Reinserting Physiology into Cardiac Mapping Using Omnipolar Electrograms

Karl Magtibay, MASc[a], Andreu Porta-Sánchez, MD, MS[b,c], Shouvik K. Haldar, MD (Res), MRCP[d], Don Curtis Deno, MD, PhD[e], Stéphane Massé, MASc[a], Kumaraswamy Nanthakumar, MD, FRCPC[a,*]

KEYWORDS

• Cardiac mapping • Omnipolar • Atrial fibrillation • Ventricular tachycardia • Electrogram direction • Wavefront orientation • Activation direction • Conduction velocity

KEY POINTS

- Unipolar electrograms are voltage signals that reflect time-varying extracellular currents. Bipolar electrograms provide differential extracellular voltages along an axis and resemble a local directional derivative. Both are based on the fundamental concept of electric fields in tissues. Omnipolar electrograms are derived from a clique, a group of nearby electrodes that generate bipolar signals from multiple directions. They are electrode and catheter-orientation independent.
- Omnipolar electrograms provide wavefront characteristics, such as amplitude, timing, direction, and speed, in physiologically relevant directions located at the center of the electrode clique. This enables determinations of a maximal bipolar voltage amplitude termed OT Vmax, the generalization of peak-to-peak in the presence of directionality, and is not affected by catheter orientation and is less sensitive to electrode distance for small cliques.
- Specialized catheters and three-dimensional mapping system software enable omnipolar electrograms and derived quantities to be generated and displayed in real-time.
- Omnipolar electrograms during atrial fibrillation are significantly less influenced by directional factors, allowing for robust and consistent substrate assessment.
- Mapping the ventricles using an equispaced electrode grid catheter and omnipolar electrograms can provide reliable substrate assessment within infarcted and noninfarcted regions of the ventricles to aid in determining ablation targets, such as a lesion gap or an isthmus.

INTRODUCTION

Cardiac mapping is an essential tool in arrhythmia diagnosis and treatment. Mapping information obtained from signal processing and image display algorithms in present day electroanatomic mapping systems are critically dependent on measured electrograms (EGMs) from catheters. A collection of local activation times (LAT) derived from EGMs within a cardiac chamber

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[a] The Hull Family Cardiac Fibrillation Management Laboratory, Toronto General Hospital, University Health Network, 200 Elizabeth Street, Toronto, Ontario M5G 2C4, Canada; [b] Hospital Universitario Quironsalud Madrid, Calle Diego de Velázquez, 1, 28223 Pozuelo de Alarcón, Madrid, Spain; [c] Fundacion Centro Nacional de Investigaciones Cardiovasculares Carlos III (CNIC), Melchor Fernández Almagro, 3, Madrid 28029, Spain; [d] Royal Brompton & Harefield NHS Foundation Trust, Harefield Hospital, Hill End Road, Harefield, Uxbridge UB9 6JH, UK; [e] Abbott Laboratories, One St. Jude Medical Drive, St. Paul, MN 55117, USA

* Corresponding author. 200 Elizabeth Street, GW 3-526, Toronto, Ontario M5G 2C4, Canada.

E-mail address: kumar.nanthakumar@uhn.ca

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characterizes the propagation of electrical waves, whereas its signal amplitude (millivolt) has been used as a surrogate to determine the health of underlying cardiac substrate. These two EGM features are the primary tools for cardiac mapping and, as such, the diagnosis and treatment of arrhythmias.

Traditionally, two types of EGMs are used for cardiac mapping: unipolar and bipolar. Unipolar EGMs are signals from a single electrode with a distant reference electrode providing measurements of change in extracellular voltage over time. Unipolar EGMs are non-directional but are susceptible to low-frequency noise, such as far-field or movement artifacts.[1–3] In contrast, bipolar EGMs are signals from a pair of neighboring electrodes and provide localized measurements of the myocardium. Although bipolar EGMs are less susceptible to low-frequency noise, they are greatly affected by the direction of wavefront propagation relative to the electrode pair[1,2] as shown in **Fig. 1**. Bipolar EGM measurements are also dependent on other parameters, such as electrode distance, electrode size, wavefront speed, and extent of activation.[4–8] Most importantly, neither bipoles nor unipoles can provide wavefront characteristics, such as speed and direction, at a single location or voltages along the wavefront direction.

We recently introduced a novel type of EGM, the omnipolar EGM, for cardiac mapping.[9,10] Omnipolar EGMs combine the strengths of unipolar and bipolar EGMs such that they are direction-insensitive and locally derived. In essence, omnipolar EGMs are orientation-independent, virtual bipolar EGMs that are aligned along the direction of a wavefront that is anatomically and physiologically meaningful. Furthermore, omnipolar EGMs provide localized and time-consistent measures, such as maximal voltage and activation speed and direction, to enable electrophysiologists to create maps that closely represent the underlying physiology of the myocardium.

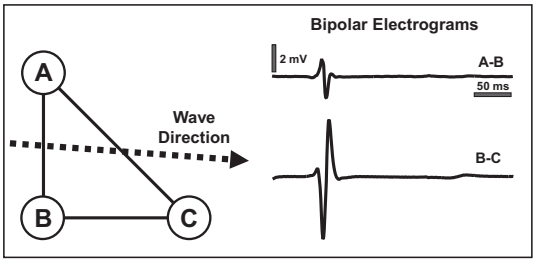

Fig. 1. Problem of directionality. Bipolar electrograms are useful in assessing local characteristics of the myocardium; however, they are catheter-orientation and wave-direction dependent. For a given wave direction within the same area, two orthogonal electrode orientations provide different bipolar electrograms in amplitude and timing. LAT derived at the -dV/dt from these two electrograms have several milliseconds difference from each other. Moreover, the bipolar electrode along the wave direction has a significantly larger bipolar electrogram amplitude compared with a bipolar electrode across a wave.

TROUBLE WITH TRADITION

LATs derived from either unipolar or bipolar EGMs over myocardial surfaces are used to create wave propagation maps to demonstrate activation sequences. There is, however, a continuing debate on the manner of timing annotations (eg, steepest negative or positive slope, minimum, maximum, first and/or last deflection, barycenter) especially in the case of bipolar EGMs because they are affected by numerous factors.[11,12] Unipolar –dV/dt is closely associated with action potential phase 0, rapid depolarization, but in practice, temporal uncertainty results over up to several milliseconds of the downslope of the signal due to local heterogeneities of activation, noise, and low-frequency baseline wander. Bipolar signals are less susceptible to noise (common mode is rejected) and filtering greatly attenuates baseline wander and so are often preferred. However, bipole directional effects may produce several milliseconds of temporal uncertainty of their own, as polarities may reverse and directional influences on amplitude may take effect. This is clearly shown in **Fig. 1** where the -dV/dt of the same wave are temporally different to each other. Also, interoperator differences on timing annotation lead to inconsistencies in LAT values, which therefore affect wave propagation profiles created post hoc. Although the resulting maps are often adequate over large regions and intervals of time, they can create locally unreliable and unreproducible characterizations of activation.

A variety of approaches using combinations of bipoles, unipoles, and time annotation criteria have been implemented for mapping.[13,14] Unfortunately, automatic algorithms incorporating such combined heuristic rules continue to facilitate temporal uncertainty. As such LAT values must be collected over an extended amount of time, over great areas of the myocardium to obtain a broadly accurate depiction of wave propagation. This low-resolution practice is time consuming because it involves spatial mapping first and then post-hoc processing and activation analysis of collected data, without any options for live mapping.

Measurements of peak-to-peak voltages (Vpp) from either unipolar or bipolar EGMs are used to

assess myocardial health and to survey for important substrate features, such as lesion gaps and isthmuses, which were found to be responsible for the maintenance and/or generation of arrhythmia.[15,16] Because unipolar EGMs are greatly affected by far-field effects, this could overestimate true Vpp values. Bipolar EGMs are dependent on orientation such that bipolar electrodes oriented along a wavefront produce an EGM with maximal bipolar Vpp, whereas those oriented across a wavefront measure a minimal bipolar Vpp. Optimizing bipolar Vpp measurements is challenging, especially in vivo, because it requires prior knowledge of the activation direction (AD) and complete control of catheter orientation. In addition to directionality, electrode pairs spaced widely apart, as in ablation catheters, can produce large Vpps and closely spaced electrodes, as seen in modern mapping arrays, produce small Vpps.[6–8] These factors create unreliable and nonreproducible characterization of the cardiac substrate.

Ironically, these EGM features and procedures that are fundamental to current cardiac mapping practices are themselves weaknesses and have not seen major innovation for almost a century. This realization fuels the need for standardized tools and methods that provide measurements with greater physiologic significance. These are the issues that omnipolar EGMs attempt to resolve. In the following section, we provide a description and derivation of omnipolar EGMs targeted to math-friendly clinicians.

OMNIPOLAR ELECTROGRAMS

Omnipolar EGMs take advantage of the directional properties of electric field (E-field) of a traveling wavefront on the surface of the myocardium (**Fig. 2**A) to produce consistent, physiologically pertinent, beat-by-beat measurements as introduced by Deno and colleagues.[9,10] An intracardiac E-field is analogous to a traditional vectorcardiogram (**Fig. 2**B) but substitutes voltage signals from catheter electrodes for surface electrocardiogram electrodes. We may understand bipolar catheter signals as manifestations of more fundamental currents and E-fields

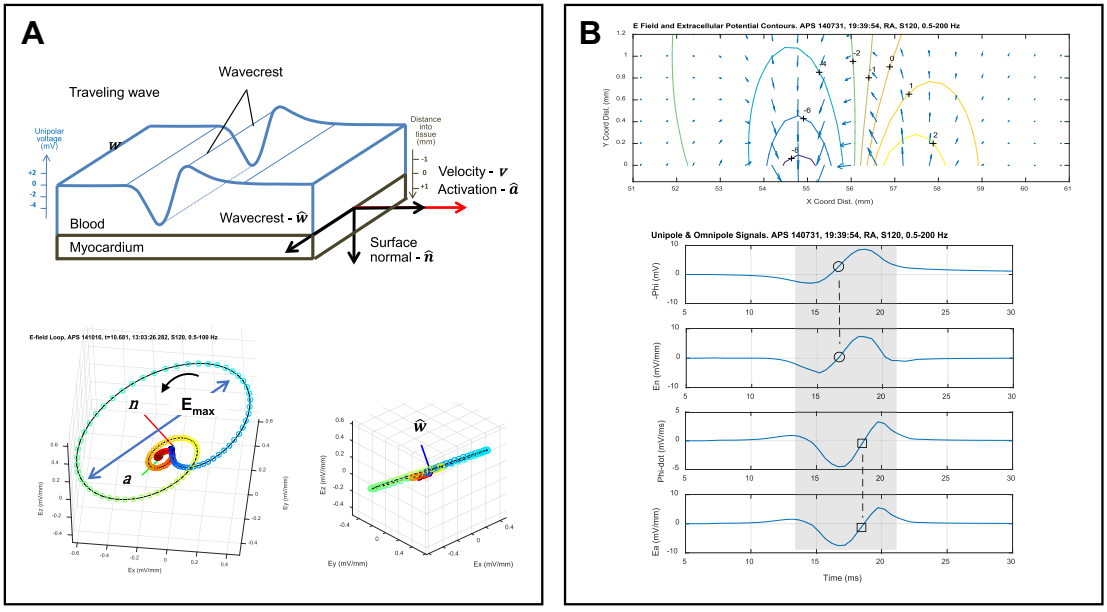

Fig. 2. (*A*) The traveling wave concept. Omnipolar electrograms are based on the concept of electric fields of a uniform traveling wave. Such a wave represents the activation of propagation of tissues along the surface of the myocardium. Illustrated is a traveling wave with constant velocity *v* along the *a*-direction. Representation of extracellular voltages as electric field loops is similar to a traditional vectorcardiogram, which describes the procession of local cardiac activation. (*B*) Omnipolar electrograms. An electric field drawn as a field of vectors represents the spatial development of extracellular voltages as a wave traverses through an observation window. Such extracellular voltages are represented as an electric field loop that is evolving through time. Characteristics of a traveling wave are maintained in this representation, such as the activation direction and normal-to-surface component. Omnipolar electrograms are derived from these components as presented. (*From* Deno DC, et al. Orientation-independent catheter-based characterization of myocardial activation. *IEEE Trans Biomed Eng* 2017;64(5):1067–77, with permission).

according to bipole direction and spacing. Omnipolar EGMs are virtual bipolar EGMs computed from nearby but differently directed bipoles. Omnipole signals leverage a local traveling wave model of propagation to avoid directional dependence and instead determine directions and corresponding signals of physiologic significance.

We begin our explanation of omnipolar EGMs and mapping with a simple two-dimensional array of electrodes laid out on a square grid and on a myocardial surface. Adjacent sets of three electrodes are referred to as cliques and produce three bipolar signals, two orthogonal and one diagonal. In keeping with a vector treatment, we note that there are three displacement vectors between electrode pairs and denote them in a 2×3 matrix dX. There is a correspondingly ordered set of unipolar voltage differences (bipoles) among these three electrodes we denote by a 3×1 vector $d\Phi$. Assuming clique electrodes are spaced closely enough that the 2×1 E-field vector E is essentially constant, from physics and matrix algebra we write $d\Phi = - dX^T E$. We then note the least-squares solution for the time-varying E-field using pseudoinverse $(dX^T)^+$ and assuming the electrode locations are effectively unchanged during depolarization is

$$E(t) = -(dX^T)^+ d\Phi(t).$$

From the time-varying two-dimensional E-field E(t) we may solve for bipolar voltages in different directions and with different electrode spacings and bring in unipole signals $\Phi(t)$ to determine conduction velocity (CV) and AD in a manner that does not rely on accurate time differences between nearby electrodes. Like the vectorcardiogram, E(t) traces out a loop during depolarization beginning near the origin when isoelectric, changing rapidly during depolarization, and returning to isoelectric when done. We exactly recover constituent bipole voltages when multiplying E(t) by the interelectrode spacing *s* and projecting the resulting voltage loop $V(t) = s\ E(t)$ onto the orthogonal bipole directions. So, one interpretation of the E-field loop is that it is a fundamental entity and bipoles in any direction may be obtained from it. We know that when local bipoles are oriented in certain directions, their amplitudes can be much smaller than in other directions. When we gauge the health of myocardium we tend to ask how large can the amplitude be. The proper generalization of peak-to-peak amplitude of an ordinary 1D bipole signal is the span of the voltage loop, a quantity we designate as OT Vmax.

Local propagation speed and direction are determined in a revolutionary way using the relationship between unipole and omnipole signals. If a wavefront near clique electrodes is moving primarily in one direction at a roughly constant speed and producing similar unipolar EGM shapes and amplitudes it satisfies conditions of a traveling wave. The E-field, up to a negative sign, is essentially the spatial derivative of the unipolar potential field. As shown elsewhere,[9,10] traveling waves possess a special relationship between the time and spatial derivatives of their unipolar waveforms. The spatial derivative (in the direction of activation) with units of mV/mm has the identical shape as the temporal derivative $\dot{\varphi}$ (units of mV/ms). They differ by a multiplicative constant, that is, the CV speed. Designating the AD as unit vector $\hat{\boldsymbol{a}}$, we recognize it is possible to determine an AD arrow by finding the angle that maximizes a cross-correlation

$$AD = \hat{\boldsymbol{a}} = \underset{\boldsymbol{a}}{\operatorname{argmax}}\{xcorr(\dot{\varphi}(t), \boldsymbol{E}(t) \cdot \boldsymbol{a})\}$$

We introduce E_a as shorthand for the E-field signal in the direction of activation $E_a(t) = \boldsymbol{E}(t) \cdot \hat{\boldsymbol{a}}$ and $E_a pp$ for its peak-to-peak amplitude. Bringing back properties of a traveling wave approximation we may now solve for CV speed in units of mm/ms as a ratio of amplitudes.

$$CV = \frac{\dot{\varphi} pp}{E_a pp}$$

This method of determining CV is not dependent on LAT; thus it differentiates itself from the time annotation-based mapping strategies. To conclude, an omnipolar EGM is an E-field based signal obtained from nearby bipolar and unipolar EGMs and electrode locations. Omnipolar EGMs do not depend on catheter-wavefront orientation and are instead linked to relevant anatomic and physiologic directions. Derived characteristics such as signal amplitude and conduction velocity are determined as outlined above and further explained by Deno and colleagues.[9]

VALIDATION OF OMNIPOLAR ELECTROGRAMS

Omnipolar mapping technology (OT) has been validated to rigorous standards using electrical and optical approaches and in various media (ie cardiac myocyte monolayers, cardiac tissue constructs, small and large isolated animal hearts, and diseased isolated human hearts) by Massé and colleagues.[17,18] A physiologic traveling wave was established with a cardiac myocyte monolayer under paced conditions. Each monolayer

was electrically mapped on a glass dish with an embedded two-dimensional microelectrode array. Some monolayers were also optically mapped while exhibiting rotational events. Data from these monolayers were processed with the omnipolar algorithm to show a vector field representative of ADs that closely corresponded to optical mapping results. This exercise validated OT AD and the traveling wave concept in real media with electrical and optical waves.

OT was further validated using only optical mapping data gathered from cardiac tissue constructs with perfusion channels. Here we showed that with complex structures coupled with well-behaved waves and reentrant activity, the concept of omnipolar signals from traveling action potential waves holds as well.

For small healthy isolated animal hearts, we presented a novel set up for simultaneous optical and electrical mapping, which has allowed for a direct comparison of electrical measurements with a grid catheter against an optical gold standard (Fig. 3A–F). The unique make of the grid catheter allowed us to stitch the catheter on the epicardium while imaging from the gaps separating each spline where myocardial tissues were exposed to a light-sensitive camera. In this study, we found that ADs and CVs calculated from optical mapping data using traditional LAT methods have similar values to the ones calculated from omnipolar EGMs.

We also mapped diseased isolated human hearts during pacing using a high-density electrode plaque with 112 channels arranged in an 8 $\times$ 14 grid. Similar to our small isolated animal hearts, even in diseased tissues, we found that ADs and CVs derived from omnipolar EGMs have values similar to those derived with traditional LAT methods using electrical data.

Finally, omnipolar methodology was validated in porcine atria in vivo using the same grid catheter by mapping around the sinoatrial node to represent an activation focus (Fig. 3G). The vector fields generated from this study clearly show the utility of E-fields in cardiac mapping.

The previously mentioned studies provide strong proof-of-concept for the use of omnipolar EGMs for determining conduction vectors, which paves the way for its use in preclinical and clinical studies.

OMNIPOLAR MAPPING APPLICATIONS IN THE ATRIA

Voltage assessment is crucial for assessment of health and arrhythmia mechanism in the atria. Evidence from experimental and clinical studies suggest that an underlying atrial fibrotic substrate as delineated by low-voltage areas (LVA) plays a key role in development of atrial fibrillation (AF) drivers and foci that maintain AF.[19–21] Assessing the underlying fibrotic substrate is currently undertaken by creating electroanatomic bipolar voltage maps. However, bipolar voltage amplitude is influenced by several factors, such as electrode characteristics (eg size, spacing, and orientation), wavefront speed and direction, and tissue structure. Omnipolar EGMs offer an alternative to mapping the atria with traditional bipolar EGMs in a manner better suited to complex and time-varying AF mechanisms, such as wave collisions and fractionations.

Haldar and colleagues[22,23] expanded on efforts by Deno and colleagues[10,24] to introduce the concept of maximal bipolar voltage derived from omnipolar EGMs. Intuitively, we expect that bipolar EGMs with maximal Vpp will be measured when the bipole is oriented in the AD, $\hat{\boldsymbol{a}}$. However, the AD must be known first to properly align the bipole and this is not always practical. Instead we rely on EGM signals from a voltage loop V(t), like the E-field loop of Fig. 2A, and determine OT Vmax from the maximal span of the loop. This is the proper generalization into two dimensions of the Vpp of a one-dimensional signal. This is challenging to obtain in vivo using traditional methods because it is difficult to align a bipole with the loop's maximal extent. Instead, an omnipolar EGM signal is mathematically determined in any direction in which a virtual bipolar EGM is derived. The derivation of this maximal bipole axis $\widehat{\boldsymbol{m}}$ and maximal bipole amplitude Vmax has been previously presented by Haldar and colleagues[23] where it was found to be especially useful when mapping a substrate during AF.

Substrate mapping during AF with traditional bipolar voltages poses significant challenges because of AF's complex mechanism. The presence of wave collisions and fractionation results in low bipolar Vpp, which is exacerbated by orientation-dependence of bipolar EGMs. This results in substrate maps that have unnecessarily large LVA, which could be erroneous targets for radiofrequency ablation. An E-field treatment allows for the calculation of OT EGMs and Vmax to improve the fidelity of atrial substrate maps and better delineate LVA during AF. This may delineate more focused targets for ablation beyond simple pulmonary vein isolation without the need for global mapping to identify electrophysiologic mechanisms that co-locate with LVAs (Fig. 4A).

Within the same study, we incorporated information gained from substrate mapping using EGMs with corresponding vector fields to characterize spatial and temporal wavefront organization. As expected, AF omnipole-based vector fields

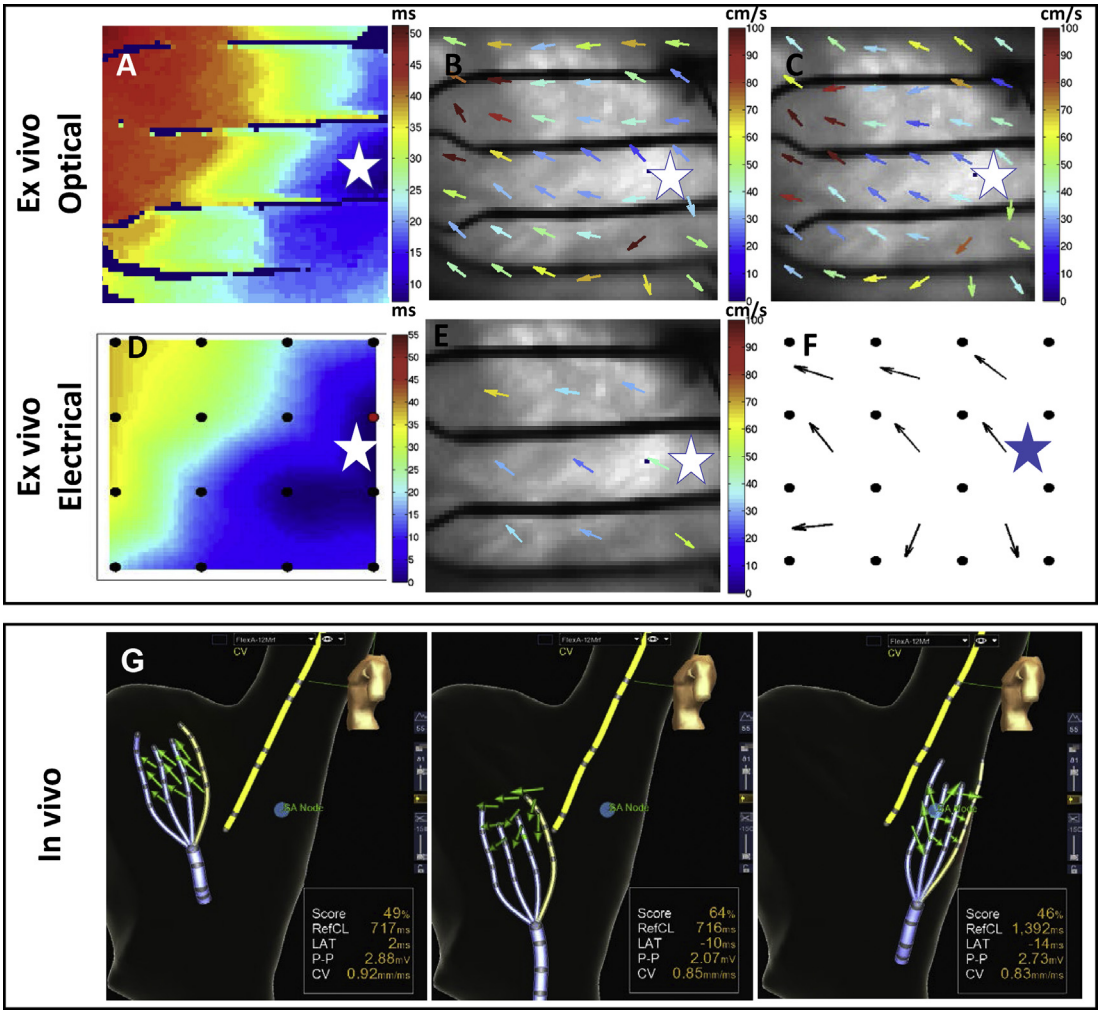

Fig. 3. Validation of omnipolar methodology. (*Top*) The concept of omnipolar electrograms was extensively validated through in vitro, ex vivo, and in vivo experiments. Shown is a simultaneous optical and electrical mapping of the epicardium of an isolated rabbit heart during pacing with the star indicating the pacing location. Traditional LAT-based methods were used to create isochronal maps from optical (*A*) and electrical (*D*) data. LAT-based vector fields were derived from both types of mapping data (*B* for optical and *E* for electrical) showing calculated speed and direction of wave propagation. Finally, omnipole-based vector fields (*C*, *F*) were calculated and were found to be a close match with traditional tools. (*Bottom*) Omnipole-based vector fields were validated in vivo in a porcine atria model using a grid-like catheter (*G*). In this model, it shows that omnipole-based vector fields accurately describe the outward propagation of tissue activation originating from the sinoatrial (SA) node. (*From* Massé S et al. Resolving myocardial activation with novel omnipolar electrograms. *Circ Arrythym Electrophysiol* 2016; 9; with permission).

have great spatial and temporal disorganization. From this we introduced a schema to improve substrate mapping during AF (Fig. 4B). This schema uses information of local organization of omnipole-based vector fields to signify coherence. We defined coherence as the organization of a 2 × 2 cluster of omnipolar unit vectors within a mapping area. If the average length of the unit vectors within a cluster is almost 1, it means that all four vectors essentially point in one direction and hence this cluster is included in highly coherent cluster. However, if the average length of the vectors within a cluster is close to 0, it means that vectors point in different, opposing directions, and hence they are included in a noncoherent cluster. Clusters with a high coherence may be included in a resultant voltage map, whereas those less than a certain threshold (<0.5 coherence) were excluded. This schema allows an operator to create a substrate map with better delineation of areas where collision and fractionation occur to better localize radiofrequency ablation treatments.

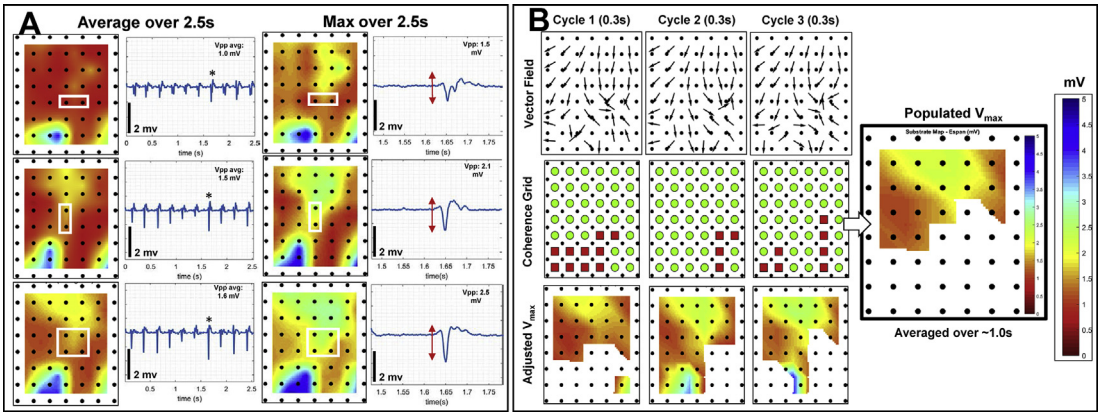

Fig. 4. Mapping atrial fibrillation with omnipolar electrograms. (*A*) Omnipolar electrograms (OT_{EGM}s) could aid in defining areas of atrial substrate for ablation during AF. Because of wave fractionation and collisions, in addition to the orientation dependence of traditional bipolar EGMs, mapping substrate during AF yields maps that are generally low voltage. Because OT_{EGM}s are catheter- and wave-orientation-independent, it provides a better representation of the substrate throughout the AF cycle since the maximal Vpp is obtained along the activation direction. (*B*) To build more robust substrate maps, we introduced a scheme where the organization of associated omnipolar vector fields are used as a guide to populate a resultant substrate map. Such a map could be used to localize areas of the substrate where wave collisions and fractionation occur as targets for radiofrequency ablation treatments. (*From* Haldar SK, et al. Resolving bipolar electrogram voltages during atrial fibrillation using omnipolar mapping. *Circ Arrhythm Electrophysiol*. 2017; 10(19); with permission).

If implemented in a commercial mapping system, this would provide rapid, high-density, orientation-independent assessment of the underlying atrial substrate.

OMNIPOLAR MAPPING APPLICATIONS IN THE VENTRICLES

The number of ventricular tachycardia (VT) ablation procedures is increasing worldwide. During the last decades, mapping procedures for localizing VT-harboring areas, either by substrate or LAT, have evolved from intraoperative mapping during cardiopulmonary bypass,[25–27] to sequential point-by-point mapping with "large" electrode ablation catheters with 3.5-mm tips,[28–30] and then to high-density, multielectrode mapping.[31–33] Advances in VT substrate mapping commonly rely on the acquisition of large numbers of points to resolve substrate features and is time consuming. However, it is important to recognize that high-density maps do not necessarily better represent underlying myocardial physiology. Traditional unipolar and bipolar EGMs have disadvantages (eg, susceptibility to noise and directionality, respectively) that omnipolar EGMs try to work around, irrespective of map point density. Overcoming these factors is critical when ablating VTs in a hemodynamically unstable patient to minimize procedure time.

Omnipolar EGMs, together with regularly spaced grid catheters, aim to provide physiologically relevant measurements of the substrate and rapidly provide high-density maps. Recent works by Porta-Sanchez and coworkers[34,35] and Magtibay and coworkers[36,37] demonstrated the use of omnipolar EGMs in ex vivo and in vivo mapping of ventricles. Both studies reinforced the concept of catheter-orientation dependence of bipolar measurements especially for voltage/substrate mapping.

Magtibay and coworkers[36,37] ex vivo work focused on building a foundation for omnipolar EGM mapping of ventricular myocardia. This preclinical work reexamined the directional dependence of bipolar EGMs for isolated animal and human hearts using different grid arrays. OT Vmax values provide the maximal bipolar Vpp in any direction along the surface of the myocardium. This was especially useful when delineating diseased tissue to locate lesion gaps or isthmuses that could be responsible for the initiation and/or maintenance of a ventricular arrhythmia (**Fig. 5**A). Because of the nature of omnipolar EGMs, a new voltage threshold for isolating scar area was also developed. Because OT Vmax always yields the maximal bipolar voltage, the established voltage thresholds currently used in clinical practice (0.5 mV for dense scar) may not well-represent the substrate. Magtibay came up with a threshold value of 1.5 mV for dense scar on the epicardium,

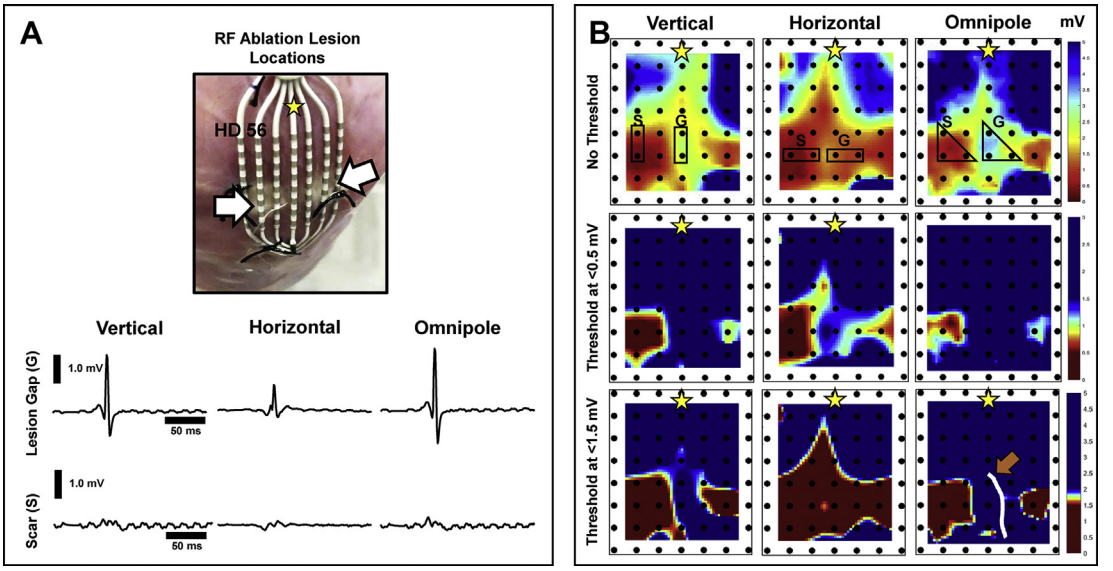

Fig. 5. Ex vivo mapping of the ventricles with omnipolar electrograms. (*A*) Ex vivo work on isolated animal hearts show the advantage of using omnipolar electrograms (OT_{EGM}) in mapping the ventricles especially in the presence of an isthmus or lesion gap. Orientation-dependence of bipolar EGMs is re-emphasized such that a lesion gap is misrepresented as a diseased area along one orientation and a normal area along another. OT_{EGM}s, however, provide EGMs with maximal voltage values regardless of orientation. (*B*) Translating to substrate maps, bipolar EGMs portray two different profiles of the substrate depending on the orientation examined. OT_{EGM}s, however, illustrate a clear delineation between the two lesion islands and the isthmus that exist between them. RF, radiofrequency. (*From* Magtibay K et al. Physiological assessment of ventricular myocardial voltage using omnipolar electrograms. *J Am Heart Assoc.* 2017; 6; with permission).

three times larger than the standard value (1.5 mV). This new threshold achieved fair sensitivity and specificity values of 0.94 and 0.82, respectively (Fig. 5B). With this threshold, OT Vmax-based substrate maps closely match diseased areas directly observed on the epicardium compared with bipolar substrate maps.

Magtibay's study also examined the consistency of omnipolar Vmax-based substrate maps for multiple beats and for different rhythms. OT Vmax was more consistent beat-by-beat than traditional bipolar Vpp. OT Vmax-based maps produced more consistent substrate map profiles regardless of rhythm.

Porta-Sanchez and coworkers'[34,35] in vivo work applied grid-like catheters and omnipolar EGMs to a preclinical environment in more realistic scenarios where factors, such as tissue contact and movement, could be detrimental. In this study, pigs with ventricular myocardial infarctions were mapped. Myocardial infarction was achieved by occluding the distal left anterior descending artery with an angioplasty balloon. Images of the whole heart were obtained 4 weeks after myocardial infarction induction using MRI with late-gadolinium enhancement to contrast infarcted against healthy tissues. In vivo mapping was performed using a research version of the Ensite Precision™ Cardiac Mapping System (Abbott, St. Paul, MN).

In addition to comparing scar areas, this work revisited the orientation dependence of bipolar EGMs. Catheter orientation can make significant differences in substrate maps such that potential isthmuses are only observable along specific bipolar orientations (Fig. 6).[38,39] Substrate maps created with bipolar Vpp values have low beat-by-beat consistency on healthy and infarcted areas. However, substrate maps created with OT Vmax values had better beat-by-beat consistency on both areas. OT Vmax-based maps also produced a better representation of the infarcted areas. The surface area of MRI late-gadolinium enhancement scar more closely corresponded to endocardial extent of LVA in OT Vmax electroanatomic maps compared with traditional bipolar maps. This allows for a better, more physiologic in vivo definition of potential VT substrate than traditional bipolar-based substrate maps. Although in this study the omnipolar Vmax threshold developed in Magtibay's work was used, additional in vivo mapping studies should be done to account for variabilities in more clinically realistic cases.

Importantly, Porta-Sanchez's work relied on triangular cliques for calculating E-fields. Previous work with omnipolar EGMs used four closely

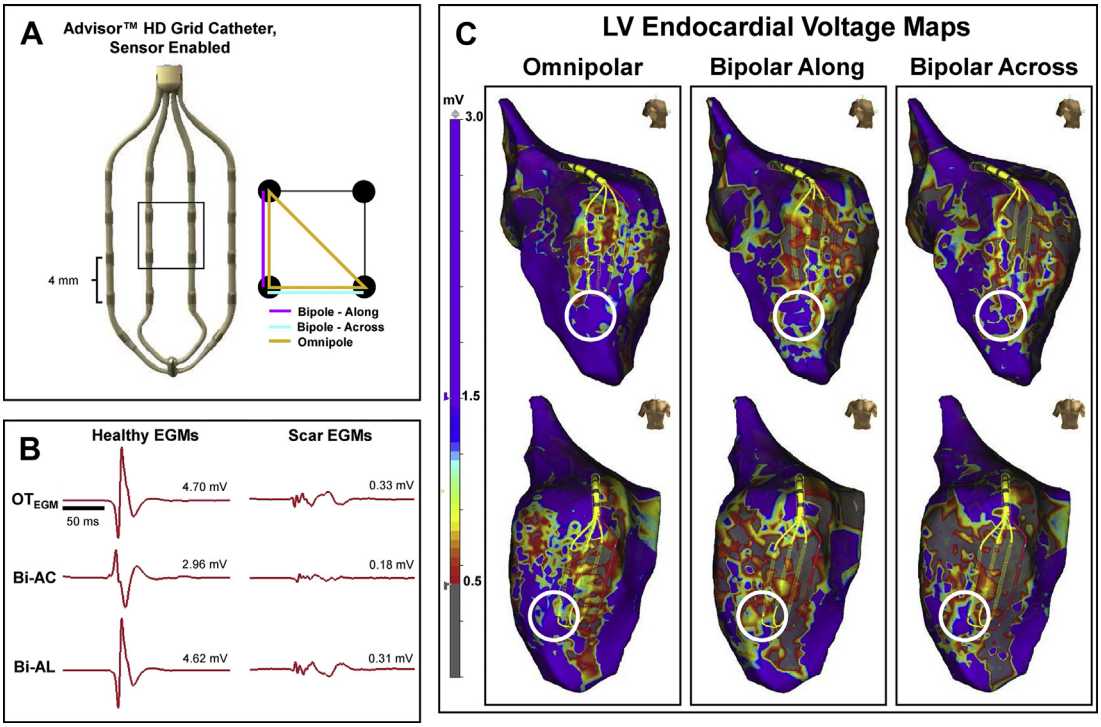

Fig. 6. In vivo mapping of the ventricles with omnipolar electrograms. (*A*) Grid-like catheter was used for mapping the ventricular endocardium of myocardially infracted (MI) porcine model. The bipolar orientations are shown along which their Vpp are calculated (magenta, along; cyan, across). The clique of electrodes used to calculate omnipolar electrograms (*yellow triangle*) are also shown. (*B*) EGMs from both bipolar orientations and electrode cliques are shown. OT_{EGM}s is comparable with the bipolar EGM with the largest Vpp but still offers largest Vpp either on scarred or healthy tissues. Again, the orientation dependence of bipolar EGMs is emphasized. (*C*) Voltage maps created from bipolar EGMs from either orientation display stark differences especially within the areas highlighted (*white circle*). OT_{EGM}s, however, provide maps that have larger Vpp values, hence better delineation of diseased areas. LV, left ventricular. (*From* Porta-Sanchez A, Magtibay K, Nayyar S, et al. Omnipolarity applied to equi-spaced array for ventricular tachycardia substrate mapping. *Europace* 2019; with permission).

spaced electrodes to comprise a square clique. However, the omnipolar framework allows for a minimum of three electrodes (making a triangular clique) to characterize a traveling wave along a two-dimensional surface. This allows grid-like catheters such as the Advisor™ HD Grid Mapping Catheter, Sensor Enabled™ (Abbott, St. Paul, MN) to quadruple the number and density of map points compared with the original square clique (36 vs 9 points for HD Grid, and decrease map point spacing from 4 to 2 mm). Traditional along spline bipolar measurements only allowed for 12 mapping points for each acquisition. This not only allowed for quicker creation of endocardial maps but also offered a more detailed view on the electrophysiology of myocardium.

FUTURE DIRECTIONS

Deno's seminal work on omnipolar EGMs has paved the way for new and exciting applications in cardiac mapping. The concepts of traveling waves and E-fields allow us to revisit our understanding of electrophysiology and re-examine our perspective toward reading and interpreting EGMs. Omnipolar EGMs show that one-dimensional signals from electrodes in arbitrary orientations cannot fully evaluate electrophysiologic events. Although appreciated earlier by Kadish and coworkers[39] and Gerstenfeld and coworkers[40,41] it was not yet practical for two- and three-dimensional electrophysiologic signals to be given physiologic and anatomic context in a three-dimensional mapping system. Today, high-density mapping catheters combine with computers with strong graphics and computational abilities and the principles of an omnipolar approach and traveling waves open the door to new understandings of mechanisms and possibly more effective arrhythmia treatments.

Most of the studies reviewed here created substrate maps of voltage to better describe the

myocardium using omnipolar EGMs. However, it is important to recognize that omnipolar EGMs also enable local accurate determinations of CV based on the characteristics of a traveling wave, independent of conventional LAT-based methods. Although omnipolar determinations of CV and AD require further and more rigorous in vivo validation, real-time, beat-by-beat, omnipolar AD vectors could be of great use especially in VT cases. The number and density of omnipolar AD vectors feasible with grid-like catheters could enable clinicians to rapidly home in on arrhythmia sources via drag-and-locate strategy[42,43] or rapidly identify reentrant pathways in a drag-and-map approach. In both instances an operator may drag a grid-like catheter within the endocardium, whereas AD vectors and CV speeds are calculated and displayed beat-by-beat. A source may be located by observing that the AD vector field radiates outward in its vicinity and at the source the coherence of direction is least. This method bypasses the need for the creation of global LAT maps and post hoc analysis, which is a time-consuming endeavor. Omnipolar-based AD vectors provide reproducible, real-time, rapid localization of VT sources independent of catheter orientation. This is analogous to a global positioning system style of locating a target on a map.

However, as with any medical diagnostic product, the omnipolar mapping algorithm and related tools must undergo rigorous performance assessments to ensure that the data we obtain from it are robust and trustworthy. We must ask, in what conditions does it fail, how does it fail, and how might we avoid improper characterizations. It is imperative to explore omnipolar algorithm sensitivities (eg, clique type, electrode distance, presence of noise, sampling rate, filter settings) from which to develop confidence metrics to indicate the reliability of data collected and maps created before it is widely adopted into clinical practice.

SUMMARY

Omnipolar EGMs make use of the biophysical E-fields that accompany activation along the surface of the myocardium. A grid-like electrode array provides bipolar signals in orthogonal directions to deliver catheter-orientation-independent assessments of cardiac electrophysiology. Omnipolar EGM features are currently used for two mapping categories: substrate voltage and activation propagation. In addition to comprehensive maps of cardiac chambers, omnipolar algorithms on three-dimensional mapping systems make possible local, beat-by-beat visualizations of maximal bipole voltage and orientation and CV. OT's E-field loop and traveling wave treatment of omnipolar EGMs enables determination of activation speed and direction, bypassing ambiguous inconsistent LAT annotation. Such abilities have made possible the live mapping of wavefront propagation without time consuming mapping of entire heart chambers.

Studies with myocyte monolayers, isolated animal and human hearts, and anesthetized animals have validated the tenets of omnipolar EGMs. Optical mapping and traditional LAT determinations of conduction speed and direction, under controlled circumstances, were found consistent with those from OT. Omnipolar EGMs from atria and ventricles avoided a tendency for bipole directional mismatch to underestimate voltage, suggesting improvements to delineation of diseased areas of myocardium responsible for the initiation and/or maintenance of arrhythmias. The combination of information from omnipolar-based vectors and voltage values may also aid in localizing areas of wave fractionation and/or collision during fibrillatory episodes. In addition to working to identify clinical benefits of omnipolar EGM, it is also important to compare traditional and omnipolar algorithms looking for situations where one or both seem less trustworthy. Confidence metrics should be developed before OT evaluations of direction and speed are pushed toward real clinical applications. Ultimately, the goal of omnipolar EGMs is to better characterize myocardial substrate through reintroducing the fundamentals of cardiac electrophysiology to avoid catheter-orientation dependence.

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