ORIGINAL ARTICLE

Toward a novel semi-invasive activation mapping tool for the diagnosis of supraventricular arrhythmias from the esophagus

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Abstract

Aims: Supraventricular arrhythmia diagnosis using the surface electrocardiogram (sECG) is often cumbersome due to limited atrial signal quality. In some instances, use of esophageal electrocardiography (eECG) may facilitate the diagnosis. Here, we present a novel approach to reconstruct cardiac activation maps from eECG recordings. **Methods:** eECGs and sECGs were recorded from 19 individuals using standard acquisition tools. From the recordings, algorithms were developed to estimate the esophageal ECG catheter's position and to reconstruct high-resolution mappings of the cardiac electric activity projected in the esophagus over time.

Results: Esophageal two-dimensional activation maps were created for five healthy individuals and 14 patients suffering from different arrhythmias. The maps are displayed as time-dependent contour plots, which not only show voltage over time as conventional ECGs, but also the location, direction, and projected propagation speed of the cardiac depolarization wavefront in the esophagus. Representative examples of sinus rhythm, atrial flutter, and ventricular pre-excitation are shown.

Conclusion: The methodology presented in this report provides a high-resolution view of the cardiac electric field in the esophagus. It is the first step toward a three-dimensional mapping system, which shall be able to reconstruct a three-dimensional view of the cardiac activation from recordings within the esophagus.

KEYWORDS

biomedical engineering, cardiac electrophysiology, cardiac mapping, esophageal ECG, noninvasive mapping

1 | INTRODUCTION

The conventional surface 12-channel electrocardiogram (sECG) is probably the most widespread diagnostic tool in clinical medicine. Despite its undisputed merits, sECG recordings may lack diagnostic accuracy, in particular in the diagnosis of supraventricular arrhythmias. For instance, while, with the typical sawtooth pattern in the

inferior leads of the sECG, the diagnosis of a typical, counterclockwise, isthmus-dependent atrial flutter may be straightforward, such clear waves are not always present and often even experienced cardiac electrophysiologists face insecurities in regard to the location of a reentry circuit (Barbato et al., 2009; Lee & Fynn, 2015). Especially in patients with a history of cardiac surgery or catheter ablation, arrhythmia diagnostics is often challenging. Thus, it is not

an uncommon clinical scenario that a patient has to undergo invasive testing to establish the correct diagnosis; moreover, planning of these procedures is often hampered due to the lack of information from the sECG.

Consequently, efforts to improve noninvasive electrophysiology have never ceased. Particularly in the last few years, these efforts were rewarded by substantial advances in noninvasive cardiac mapping technologies, some of which have shown impressive results in their ability to trace the heart depolarization process in a three-dimensional (3D) manner. On the forefront of the field are electrocardiographic imaging (ECGI) systems, which combine multi-electrode measurements from up to 252 body surface electrodes with patient-specific anatomical information from computed tomography (CT) imaging to reconstruct epicardial depolarization sequences (Rudy, 2013; Shah, Hocini, Xhaet, et al., 2013). Alternative approaches include measurements of the heart magnetic field (Ha, Kim, Lim, Yu, & Kwon, 2015; Kim, Kim, Lee, & Ahn, 2007; Sorbo et al., 2018), the exploitation of vectorcardiograms (Castells et al., 2011; Hasan, Abbott, & Baumert, 2012; Man, Maan, Schali, & Swenne, 2015), or the acquisition of esophageal electrocardiograms (eECGs) (Haeberlin, Niederhauser, et al., 2013; Haeberlin et al., 2012; Niederhauser et al., 2012). Esophageal ECGs have interesting properties, the most notable of which is an excellent atrial signal quality. As fast, uncostly, and easily applicable methods beyond sECG to distinguish especially supraventricular arrhythmias are missing, we decided to explore and utilize the strength of eECGs to develop a novel mapping tool that shall aid in the diagnostics of atrial rhythm disorders. Subsequently, the mapping methodology and results of the approach will be presented and an outlook on future steps is outlined.

2 | METHODS

2.1 | Design and population

Between November 2015 and December 2016, a total of 20 eECGs were acquired from 14 patients with various cardiac arrhythmias and five healthy volunteers in the frame of the Multi-Channel Esophageal ECG Signal Classification study (NCT02541175). In this prospective observational single-center study, we included adult individuals (≥ 18 years) presenting for inpatient or outpatient evaluation at our department. Informed consent was obtained from all participants before inclusion. Patients with acute coronary syndrome, uncontrolled hypertension or hypotension, known bleeding diathesis, malformations, or disease of the upper airways or the esophagus

conflicting with catheter insertion were excluded, as well as patients with history of atrial fibrillation ablation, cardiac transplantation, or valve replacement within 4 weeks. The study was approved by the local ethics committee.

2.2 | Surface ECG data acquisition and signal processing

In all participants, esophageal as well as 12-lead surface ECGs were registered simultaneously for 60 min using a biosignal recorder (g.USBamp, g.tec medical engineering GmbH, Schiedlberg, Austria). The sECG was registered with electrodes placed at the standard positions. Recorded sECG signals were bandpass-filtered with cutoff frequencies at 2 and 40 Hz and not processed any further otherwise.

2.3 | Esophageal ECG data acquisition and signal processing

For acquisition of eECGs, FIAB Esoflex 10S catheters (FIAB SpA, Vicchio, Italy) were used. These nine French polyurethane catheters, which have 10 olive-shaped stainless steel ring electrodes with an interelectrode spacing of 10 mm each, were used to acquire nine bipolar electrograms along the esophagus. The catheter was inserted through the patient's nostril after application of a local anesthetic and lubricant (oxybuprocaine 0.2% gel) and placed at height of the best atrial signal (largest amplitude on the eECG).

To reconstruct the cardiac electric field from the eECGs, a novel algorithm was implemented as detailed in a technical article (Wildhaber et al., 2018). In summary, the algorithm utilizes the constant slight cranio-caudal movement of the esophageal electrodes in relation to the heart (due to breathing, esophageal peristalsis, swallowing, heart movements, aortic pulsations) to calculate the cardiac electric activity projected into the esophagus with a much higher (i.e., subelectrode) resolution. These natural movements cause low-frequency signal disturbances in the ECG, which are usually filtered out with considerable efforts to improve the ECG signal quality (Luo & Johnston, 2010; Niederhauser et al., 2016). However, here the movements are used to "scan" the left atrium along the longitudinal axis of the esophagus to obtain a higher number of virtual electrodes exceeding the ones physically mounted on the catheter. This allows the estimation of the varying height position of the esophageal electrodes inside the body (Figure 1) by morphological comparison of all recorded beats within a selectable time frame and computation

FIGURE 1 Time evolution of estimated height of the esophageal tip in the esophagus during a period of 1 min. A time-varying movement in the range of $[-1 \text{ cm}, +1 \text{ cm}]$ can be clearly seen

of the relative displacement in between. By subsequent alignment and spatial fusion of the signals according to the estimated position, time-dependent isopotential maps (showing the projected cardiac field in the esophagus as a contour plot) are created.

3 | RESULTS

3.1 | Baseline characteristics

Esophageal electrocardiograms were obtained from 19 individuals (14 patients and 5 healthy volunteers) (68% male, median age 67 years [IQR 47–75 years]). Apart from one patient, who complained about strong nasopharyngeal discomfort during esophageal lead insertion (the eECG registration was aborted prematurely in that patient), the esophageal ECG acquisition was tolerated well by all participants.

3.2 | Arrhythmia mapping in the esophagus

Esophageal isopotential maps were reconstructed from all recordings. A representative example of an isopotential map and the corresponding conventional sECG leads I–III of a healthy individual in sinus rhythm is shown in Figure 2. The isopotential map shows a high-resolution two-dimensional representation of the esophageal ECG due to the constantly moving “scanning” esophageal catheter—that is, with much higher resolution than it would be

possible from the nine raw eECG channels which are acquired. Besides the activation direction, the projected conduction speed of the depolarization wavefront can be estimated by inspecting the slope of the direction vector.

A representative example of a 67-year-old patient with ongoing arrhythmia is shown in Figure 3. This patient suffered from clockwise cavotricuspid isthmus-dependent atrial flutter with 4:1 atrio-ventricular conduction. As in the sECG, the time sequence of atrial and ventricular activations can be assessed. Moreover, the localization of the electrodes along the esophageal lead depicts where on a cranio-caudal axis the electrical activation takes place, which allows for a better electroanatomical understanding.

Finally, Figure 4 (top panel) shows an esophageal isopotential map from a patient (male, 18 years old) with diagnosed atrioventricular reentrant tachycardia. The electrocardiograms were obtained in sinus rhythm. The isocontour lines might show atrioventricular signal fusion on the cranio-caudal level of the AV-plane. The patient underwent an electrophysiological study revealing a right atrial antero-septal accessory pathway.

4 | DISCUSSION

The article presents a novel mapping approach to compute the time-varying cardiac electric field as projected in the esophagus.

FIGURE 2 Top panel: Example of a single sinus rhythm beat from a healthy individual, displayed as esophageal isopotential map. The horizontal axis shows the time (in seconds) while the vertical axis denotes the relative position of the electrical field along the esophageal catheter (in cm) with increasing values for more cranial positions. The colors are proportional to the signal amplitude (in mV) as shown in the color bar scale on the right side. (1) represents the atrial electric activity, (2) are baseline artifacts while (3) denotes the ventricular activity. By aligning a line to the isocontour plots (black arrows), the projected conduction speed of the depolarization wavefront can be estimated as referenced in the upper right corner. The map was generated from 59 filtered single beats (low-pass cutoff frequency of 2 Hz). Bottom panel: The same heartbeat as conventional esophageal (e1–e10 where e9→e10 is the most proximal lead) and surface ECG (leads I, II, III) (same time scale)

FIGURE 3 Top panel: Esophageal isopotential map of a patient with atrial flutter with 4:1 atrioventricular conduction. In the upper part of the plot, atrial signals can be identified (1), corresponding to the high amplitude electrograms in the proximal channels of the esophageal lead (e.g., e7–e8, bottom panel). Ventricular depolarization (2) and repolarization (3) can be identified. The map was generated from 46 filtered single beats (low-pass cutoff frequency of 2 Hz). Bottom panel: The corresponding raw electrograms obtained via the esophageal lead and surface ECG channels I, II, III (same time scale)

The resulting isopotential maps display the location, the direction, and the projected propagation speed of the cardiac depolarization wavefront and might be helpful in the diagnostics of especially supraventricular arrhythmias.

Supraventricular arrhythmias can be considered as the Achilles' heel of standard 12-channel ECGs due to the low atrial signal quality, the amplitude of which is merely a 10%–20% of that of the ventricles and consequently often masked or heavily perturbed by either the QRS complex, the T wave, or artifacts. Since the atrial signal amplitude is about seven times higher in the eECG compared to the sECG (Haeberlin, Niederhauser, et al., 2013), it may be an useful tool for the discrimination of supraventricular heart rhythm disorders (Haeberlin, Shakir, Vogel, & Tanner, 2013). The presented two-dimensional isopotential maps are the first step toward a three-dimensional mapping system from the esophagus view, which aim to allow simple bedside observational electrophysiological studies without invasive catheters. However, this is a proof-of-concept study and the clinical value of the proposed method still requires further validation.

The number of channels that are registered is one of the most important determinants of a map resolution. Therefore, any electrocardiographic mapping and imaging modality have increased its count—for example, compared to the 10 electrodes, which are used to record standard 12-lead ECGs, the Cardiolsight® ECGI technology (Medtronic Inc., Ireland) utilizes 252 electrodes, which are integrated and applied in so-called multi-electrode vests (Knecht et al., 2017; Shah, Hocini, Pascale, et al., 2013). In the esophagus, the space

is restricted and any increase in the number of electrodes is rapidly paralleled by an increase in catheter diameter and stiffness and in turn diminished patient comfort. For the eECGs in this manuscript, catheters with 10 ring electrodes with 1 cm interelectrode spacing were used. However, due to the utilization of catheter movements to “scan” the heart from multiple positions along the esophageal axis, the resolution of the presented mapping methodology lies in the range of millimeters. With this, the maps do not only provide a high-resolution view of the projected cardiac activation sequence in the esophagus, but can moreover be used as a basis for inverse reconstructions of the electric field in the heart, which is the goal of ongoing research.

The most important downside of the presented approach is that it requires a repetition of the examined heartbeat morphology, as the algorithms rely on morphological ECG criteria to estimate the catheter's position and fuse according to beats.

Moreover, with the catheters used in this manuscript, only one-dimensional activation patterns over time can be taken into account. Thus, noninvasive localization of accessory pathways as for instance in Figure 4 is not possible. To overcome this limitation, a novel esophageal ECG catheter was developed (Figure 5). In contrast to conventional electrode catheters, which have ring electrodes with all channels lying in one axis, the newly developed catheter uses axially split electrodes, which allows the additional delineation of excitation wavefronts approaching the esophagus in a perpendicular fashion and thus has the potential for a three-dimensional mapping capability. It currently undergoes clinical testing and validation using

FIGURE 4 Top panel: Isopotential map of a patient with pre-excitation syndrome due to a right atrial anteroseptal accessory pathway. (1) represents the atrial activity which continues into ventricular activity (3) with a fusion that might represent the accessory pathway (2). The map was generated from 42 filtered single beats (low-pass cutoff frequency of 2 Hz). Bottom panel: The patient's 12-lead surface ECG

FIGURE 5 Schematic representation of the novel esophageal catheter for three-dimensional mapping of the cardiac activity from the esophagus. On the left, a ring electrode is shown as it is used on conventional esophageal leads and invasive electrophysiology catheters. On the right, a split electrode is shown. The three different components register the signal independently and allow for a signal observation not only along the axis of the catheter

invasive electrophysiology catheters and dedicated stimulation protocols as reference (Esophageal 3D Mapping System for Cardiac Arrhythmias (esoECG-3D), NCT03365440).

Importantly, the presented two-dimensional and the envisioned three-dimensional esophageal mapping technologies are not thought as a replacement or competitor to current ECGI systems or invasive electrophysiology studies. They shall rather be regarded as an additional, simple, and readily available tool that might be used in situations with limited resources and when more detailed information about a supraventricular arrhythmia is desired (e.g., in the emergency room). As this, they may potentially fill the gap between

the deep and robust roots of the well-established 12-channel ECG and the advanced techniques of invasive electrophysiological studies and electrocardiographic imaging systems.

5 | CONCLUSION

The methodology presented in this report provides a high-resolution view of the projected cardiac electric field in the esophagus and is the first step toward a three-dimensional estimate of the cardiac activation sequence from the esophagus' view, which inherently will put an emphasis on the left and right atria.

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