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Journal Review

Journal of Atrial Fibrillation

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Advanced Mapping Systems To Guide Atrial Fibrillation Ablation: Electrical Information That Matters

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Abstract

Catheter ablation is an established and widespread treatment for atrial fibrillation (AF). Contemporary electroanatomical mapping systems (EAMs) have been developed to facilitate mapping processes but remain limited by spatiotemporal and processing restrictions. Advanced mapping systems emerged from the need to better understand and ablate complex AF substrate, by improving the acquisition and illustration of electrophysiological information. In this review, we present you the recently advanced mapping systems for AF ablation in comparison to the established contemporary EAMs.

Introduction

Atrial fibrillation (AF) is the most common arrhythmia with an increasing prevalence and a high socio-economical health burden. Catheter ablation (CA) is an established and widespread AF treatment. After the initial discovery and abolishment of focal pulmonary vein (PV) activity as AF triggers,[1-3] CA treatment has undergone considerable improvement over the last years aiming always for better results with faster, safer and easier procedures.

Electrical pulmonary vein isolation (PVI) is the cornerstone of AF treatment.[4-6] In patients with paroxysmal AF, recovered PV conduction is the most common reason for recurrence and can be successfully treated by a new ablation session.[7, 8] In patients with chronic AF though, success-rates are lower and AF triggers from a diseased left atrium (LA) are more common, requiring additional substrate modification, defragmentation or linear ablations.[9,10] Multiple atrial wavelets, macro-reentries, and localized sources (drivers) have been reported to contribute to this substrate.[11, 12]

Achieving electrically continuous, transmural lesions in a beating heart is challenging and requires a reliable three-dimensional (3D) navigation, in order to avoid complications (PV stenosis, perforation, phrenic nerve or esophageal injury). In order to facilitate this task with less radiation than plain fluoroscopy, electroanatomical-mapping systems (EAMs) have been developed, enabling the tracking of intracardiac electrodes in 3D maps and the navigation of catheter ablation.

Conventional mapping systems though cannot adequately detect localized AF drivers due to their sequential spatiotemporal characteristics, their intermittent firing and spatial meandering.[13] For this reason advanced mapping tools have been developed to visualize and better understand the AF-maintaining drivers. These systems have shown promising results for AF ablation and could path the way to a new era of substrate characterization and individual ablation strategies. In this context, the current article aims to review the modern advanced mapping systems for AF ablation in comparison to the established contemporary EAMs.

Contemporary Mapping Systems

All mapping systems are based on non-fluoroscopic visualization of mapping catheters and a 3D reconstruction created by the manipulation of a mapping catheter. Electrical information at map points is recorded and can be used for the color-coded display of the electrical activation sequence known as "activation mapping", the display of post-pacing intervals known as "entrainment mapping" or the display of unipolar/bipolar electrograms as part of "fractionation" or "voltage mapping".[14] The most common EAMs for AF ablation are the Carto (Biosense Webster, Baldwin Park, CA, USA) and the EnsiteNavX system (St. Jude Medical, St. Paul, MN, USA).

The latest version of Carto system is based on a hybrid of magnetic and current-based catheter localization technology and enables visualization of multiple catheters simultaneously. Three active magnetic fields generated by a location pad placed underneath the patient act on mini-sensors embedded in the catheter tip providing information about its exact position and orientation, in relation to a reference sensor on the skin. Additionally, six electrode patches positioned at the patient's back and chest, screen a unique current

Key Words:
Electroanatomic Mapping, Atrial Fibrillation, High Density Mapping.

Disclosures:
None.

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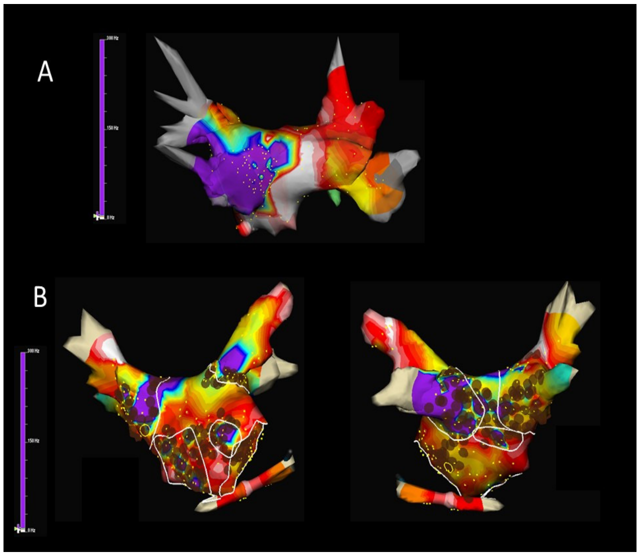

Figure 1: Time-frequency analysis of atrial fibrillation (AF) with Dominant Frequency (DF) maps showing A. a patient with paroxysmal AF in whom DF guidead isolation of the left inferior pulmonary vein antrum lead to AF termination and B. a patient with persistent AF in whom a combined ablation approach with both high-frequency source ablation and circumferential pulmonary vein isolation was performed (Courtesy of Felipe Atienza, Hospital General Universitario Gregorio Marañón, Madrid, ES)

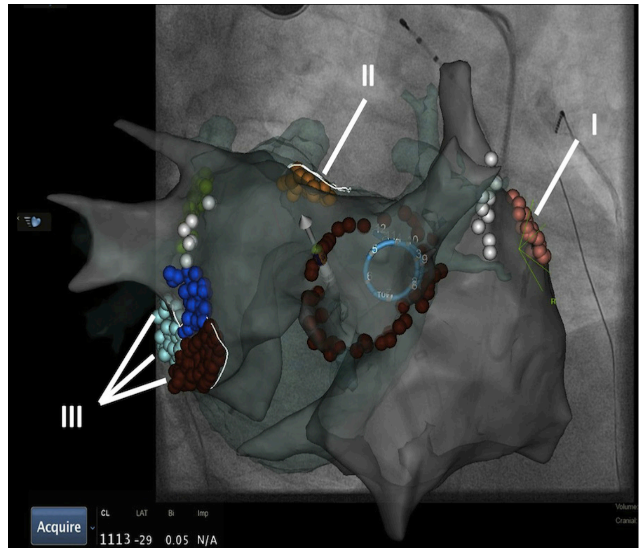

Figure 2: Electroanatomical map (Carto 3, UniVu®) with annotation of AF rotors located by the RhythmView mapping system (Topera) on the right (grey shell, red points; I) and the left atrium (fused with a green 3D CT shell): close to the left atrial appendage (orange, II) and the mitral isthmus region (red, purple, blue, III). A circular mapping catheter (blue) is placed in the right superior pulmonary vein and an ablation catheter is at the posterior wall. The white points show the area of phrenic nerve capture

emitted from different catheter electrodes.[15] Multipolar mapping catheters can be used for fast anatomical mapping (FAM) by registering and reentering 3D models. Respiratory gating is possible through thoracic impedance measurement, but patient movement or dislocation of the location pad may lead to uncorrectable map shifts. In order to enhance recognition of anatomical variations, integration of pre-aquired CT/MRI data or intraprocedural inctracardiac echocardiography (ICE, CartoSound®, Biosense Webster) is possible through merging of the 3D models.[16]

The EnsiteNavX Velocity system is based on an impedance-based tracking technology, capable of tracking intracardiac electrodes as well as tagging points in a high-frequency (8 kHz) electric field produced by six skin electrodes. The 3D-localization of the catheters is calculated based on an impedance gradient in relation to a reference electrode.[17] A process called field-scaling aims to correct for the body's non-linear impedance and the use of intracardiac refrence-catheters reduces motion artifacts. However, dislocation of the reference catheter may lead to uncorrectable map shifts. EnsiteNavX allows for visualization of multiple catheters from different manufacturers and simultaneous collection of anatomical and electrophysiological data from all electrodes of any catheter.[18] Integration of CT/MRI data though requires an extensive registration called fusion.[19]

Both of these EAMs have been proven to reduce radiation and procedural duration[20-22] and in combination with pre-acquired imaging data can lead to less complications and better results.[23,24] Additionally, integration of electrode-tissue contact force data by special catheters (SmartTouch, Biosense Webster or TactiCath, St. Jude Medical) can provide feedback for lesion creation and improve efficacy, reduce risks and procedural parameters.[25-29] The most important contribution of these systems though is the characterization of the AF substrate through fractionation (quality and temporal characteristics of the electrical signals) or voltage mapping (amplitude of electrical signals), which has been the stimulus for further mapping developments. These tools aim to identify additional ablation targets and allow a patient-tailored approach.

Fractionation Mapping

Complex fractionated atrial electrograms (CFAEs) are regarded as surrogates of asynchronous activation of myocyte bundles through a fibrotic myocardium. They are defined as atrial electrograms with low voltage (≤0.15 mV) signals with ≥2 deflections/perturbations of the baseline with continuous deflection of a prolonged activation complex; and/or a very short cycle length (≤120 milliseconds), with or without multiple potentials. The mechanisms of CFAEs creation has been related to factors which perpetuate AF, but it has been also been considered to be passive consequences of near-by rapid AF drivers.[30] Contemporary EAMS integrate automated algorithms that provide CFAEs maps, but this has not been proved superior to conventional CFAE mapping and ablation.[31] Despite the initally encouraging results, recent studies showed a higher rate of resulting atrial tachycardias and failed to reveal a benefit of additional CFAE ablation.[32, 33]

Voltage Mapping

Voltage mapping is based on the correlation of low-voltage areas (<0.5 mV) in the left atrium with endocardial scar and/or structural defects as a substrate that can diminish success rates after AF ablation.[34-38] Supplementary ablation of low-voltage zones as an additional target to PVI serves as an individualized substrate modification (similar to unstable ventricular tachycardias). According to our experience such low-voltage areas are found in 35% of patients with persistent AF and in 10% of patients with paroxysmal AF, most commonly in the septal, anterior, or posterior LA wall. Patients with low-voltage substrate have lower success rates after AF ablation (23% after PVI only) that can be significantly improved by targeting these in a patient-tailored approach (70% after a year). Moreover, this strategy could spare the majority of patients (2/3 of those with persistent AF) from additional ablation lesions and potential complications, without compromising the ablation outcomes.[39] Prospective, randomized clinical studies are needed to clarify the role of a voltage-based AF

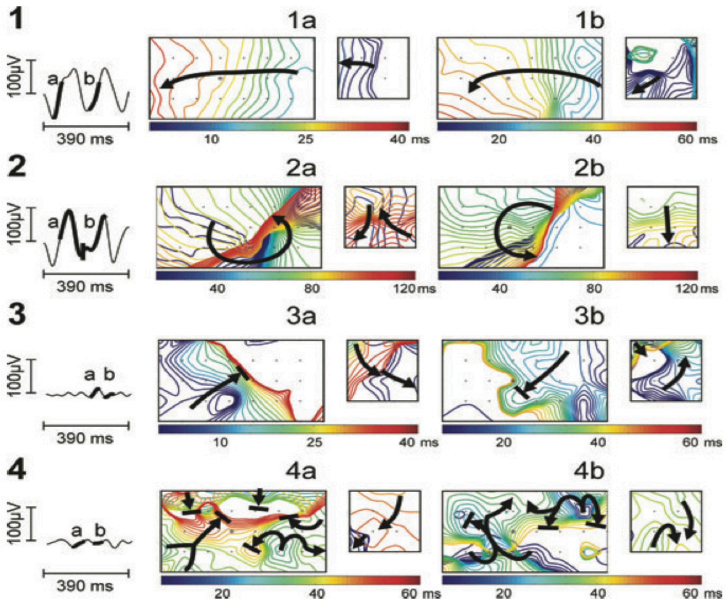

Figure 3: Noninvasive AF mapping using body surface recordings from a uniform grid-torso placed around a patient with persistent AF. On the left, tracings correspond to V1. Panels a and b correspond to wavefront propagation maps of two intervals of the same segment in a color scale. On the left in each panel, maps correspond to the front part of the thorax and on the right, maps correspond to the back. Each electrode position is labelled with a '+' sign and V1 by a circle. Wavefront propagation lines are drawn every 2 ms, drawn blue when appearing first or red when appearing last. Arrows indicate the direction of propagation of each wavefront.[49]

ablation in comparison to established strategies.

Advanced Mapping Systems

Contemporary EAMs have been very valuable for the navigation of AF ablation, but have some limitations. The integrated automated mapping algorithms are susceptible to annotation and interpolation errors that require a manual point-by-point verification of annotated points. This is a time-consuming process that is prone to incorrect judgment regarding signal selection, the window-of-interest and the presence of fragmented/double potentials or areas of very-low continuous potentials. Moreover, spatiotemporal analysis and registration of electrograms on a map as well as the creation of a new map in case of tachycardia change, remains a slow process limited by the speed of signal acquisition. The need to overcome these disadvantages and to improve illustration of the underlying AF mechanisms, has led to the development of advanced mapping systems.

Advanced mapping systems for AF ablation have focused on improving signal quality (high-resolution), acquisition and processing time, precision of annotation and development of automated algorithms that visualize electrophysiologic information. These efforts refer once again to the core principle of electrophysiology: the electrical signals, which guide AF ablation, should be reliable (with high resolution and low noise), appropriately acquired and processed in a timely manner. In this sense, new diagnostic catheters and novel mapping technics have been developed and will be presented here.

Ripple Mapping

Ripple Mapping is a novel technique that displays time-voltage data as dynamic bars on Carto surface shells.[40] Electrograms are visualized as color bars on 3D models, changing colors and dimensions

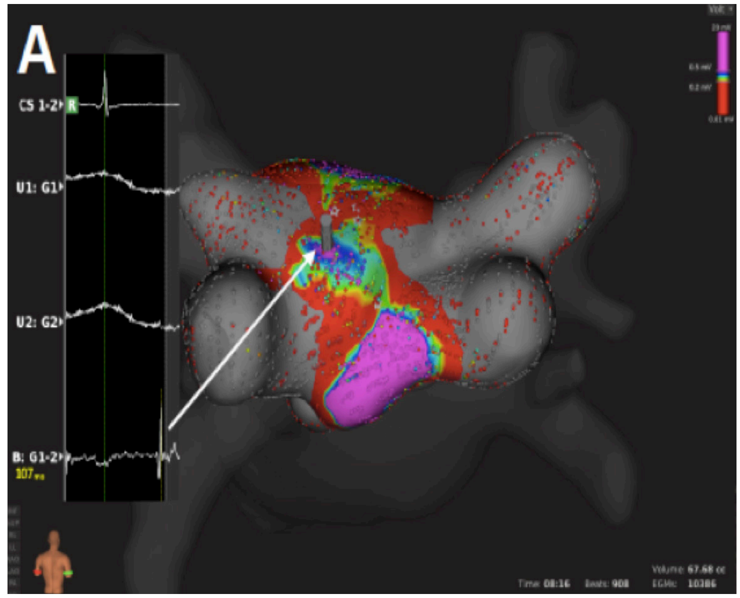

Figure 4A: Voltage base verification of linear lesions: High-density voltage map of the roof region during a redo case with previous box lesion. Note high voltage regions within the box lesion (corresponding local electrograms shown in the box)

according to the voltage-time relationship, time-gated to a pre-selected electrograms (reference). The operator has the impression of a "wave-like" movement of the propagation, without any manual or automatic annotations. This way ripple mapping compensates for isolated annotation and interpolation errors and as recently reported, demonstrates higher diagnostic accuracy for atrial tachycardias compared to conventional activation mapping.[41] Although it is an offline system that requires time for post-processing, ripple mapping has the potential to simplify mapping and minimize operator-dependence. Further evaluation and comparison with other systems is needed to prove if this technology will be integrated in "real-time" clinical practice.

High Dominant Frequencies Mapping

Dominant frequency (DF) maps derive by high-resolution analysis of the Fourier power spectrum and enable the color-coded hierarchical visualization of frequencies in combination with contemporary catheters and EAMs.[42] High DF sites are defined by 20% frequency gradient relative to the surrounding tissue and represent localized reentrant sources (ablation-targets). Multiple DF sites are usually found in a patient with variable distribution (predominantly PV-sites in paroxysmal and more atrial sites for persistent AF) and intra-procedural spatiotemporal stability, which has raised some concern about their role as AF drivers. Ablation of DF sites may result in significant slowing of AF cycle length, reduction of AF inducibility, and AF termination especially in paroxysmal AF patients.[43, 44] The RADAR-AF study compared DF ablation vs. circumferential PVI and found no incremental value for persistent AF but a non-inferiority for paroxysmal AF (Fig. 1).[45] However, more clinical studies are needed to further evaluate the role of DF ablation.

Focal Impulse and Rotor Mapping

In order to improve the identification and abolishment of local reentrant sources a novel computational approach with the concept of focal impulse and rotor modulation (FIRM) has been developed.[46] For this technique, a dedicated 64-pole basket catheter (8 splines with 8 electrodes per spline) is used for panoramic intra-cardiac

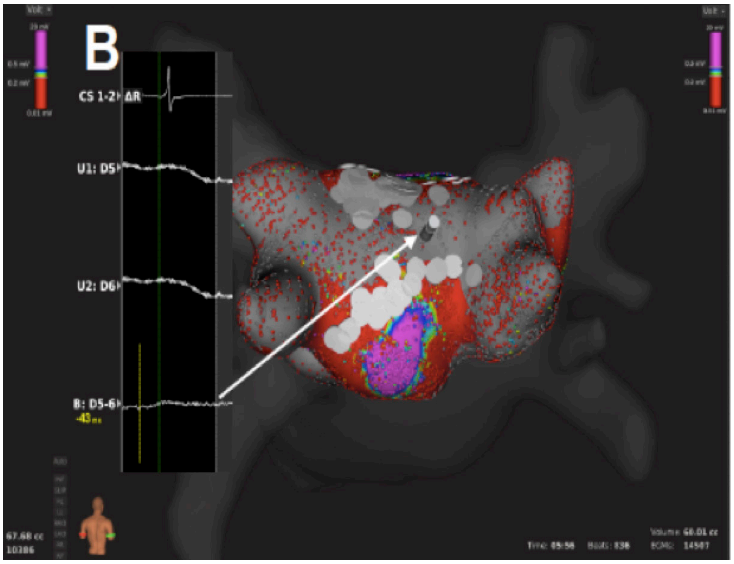

Figure 4B: Voltage base verification of linear lesions: re-map of the same region after additional ablation shows elimination of high voltage potentials

mapping during AF. Automated intra-procedural processing by the RhythmView mapping system (Topera, Menlo Park, CA, USA) enables the depiction of AF propagation maps projected onto grids. These maps are then used to guide ablation of AF drivers (usually 2-3 rotors or focal impulses per patient). Rotors are defined as stable and sustained spiral activation around a center of rotation, whereas focal impulses are defined by centrifugal activation from a source. Target sites are located by their electrode coordinates and radiofrequency ablation with a conventional catheter is usually applied for 15–30 sec up to 10 min, aiming for slowing or termination of AF. Conventional EAMs can integrate tracking of the basket catheter, annotation of target and ablation sites and simultaneous creation of atrial geometries, which may then be used for PV isolation (Fig. 2). PVI with additional direct or coincidental FIRM ablation has been shown to improve mid-term and long-term AF ablation outcome.[46-48] Similar to other technologies though, which are used to supplement conventional AF ablation, additional costs and processing time remain an issue and remain to be proofed for their clinical value.

Non-Invasive Body Surface Mapping

Body surface mapping (BSM) is a non-invasive bedside mapping system that aims to identify AF drivers by using an array of multiple surface electrodes and by projecting this information on a pre-acquired CT/MRI-based 3D model of the atria. Initial research revealed that using a 56-electrode vest around the patient's torso, non-invasive mapping could depict wavefront propagation maps and identify specific patterns like single wavefronts, wave-breakages/splitting or multiple simultaneous wavefronts (Fig. 3).[49] Further development of this kind of mapping led to a 252-electrode vest connected to a special system (ECVUE, CardioInsight Technologies Inc, Cleveland, OH) that records unipolar surface potentials. Biatrial unipolar electrograms are then automatically reconstructed from torso potentials and epicardial activation maps are computed by using the intrinsic deflection-based method. The windows with long ventricular pauses (spontaneous or diltiazem-provoked) are usually randomly selected for AF electrogram analysis. Maps of AF are generated by algorithms with a combination of signal filtering and phase mapping.[50-53] Wave propagation is then depicted color-coded on a beat-to-beat basis and spatiotemporal density maps are analyzed to identify active driver regions (classified as focal or reentrant) and the repetition of this activity. In contrast to focal impulse rotor mapping, AF drivers by BSM are usually (2-3) repetitive reentries clustering in the LA and increase with the duration of continuous AF. Their elimination could lead to AF termination (especially in paroxysmal AF) with a shorter procedural time in comparison to conventional ablation techniques.[54] Despite the need for additional off-line analysis, BSM allows for pre-procedural non-invasive AF mapping and preparation of an individual ablation strategy. Further clinical studies are needed though to elucidate the utility of this system.

High Density Mapping

The concept of high-density mapping refers to the simultaneous acquisition and annotation of multiple electrograms, including activation and voltage information, which are then analyzed by automated algorithms in order to generate precise activation and substrate (voltage) maps. These algorithms were initially applied for macro-reentrant tachycardias, but they have been further developed and adapted for complex arrhythmias like AF, providing us with new insights and a better understanding. In order to achieve this novel mapping catheters have been developed; multiple electrodes serve for fast acquisition of data whereas a smaller electrode size and a shorter inter-electrode distance provide a better signal quality with less noise to far field ratio.

The PentaRay (Biosense-Webster) is a two-dimensional catheter with 20-poles arranged in 5 soft radiating splines (1-mm electrodes separated by 4-mm interelectrode spacing) laid out flat to cover an area with a diameter of 3.5 cm. The multi-branch configuration provides a broader access to information with high resolution.[55] It can be used with conventional EAMs and simplify the identification of focal or microreentry sources, scar borders and critical electrical pathways for the abolishment of macroreentrant tachycardias.[56,57] Recently, 3D high-density maps are made possible by using a specially-designed 64-pole basket array (8 splines with 8 electrodes per spline, 0,4 mm^2 electrode size and 2.5-mm interelectrode spacing) attached to a bi-directional deflectable catheter (IntellaMap Orion® High Resolution Mapping Catheter) in combination with a novel EAM system (Rhythmia Mapping, Boston Scientific, Marlborough, Massachusetts, USA). The Rhythmia system uses a hybrid of magnetic-based tracking for a sensor at the catheter tip and impedance-based tracking for all 64 electrodes for catheter navigation and geometry creation. The greatest advantage of this system is the rapid and automatic acquisition of maps with high spatiotemporal resolution and without the need for extensive manual annotation. Activation maps with thousands of electrograms can be created within minutes.[58-61] Post-processing is not necessary and map-reconstruction (in case of tachycardia change or after lesion deployment) is very fast.

This is accomplished through integrated automated algorithms that meticulously select cardiac beats (based on stability of cycle length, timing, location and respiratory cycle) and filter-out points with discrepancy in comparison to those of close proximity. Far-field components are reduced by combining unipolar and bipolar electrograms. Moreover, the low noise level in the system (0.01 mV) allows the recording of very low-amplitude potentials indicative of scarred atrial myocardium.[62] As a result, the improved differentiation of signals enables depiction of narrow activation waves with high precision. Adjustment of the window of interest in an activation map can reveal early local potentials or eliminate far-field noise on the map. Similarly, changing the voltage scale can reveal electrical gaps through low-voltage areas or a breakthrough in ablation lines and it can be used to achieve the continuity of lesions (Fig. 4).

To further evaluate the application of this technology, our group has performed feasibility and efficacy studies in patients with supraventricular tachycardias, including AV nodal reentrant tachycardias, atrial flutter and fibrillation.[63, 64] The initial experience of pulmonary vein mapping and ablation in a porcine model has now been expanded to human atria and pulmonary vein ablation.[65,66] Resent studies have provided more confirming results about the use of the mini-basket catheter alone to sufficiently determine PV isolation. Along with improved recording of PV potentials after incomplete ablation, this catheter also registers "PV-like" potentials from neighboring structures. In these cases, pacing maneuvers are helpful to determine PVI and avoid excessive ablation.[67] These results though support the safety of the system and encourage further clinical evaluation.

Conclusions

Contemporary EAMs provided the 3D navigation for AF ablation in order to reduce radiation and improve safety, procedural time and efficacy. Image integration and tools, like fast mapping and contact-force feedback, act complementary towards that goal. Based on EAMs, fractionation and voltage mapping evolved and provided the stimulus for further developments that focused more and more on the visualization and analysis of the myocardial electrical signals. Advanced mapping systems emerged from the need to better understand and ablate complex AF substrate. These efforts tried to overcome the spatiotemporal and processing limitations of contemporary EAMs and focused on improving the acquisition and illustration of electrophysiological information. Innovative mapping approaches like ripple mapping may someday allow experienced operators to create maps of complex atrial tachycardias without assisting experts. Mapping technics that aim to visualize AF drivers through depiction of dominant frequency areas and characterization of rotors or focal impulses during (intracardiac) or prior (non-invasive) to the procedure, have shown promising results in terms of AF termination and will be further evaluated.[68] The improved electrical signals produced by narrow-spaced catheters and the automated high-density maps may also prove valuable for scar-based ablation strategies.

Characterization and redefinition of AF substrate is a key-element for future mapping systems and personalized AF ablation. Ideally, future mapping-systems would allow visualization of the atrial anatomy and pathophysiology, in order to individualize and monitor lesion formation in a real-time fluoroscopy-free environment, like in the MRI suite.[69-71] Although there is a long way ahead, it remains an exciting time with many improvements and a bright future for AF mapping systems.

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