Virtual Bipolar and Laplacian Electrodes for Activation Map Construction in ECGi

Josselin Duchateau[1,2,3], Yves Coudière[1,4], Mélèze Hocini[1,2,3], Michel Haïssaguerre[1,2,3], Rémi Dubois[1,2]

[1]Electrophysiology and Heart Modelling Institute (LIRYC), Bordeaux, France
[2]CRTCB Inserm U 1045, Université de Bordeaux, France
[3]Hopital Cardiologique du Haut Lévèque, CHU de Bordeaux, France
[3]INRIA Bordeaux Sud Ouest, France

Abstract

Activation map computation represents an important post-processing step in ECGi.

We sought to determine if inverse reconstructed potential gradient in the direction normal to the epicardial surface (virtual bipolar electrode) and the laplacian of the potential along this surface (virtual laplacian electrode) would enhance non-invasive activation maps compared to the standard approach of using reconstructed unipolar electrograms (virtual unipolar electrode).

After analytical derivation, virtual unipolar, bipolar and laplacian electrograms (EGMs) were computed for all epicardial nodes. Local activation time (LAT) at each node was determined using the maximal downstroke (maximal negative ds/dt) for the 3 EGMs.

The techniques were evaluated in-silico using simulated data of 7 different pacing sequences and on clinical data from 12 different activation patterns.

The use of virtual bipolar EGMs for activation map construction resulted in a significant relative reduction of error of 8% compared to unipolar EGMs on clinical data. A similar albeit non-significant trend existed in simulated data. Virtual Laplacian electrode use resulted in a non-significant enhancement of activation maps for both datasets.

1. Introduction

1.1. Inverse problem and ECGi

The inverse problem of the ECG has been the subject of research for several decades [1]. ECGi, which is the formulation of the inverse problem in terms of epicardial potential sources, and its resolution using a boundary element (or affiliated) method in a homogeneous thorax is one of its most simple formulations.

This simplicity has allowed its recent use in a clinical setting, and renewed interest for the inverse problem resolution techniques in general [2].

As ECGi reconstructs epicardial potentials, post processing steps are necessary to display maps containing synthetic information concerning the patient's condition. One such step is the computation of activation maps.

1.2. Bipolar and Laplacian electrodes

Unipolar EGMs suffer from signal contamination from remote sources. Bipolar or Laplacian electrodes are often used in clinical routine for activation map construction to reduce contamination from far field activity [3].

One of the main caveats of using bipolar electrodes is that the acquired signal morphology is dependent on the orientation of the electrode dipole with respect to the wavefront [3]. Although nearly impossible in invasive measures, placing the dipole axis along the local surface normal provides a theoretical solution to this problem. Laplacian electrodes also provide local information, but must similarly be positioned along the measured surface.

2. Methods

2.1. Inverse problem resolution

The inverse problem resolution method of ECGi has been described previously [4].

Briefly, the inverse problem is formulated in terms of epicardial unipolar sources. The torso conductor volume is considered homogeneous, and the transfer matrix linking the epicardial potentials to the measured body surface potentials is computed using the method of fundamental solution (MFS), assuming zero normal flux on the torso surface.

The inverse problem is regularized using a 0-th order

Tikhonov method, with a fixed regularization parameter.

2.2. Virtual bipolar and Laplacian electrodes

From the MFS virtual sources, analytical expression of the potential gradient $\partial\varphi/\partial\vec{n}$ along the heart surface normal $\vec{n}$ yields:

$$\frac{\partial\varphi}{\partial\vec{n}} = -\frac{1}{4\pi}\sum_{i=1}^{N} a_i \frac{\vec{r}_i \cdot \vec{n}}{\|\vec{r}_i\|^3} \quad (1)$$

With $\vec{r}_i$ are the virtual epicardial sources' positions and a_i their activity.

The name of virtual bipolar electrode comes from the fact that the potential gradient can be seen as an ideal bipolar electrode, with an infinitesimal inter-electrode distance. Choosing the gradient along the local surface normal allows us to avoid any issues linked to wavefront propagation direction as mentioned previously.

Similarly, the potential surface Laplacian is equal to $\partial^2\varphi/\partial\vec{n}^2$ and has the following expression [5]:

$$\frac{\partial^2\varphi}{\partial\vec{n}^2} = \frac{3}{4\pi}\sum_{i=1}^{N} a_i \frac{(\vec{r}_i \cdot \vec{n})^2}{\|\vec{r}_i\|^5} \quad (2)$$

It is similar to an infinitesimal concentric Laplacian electrode.

2.3. Local activation time computation

Local activation time (LAT) was determined at each epicardial node at the EGMs' maximal negative slope:

$$\mathrm{LAT}_i = \arg_t \max \frac{\mathrm{d}\psi_i}{\mathrm{d}t} \quad (3)$$

With ψ_i the chosen scalar (φ, $\partial\varphi/\partial\vec{n}$ or $\partial^2\varphi/\partial\vec{n}^2$) at the epicardial node i. Different markers such as maximal amplitude are often used in bipolar EGMs [3]. Using a dipole normal to the mapped surface ensures however that this time point will indeed correspond to LAT.

2.4. Simulation dataset

Simulated data was provided by the Karlsruhe Institute of Technology as part of the Consortium for ECG Imaging EDGAR project [6].

Details concerning the simulation have already been published [6]. Briefly, MRI acquired geometry from a healthy human male subject was used to build a complete heterogeneous torso model including heart, lungs, vessels, liver, spleen, stomach, kidneys and aorta.

Heart model anisotropy was modeled using a rule based fiber orientation. Transmembrane voltages were used as a source, and a bidomain bioelectric model was used. 163 electrode body surface potentials were computed using a finite element forward propagation scheme, and used as an input for the inverse problem workflow.

7 different single site pacing configurations were simulated on this geometrical model.

Reference activation times were determined from simulated contact epicardial potentials.

2.5. Clinical dataset

Clinical data was collected from 10 different patients admitted for epicardial ablation of ventricular tachycardia or fibrillation at the Bordeaux university hospital.

Invasive activation map data was acquired using an electro-anatomical mapping system (CARTO v3, Biosense Webster Inc., Diamond Bar, CA) and a bipolar mapping catheter. The mapping procedure consisted in the construction of an epicardial map in stable sinus or paced rhythm. Epicardial access was obtained using a percutaneous subxyphoid approach. For two patients, 2 different activation maps were obtained by pacing from 2 different sites.

Gold standard activation maps were constructed from the invasive contact bipolar signals using the default constructor algorithm, based on maximal signal amplitude. Maps were dense, with a median of 975 points (range 666 - 3107).

Body surface data was acquired immediately prior to the procedure using a 252 electrode vest (ECVUE, CardioInsight Inc., Cleveland, OH). Heart and torso geometries were acquired for each patient using a low-dose CT, and segmented along with electrode positions using the bundled software.

All acquired signals were sampled at 1000 Hz, and processed using custom designed software (Matlab, The Mathworks Inc., Nattick, MA).

2.6. Data analysis

Root mean square errors between reference and computed activation times using the three methods were computed for each simulation or clinical case. Significance of differences between methods was evaluated using a paired *t-test*.

3. Results

3.1. General considerations

Virtual unipolar, bipolar and Laplacian EGMs could yield similar or different LATs in different situations.

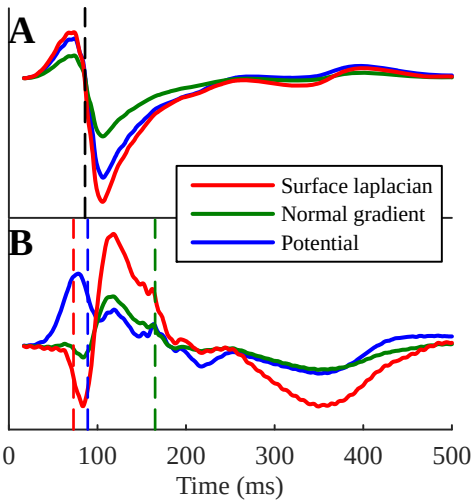

Figure 1. Example LAT computation at two different points.

Measurements at point A yield a similar LAT whatever the technique, but there is considerable variability in activation time for point B which displays important fragmentation.

3.2. Simulation results

Results on simulated data showed a trend in map enhancement using either the virtual bipolar (MSE= 25.7 ±4.3ms) or Laplacian (25.2 ±4.3ms) EGMs compared to virtual unipolar EGMs (27.9 ±6.8ms).

Enhancement was strongest in the right ventricle, and when right ventricular activation was late. Virtual unipolar measures were more precise for the left ventricle.

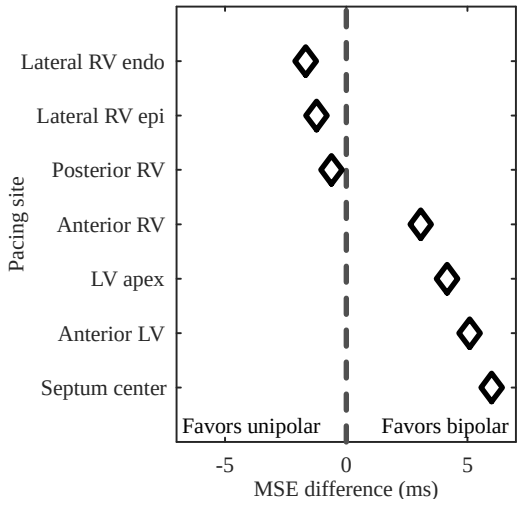

Figure 2. Differences between virtual unipolar MSE and virtual bipolar MSE for the different pacing sites.

3.3. Clinical data results

3.3.1. Patient characteristics

Patients were all male. 6 of 10 had structural heart disease (ARVC, ischemic cardiomyopathy or dilated cardiomyopathy). 4 patients had either Brugada syndrome or early repolarization syndrome.

Table 1. Activation patterns

Activation pattern	Number
Narrow QRS	2
NICD	3
RBBB	3
RV pacing	1
BiV pacing	2

3.3.2. Activation map precision

Using virtual bipolar EGMs resulted in a significant enhancement of activation maps compared to virtual unipolar EGMs. Laplacian EGMs also enhanced the maps albeit non-significantly.

MSE using unipolar signals was 35.7 ±19.5ms vs. 32.5 ±16.9ms for virtual bipolar (p=0.04) and 33.0 ±16.1ms for the virtual Laplacian electrode recordings.

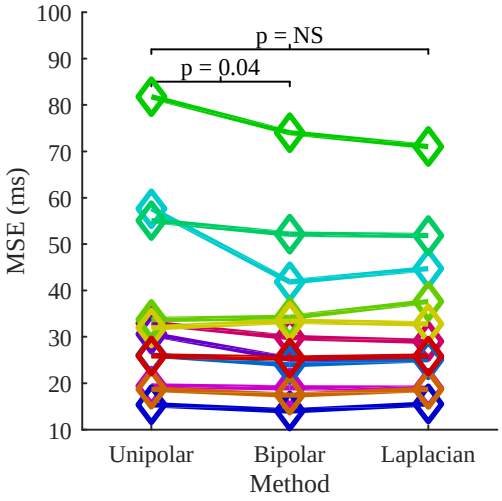

Figure 3. Activation map comparison for clinical dataset

4. Discussion

4.1. Bipolar and laplacian recordings

The main goal of invasive bipolar and laplacian recordings is to reduce the impact of remote sources on a

measured potential. In the context of ECGi, propagation of potentials from epicardium to body surface essentially acts like a spatial filter, generating uncertainty in source localization when inverse computation is undertaken [7]. This further amplifies the contribution of remote sources on measured epicardial potentials.

Using spatial derivatives of the potential instead of the potential itself allows us to regain access to more local contributions. It is noteworthy however that the reconstructed bipolar and laplacian EGMs do not resemble the contact recordings they simulate, as high frequency components are destroyed by the forward/inverse process.

Another advantage of looking at local gradient is the absence of impact of reference electrode choice, upon which unipolar potential recordings dependant.

4.2. Analogies to existing work

Other authors have proposed to use current density as an interesting scalar to estimate activation time [8]. Although the resolution process is different, potential gradient measures (virtual bipolar EGMs) are directly linked to current density by Ohm's law. Computing potential gradient in all directions and taking the maximal resulting norm is another way of extracting epicardial activation time without changing the inverse problem resolution process.

4.3. Simulation and clinical results

Our data shows a small enhancement of activation maps, which is present essentially in the right ventricle, especially when activation of the latter is late (RBBB or LV pacing patterns).

A possible explanation for these results is that right ventricular electrical activity is small compared to the left ventricular contribution to body surface recordings (due to differences in mass), and geometric distance between RV free wall and septum can sometimes be small. These two effects combined result in measured unipolar signals on the RV free wall that reflect both RV and septal electrical activity. When the right ventricle is diseased (ARVC patients for example), right ventricular contribution to measured potentials is further reduced. The sharpest downstroke can therefore come from remote left ventricular contributions. Virtual bipolar or laplacian electrodes reduce these remote contributions and correct the measure.

The explanation for the heterogeneity of the results is that virtual bipolar and laplacian EGMs are more susceptible to noise.

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Address for correspondence.

Josselin Duchateau.
IHU LIRYC – Hôpital Xavier Arnozan, Avenue du Haut Lévèque, 33604 Pessac, France.
josselin.duchateau@ihu-liryc.fr