensions of these bars (which is, like in a standard activation mapping, time-gated to a pre-selected reference electrogram). Just by looking at these bars, without any annotation (manual or automatic), we can see the signal propagation. Thus the entire mapping process, alias the effort to understand the type of arrhythmia, should be considerably simplified just by this automatization. Unfortunately the maps are not created in real time and the post-processing lasts a while. Despite this limitation, the system should attain a higher diagnostic accuracy than the conventional 3D mapping [14]. However its benefits for daily practice should be proven by a prospective comparative study.

Another potentially promising and fast technique of mapping arrhythmias is seen in *Rhythmia* (Boston Scientific, Marlborough, Massachusetts, USA), the new electromagnetic system. This system (like CARTO) is based on a magnetic sensor at the catheter tip and impedance-based tracking. A specially designed mini basket array with 8 splines, each containing 8 electrodes attached to a bi-directional deflectable catheter (IntellaMap Orion) can be used for *automatic high resolution mapping*. Thus in total 64 electrodes are available for assessing the signals and generating the map. Electroanatomical contact maps can be produced without the need for extensive manual annotation very fast (a map with 4000 electrograms in 7 min in average) [15]. Apart from speed and automatic annotation, another great advantage is a low level of noise which enables to assess even very small signals in the area of a scarred myocardium.

A separate chapter should be dedicated to mapping chaotic signals during AF. For some time the signals during AF have been assessed on the basis of mapping *complex fractionated atrial electrograms (CFAEs)*. These electrograms are defined as low voltage (≤0.15 mV) multiple potential signals with one or both of the following characteristics: [1] atrial EGMs composed of two deflections or more, and/or perturbations of the baseline with continuous deflection of a prolonged activation complex; [2] atrial EGMs with a very short cycle length (≤120 ms), with or without multiple potentials. CFAEs can be connected with factors which perpetuate AF or be passive consequences of rapid AF drivers originating elsewhere [16]. The CFAEs-based ablation improves outcomes in patients with persistent and long-lasting persistent AF [17]. CFAEs can be assessed automatically and displayed in the electroanatomical map (*CFAE-CARTO*) [18]. Nevertheless, no one has proven so far that ablation assisted by this CFAEs automatic registration improves the outcome when compared to conventional CFAE mapping and ablation [19]. The CFAEs ablation is time consuming and such a widespread treatment is often subsequently associated with higher rates of post-procedural atrial tachycardias [20].

A new method of analyzing signals during atrial fibrillation is *mapping of high dominant frequencies* [21]. Using the high-resolution signal analysis we should be able to reveal localized reentrant sources of AF by following the signal propagation known as *rotors* or *focal impulses*. The presence of these sources results in a hierarchical distribution of frequencies throughout the atria. High dominant frequency sites have more than 20% frequency gradient relative to the surrounding tissue. These dominant frequencies can be automatically displayed in the contemporary electroanatomical systems and could represent possible targets for ablation. As for paroxysmal AF, these areas are often found in the pulmonary veins antra, whereas in treating patients with persistent atrial fibrillation they are detected somewhere else in the atria outside the pulmonary veins. We should bear in mind that even more such areas may be found on one patient. According to initial studies, ablations performed in these areas could organize or terminate the AF [22].

A new system for analyzing signals in AF is *RhythmView mapping system* (*Topera*, Menlo Park, CA, USA) which is based on use of 64-pole basket catheters for automatic mapping of many points during AF capable of creating AF propagation maps. Focal impulses show centrifugal activation, rotors should have stable spiral activation around a centre of rotation. Usually 2–3 rotors or focal impulses can be demonstrated in one patient. Ablation in these spots is the foundation underlying the concept of *focal impulse and rotor modulation (FIRM)* [23]. This mapping system is not used separately, since isolation of pulmonary veins should be completed after ablations carried out on these spots (using CARTO or EnSite mapping systems). FIRM target sites can be marked on the maps generated in these systems, so we can avoid making a mistake in case of a basket catheter dislocation. The question whether rotors can indeed be localized so simply in running AF and the atrial fibrillation can be in most patients terminated or at least slowed down, or eventually converted to AT, will be answered in the future as well as the practical use of this system in reality. Financial aspects should not be neglected either.

An attractive option is a non-invasive assessment of mechanisms during AF by means of a new technology entitled

body surface mapping. This *noninvasive signal processing* is aimed at identifying drivers in persistent AF. It seems that persistent AF in early months is maintained predominantly by drivers clustered in a few regions, most of them being unstable reentries, with a high rate of AF termination from limited catheter ablation. Since the process of progressive remodelling of atrial tissue is proportional to the duration of running AF, we deem ideal to apply the mapping systems for an accurate localization of a few target points when timely effect on AF is exerted only by limited ablation. The current resolution of body surface mapping has limited sensitivity in the case of highly localized sources, small signals (<0.15 mV) and far-field signals, particularly in scar tissue [24].

Measuring of contact force

The cornerstone of an effective ablation with a subsequent arrhythmia free follow up is achievement of transmural and durable lesions. It is even more important to avoid excessive contact to prevent severe complications. So far we cared mostly about time and power of ablation. But a catheter stability and adequate tissue contact are even more important. A useful technique of great importance is visualizing the contact by ICE, same as catheter movement along the structures clearly defined on a CT reconstruction. A minor aid, rather illusionary, is contact perception of the catheter held in hand or catheter movement on fluoroscopy. Same inaccuracy in contact assessment is shown by the intracardiac ECG signals and monitoring impedance changes during ablation [25].

Notwithstanding, we are indeed able to measure precisely a contact extent of the catheter with tissue and stability of the catheter during ablation. The catheters being currently used to measure the electrode contact with tissue are *SmartTouch* catheter (Biosense Webster) for CARTO and *TactiCath* Quartz catheter (St Jude Medical) for NavX (Fig. 16). Both systems enable to measure a contact continuously, indicate the extent of real-time contact in grams, display the catheter pressure vector and time during which the catheter is in optimal contact (optimal pressure is 10–30 g depending on the ablation spot). The value of catheter pressure on tissue in grams, time duration of this contact and eventual extent of contact oscillation are displayed, like a force vector, on the CARTO screen with an electroanatomical map. Contact force data are depicted in a separate screen in the Ensite NavX system. In the CARTO system, ablation points can be acquired automatically depending on pre-defined force-time integral (*CARTO VisiTag*). Each ablation point has a colour-coded information about the force and time applied in individual spots. This information indicates if minimum criteria have been met (adequate force with an increasing colour value based on time selected). Both systems, in terms of their effectiveness and safety, have been verified in prospective multicenter studies [26].

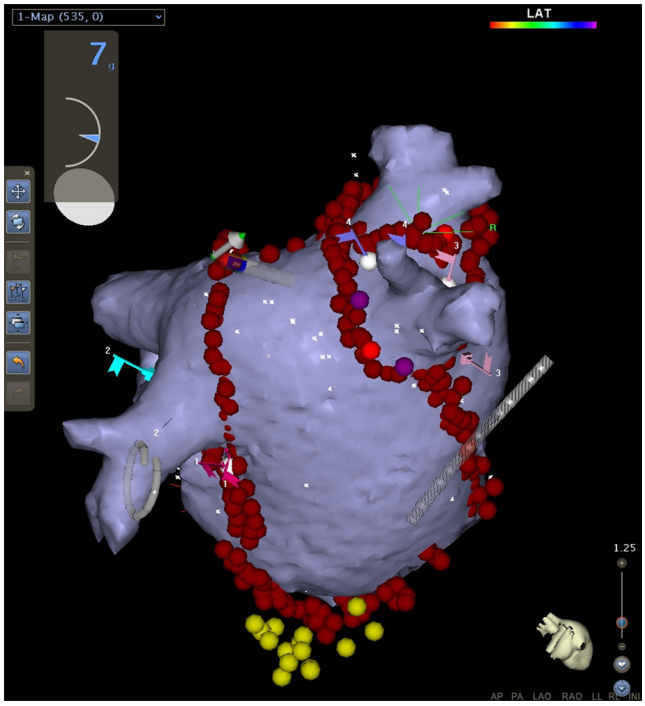

Fig. 16 – Measuring of Contact Force. SmartTouch catheter (CARTO). Visualization of the extent of real-time contact in grams (left upper corner) and catheter pressure vector (arrow near catheter tip).

Integration of fluoroscopic and non-fluoroscopic techniques

The MediGuide Technology (St Jude Medical) system allows for visualization of small sensors which, due to their small size, can be embedded not only in catheters, but also in sheaths and even in wires. The system is based on integration of electroanatomical transmitters into an X-ray detector. The combination of fluoroscopy and magnetic tracking enables us to register fluoroscopic cine-loops and, subsequently, display the catheters (or any sensor-equipped materials) over a pre-recorded cine-loop. These cine-loops can change speed in response to the patient's current pulse. The system allows for a virtual biplane catheter visualization displaying two screens with two different projections simultaneously. The MediGuide system, combined with EnSite NavX, is capable to reduce skiascopic time considerably. The system is free of any significant danger of complications, extended ablation, or its deteriorated result [27]. However, total skiascopic time is reduced in the event of an electrophysiologist who is still dependent on fluoroscopy mainly, yet electrophysiologists turning to non-fluoroscopic imaging methods (mainly ICE) will hardly note any valuable difference, as the already short skiascopic time is not dramatically reduced, but on the contrary the total skiascopic dose is, with regard to the angiography performed in left atrium during AF, higher than in conventional ICE ablation.

The CARTO system has also the capability of integrating electroanatomical mapping and live fluoroscopy (*CARTO-UNIVU*) into a single view (Fig. 17). Similar as the MediGuide system, it allows for creating an electromagnetic map in the background of an RTG image as well as simultaneous depiction of two different projections on the same screen. This integration eliminates the need for additional fluoroscopy

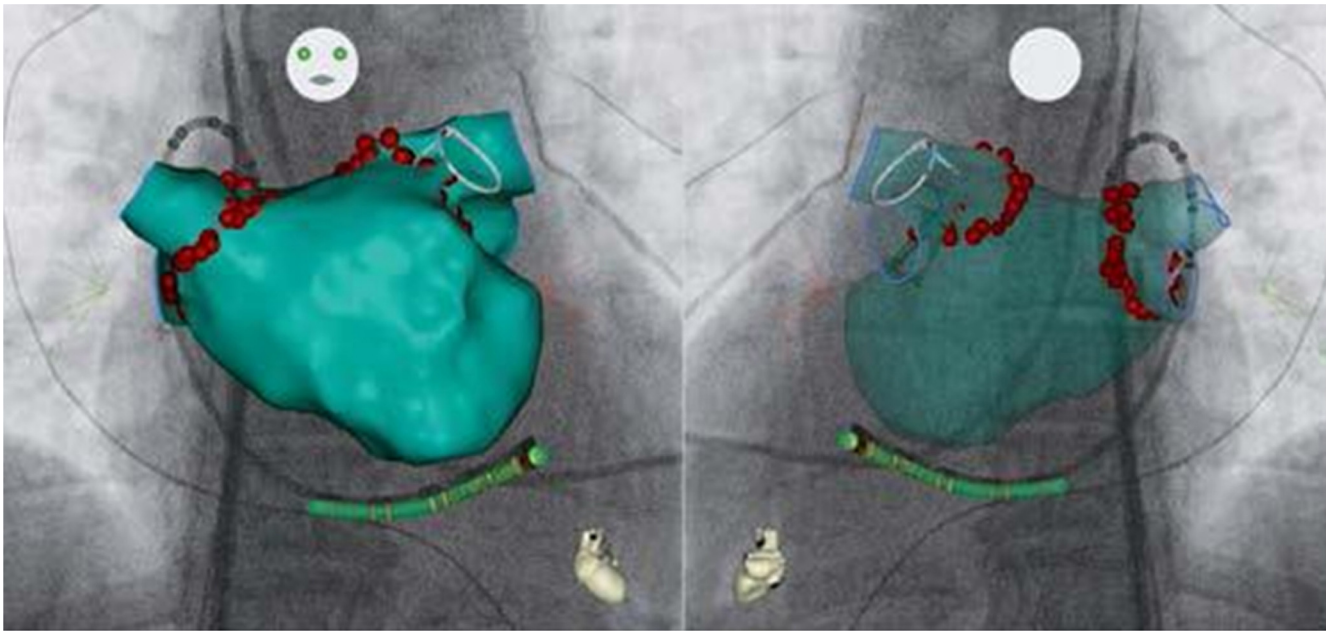

Fig. 17 – CARTO-UNIVU. Integration of electroanatomical mapping and live fluoroscopy into a single view (Biosense Webster).

during ablation procedure. Nevertheless, even if this system is used, as with MediGuide, a significant reduction of skiascopic time can be expected only in operators depending highly on fluoroscopy.

Multipolar mapping and ablation of atrial fibrillation

CARTO System also allows sampling multiple points of cardiac mapping data simultaneously using *PentaRay catheter*. This mapping catheter maps and records signals with high resolution over a large area (*Multi-Electrode Mapping – MEM*). This fast multi-electrode mapping can be used for atrial tachycardias, ventricular tachycardias, and complex fractionated electrograms in atrial fibrillation. The aim is reduced procedure and fluoroscopy time. This new feature of CARTO system (fast multi-electrode mapping) can be used also with MEM versions of standard catheters (circular LassoNAV and decapolar DecaNAV mapping catheters). Recently a *CONFIDENSE mapping module* for CARTO was introduced. This refined MEM mapping module, fully integrated into the CARTO system, allows for automated point acquisition (when physician set-criteria are met) with automated point annotation. Tissue proximity indication allows for proximity-based filtering of points acquired with MEM catheters.

The dramatic increase in quantities of ablations for AF is in parallel accompanied by the endeavour to simplify pulmonary veins isolation. The non-irrigated duty-cycled bipolar and unipolar radiofrequency ablation *PVAC catheter* (Medtronic, Minneapolis, MN, USA) has been employed for some time, but its use has been dramatically reduced after documenting a high number of silent cerebral ischaemia, in comparison with the standard cool-tip ablation catheter [28]. Recently, a new multipolar (but this time open-irrigated) radiofrequency ablation catheter *nMARQ* (Biosense-Webster) was introduced [29]. This catheter can be visualized on an electroanatomical map of CARTO system and can be used for ablation as well as for mapping. It is equipped with a circular or semilunar distal tip section that contains 10 platinum ring electrodes. Radiofrequency energy generator delivers unipolar or bipolar radiofrequency energy over multiple electrodes. Feasibility and safety of ablation with this catheter has been shown in patients with paroxysmal AF. However, issues regarding silent cerebral ischaemia remain to be addressed [30].

Remotely controlled ablation systems

Both currently used remotely controlled systems are based on the already existing systems of electroanatomical mapping. *The magnetic navigation system Niobe* (Stereotaxis, St. Louis, MO, USA) is integrated in *CARTO-RMT* system (it is also possible to use it with EnSite NavX system). The Niobe system is completely integrated into the electroanatomical system, and a movement of catheter (i.e. movement of a magnetic vector followed by the catheter movement) is controlled using mouse. No other devices than those which are used for working on an electroanatomical map are needed to bring about a movement of the catheter. As results from a meta-analysis of more than 900 patients, use of magnetic navigation does not lead to a better clinical success rate. The fact is that a lower amount of complications and reduced fluoroscopic time have been documented, yet at the cost of extended procedure time and price of ablation [31].

The *electromechanical robotic navigation system Sensei* (Hansen medical, Mountain View, CA, USA) is designed for use with EnSite NavX. Neither a mouse nor the electroanatomical map

environment is used to move the catheter, but a roller ball in the workstation simultaneously with the joystick controlling the ablation catheter. The robotic system uses the *Intellisense*, specific system for measuring the catheter contact force.

The biggest hurdle hindering use of these remotely controlled ablation systems in practice is undoubtedly their price in terms of both the purchase of the device and disposable material costs. Another aspect to be taken into consideration is the absence of superiority for these expensive systems, in contrast to conventional manual ablations.

Mapping in electrophysiology and beyond – coronary artery disease

The most common arrhythmias directly linked to coronary artery disease (CAD) and to a history of myocardial infarction (MI) are ventricular tachycardias. Mapping of these arrhythmias is based on the before mentioned electrophysiological principles (3D anatomic map, voltage, activation and entrainment mapping) similar to supraventricular tachycardias including atrial fibrillation. Pace mapping is used in search for focal premature ventricular beats from Purkinje system triggering ventricular fibrillation. MRI with LGE is used extensively to define myocardial substrate before catheter ablation.

A different approach is used in endomyocardial mapping and *stem cells delivery* in patients with ischaemic heart failure and refractory angina. Catheter-based delivery of stem cells to the heart aims to repair or perhaps reverse the effects of myocardial ischaemia and injury. For a direct intramyocardial injection of progenitor cells a *NOGA* system (Biologics Delivery Systems, Diamond Bar, CA, USA) can be used. This system allows for a real time assessment of electrical (voltage map) and mechanical (linear local shortening – wall motion) parameters within the left ventricle (LV), enabling online assessment of myocardial viability. It is based on CARTO XP technology and allows for creation of a 3D map of LV. This map is colour-coded to delineate regions of viable, ischaemic myocardium. Map is created with a *Myostar* catheter. This catheter is similar to a standard ablation CARTO Navistar catheter with a sensor integrated within the distal tip of the catheter, through which the injection needle is extended and stem cells applied. Target areas can be precisely identified and electronically marked with each injection. Although extensive experience with this system has been accumulated in both preclinical and clinical studies NOGA is still in the research phase and is not commercially available so far [32,33].

Conclusion

The quality of the contemporary systems of electroanatomical mapping is sufficiently high in terms of both standard ablations, such as isolation of pulmonary veins, and evaluation and elimination of complex tachyarrhythmias regardless of being caused primarily by an impaired myocardium or as a consequence of an extensive ablation. Nowadays new instruments and devices are coming out to facilitate the process of understanding arrhythmias and thus simplify their elimination. The trend apparently shows a deflection from fluoroscopy towards more advanced technologies aimed at maintaining safety standards, higher speed and a better outcome of ablations at hopefully reasonable purchase prices. The evaluation of complex signals in running AF should lead in the future to an improved ablation targeting. Assisted by automatic registration of intracardiac electrograms and integration of other imaging methods, even less experienced operators could be able to analyze complex arrhythmias within a reasonable time.

Conflict of interest

None declared.

Ethical statement

All authors declare that the research was conducted according to Declaration of Helsinki.

Funding body

None.

REFERENCES

[1] L. Gepstein, G. Hayam, S.A. Ben-Haim, A novel method for nonfluoroscopic catheter-based electroanatomical mapping of the heart. In vitro and in vivo accuracy results, Circulation 95 (1997) 1611–1622.
[2] M.J. Earley, R. Showkathali, M. Alzetani, et al., Radiofrequency ablation of arrhythmias guided by non-fluoroscopic catheter location: a prospective randomized trial, European Heart Journal 27 (2006) 1223–1229.
[3] F. Wittkampf, E. Wever, R. Derksen, et al., LocaLisa: new technique for real-time 3-dimensional localization of regular intracardiac electrodes, Circulation 99 (1999) 1312–1317.
[4] X. Liu, X.H. Wang, J.N. Gu, et al., Electroanatomical systems to guided circumferential pulmonary veins ablation for atrial fibrillation: initial experience from comparison between the Ensite/NavX and CARTO system, Chinese Medical Journal 118 (2005) 1156–1160.
[5] Y. Khaykin, R. Oosthuizen, L. Zarnett, et al., CARTO-guided vs. NavX-guided pulmonary vein antrum isolation and pulmonary vein antrum isolation performed without 3-D mapping: effect of the 3-D mapping system on procedure duration and fluoroscopy time, Journal of Interventional Cardiac Electrophysiology 30 (2011) 233–240.
[6] P.M. Kistler, K. Rajappan, M. Jahngir, et al., The impact of ct image integration into an electroanatomic mapping system on clinical outcomes of catheter ablation of atrial fibrillation, Journal of Cardiovascular Electrophysiology 17 (2006) 1093–1101.
[7] P.M. Kistler, K. Rajappan, S. Harris, et al., The impact of image integration on catheter ablation of atrial fibrillation using electroanatomic mapping: a prospective randomized study, European Heart Journal 29 (2008) 3029–3036.
[8] J. Biermann, C. Bode, S. Asbach, Intracardiac echocardiography during catheter-based ablation of atrial

fibrillation, Cardiology Research and Practice 2012 (2012) 921746.
[9] N.F. Marrouche, D. Wilber, G. Hindricks, et al., Association of atrial tissue fibrosis identified by delayed enhancement MRI and atrial fibrillation catheter ablation: the DECAAF study, Journal of the American Medical Association 311 (2014) 498–506.
[10] J.E. Taclas, R. Nezafat, J.V. Wylie, et al., Relationship between intended sites of RF ablation and post-procedural scar in AF patients, using late gadolinium enhancement cardiovascular magnetic resonance, Heart Rhythm 7 (2010) 489–496.
[11] F. Bisbal, E. Guiu, P. Cabanas-Grandio, et al., CMR-guided approach to localize and ablate gaps in repeat AF ablation procedure, JACC: Cardiovascular Imaging 7 (2014) 653–663.
[12] R. De Ponti, R. Verlato, E. Bertaglia, et al., Treatment of macroreentrant atrial tachycardia based on electroanatomic mapping: identification and ablation of the mid-diastolic isthmus, Europace 9 (2007) 449–457.
[13] N.W. Linton, M. Koa-Wing, D.P. Francis, et al., Cardiac ripple mapping: a novel three-dimensional visualization method for use with electroanatomic mapping of cardiac arrhythmias, Heart Rhythm 6 (2009) 1754–1762.
[14] S. Jamil-Copley, N. Linton, M. Koa-Wing, et al., Application of ripple mapping with an electroanatomic mapping system for diagnosis of atrial tachycardias, Journal of Cardiovascular Electrophysiology 24 (2013) 1361–1369.
[15] H. Nakagawa, A. Ikeda, T. Sharma, et al., Rapid high resolution electroanatomical mapping: evaluation of a new system in a canine atrial linear lesion model, Circulation: Arrhythmia and Electrophysiology 5 (2012) 417–424.
[16] K. Miyamoto, T. Tsuchiya, Y. Nagamoto, et al., Characterization of bipolar electrograms during sinus rhythm for complex fractionated atrial electrograms recorded in patients with paroxysmal and persistent atrial fibrillation, Europace 12 (2010) 494–501.
[17] M. Rotter, Y. Takahashi, P. Sanders, et al., Reduction of fluoroscopy exposure and procedure duration during ablation of atrial fibrillation using a novel anatomical navigation system, European Heart Journal 26 (2005) 1415–1421.
[18] R.J. Hunter, I. Diab, G. Thomas, et al., Validation of a classification system to grade fractionation in atrial fibrillation and correlation with automated detection systems, Europace 11 (2009) 1587–1596.
[19] A. Verma, P. Novak, L. Macle, et al., A prospective, multicenter evaluation of ablating complex fractionated electrograms (CFEs) during atrial fibrillation (AF) identified by an automated mapping algorithm: acute effects on AF and efficacy as an adjuvant strategy, Heart Rhythm 5 (2008) 198–205.
[20] S.H. Wu, W.F. Jiang, J. Gu, et al., Benefits and risks of additional ablation of complex fractionated atrial electrograms for patients with atrial fibrillation: a systematic review and meta-analysis, International Journal of Cardiology 169 (2013) 35–43.
[21] P. Sanders, O. Berenfeld, M. Hocini, et al., Spectral analysis identifies sites of high-frequency activity maintaining atrial fibrillation in humans, Circulation 112 (2005) 789–797.
[22] F. Atienza, J. Almendral, J. Jalife, et al., Real-time dominant frequency mapping and ablation of dominant frequency sites in atrial fibrillation with left-to-right frequency gradients predicts long-term maintenance of sinus rhythm, Heart Rhythm 6 (2009) 33–40.
[23] S.M. Narayan, D.E. Krummen, K. Shivkumar, et al., Treatment of atrial fibrillation by the ablation of localized sources: confirm (conventional ablation for atrial fibrillation with or without focal impulse and rotor modulation) trial, Journal of the American College of Cardiology 60 (2012) 628–636.
[24] M. Haissaguerre, M. Hocini, A. Denis, et al., Driver domains in persistent atrial fibrillation, Circulation 130 (2014) 530–538.
[25] H. Nakagawa, J. Kautzner, A. Natale, et al., Locations of high contact force during left atrial mapping in atrial fibrillation patients: electrogram amplitude and impedance are poor predictors of electrode-tissue contact force for ablation of atrial fibrillation, Circulation: Arrhythmia and Electrophysiology 6 (2013) 746–753.
[26] V.Y. Reddy, D. Shah, J. Kautzner, et al., The relationship between contact force and clinical outcome during radiofrequency catheter ablation of atrial fibrillation in the toccata study, Heart Rhythm 9 (2012) 1789–1795.
[27] P. Sommer, S. Rolf, C. Piorkowski, et al., Nonfluoroscopic catheter visualization in atrial fibrillation ablation: experience from 375 consecutive procedures, Circulation: Arrhythmia and Electrophysiology 7 (2014) 869–874.
[28] M. Wieczorek, M. Lukat, R. Hoeltgen, et al., Investigation into causes of abnormal cerebral MRI findings following PVAC duty-cycled phased RF ablation of atrial fibrillation, Journal of Cardiovascular Electrophysiology 24.2 (2013) 121–128.
[29] S. Zellerhoff, M. Daly, H.S. Lim, et al., Pulmonary vein isolation using a circular, open irrigated mapping and ablation catheter (nMARQ): a report on feasibility and efficacy, Europace 16 (2014) 1296–1303.
[30] C. Herrera Siklody, T. Deneke, M. Hocini, et al., Incidence of asymptomatic intracranial embolic events after pulmonary vein isolation: comparison of different atrial fibrillation ablation technologies in a multicenter study, Journal of the American College of Cardiology 58 (2011) 681–688.
[31] R. Proietti, V. Pecoraro, L. Di Biase, et al., Remote magnetic with open-irrigated catheter vs. manual navigation for ablation of atrial fibrillation: a systematic review and meta-analysis, Europace 15 (2013) 1241–1248.
[32] P.R. Vale, D.W. Losordo, C.E. Milliken, et al., Left ventricular electromechanical mapping to assess efficacy of phVEGF165 gene transfer for therapeutic angiogenesis in chronic myocardial ischemia, Circulation 102 (9) (2000) 965–974.
[33] D.W. Losordo, P.R. Vale, J.F. Symes, et al., Gene therapy for myocardial angiogenesis initial clinical results with direct myocardial injection of phVEGF165 as sole therapy for myocardial ischemia, Circulation 98 (25) (1998) 2800–2804.