# A Method for Assessing the Sampling Bandwidth for Activation Time and Voltage Maps in Cardiac Navigators

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## Abstract

*Current Sequential Cardiac Navigation Systems (SCNS) are widely used for creating either voltage or delay maps of the heart, allowing the physician to determine adequate therapy strategies and ablation targets. Given that the number or recorded electrograms (EGM) is a major determinant of the clinical procedure duration, our aim was to propose a method suitable for analyzing the spatial sampling rate that is required for obtaining quality spatial maps. A simple approach consisted on projecting a given feature measured from the available set of EGM (activation time, unipolar and bipolar EGM amplitudes) into a 2D image, according to the azimuth and elevation coordinates of its spatial location, using the chamber gravity center as coordinate origin. This image was reinterpolated into a uniform grid by using a k-Nearest Neighbor method, and the bandwidth was determined from the 2D Fourier Transform. A conservative bandwidth of 10dB was used. We analyzed cases of right atria focal tachycardia (2) and flutter (2), using Carto$^{TM}$XP SCNS. Average bandwidths for activation time and (unipolar and bipolar) voltage maps were (2.19, 1.25, 1.48 $rad^{-1}$) for atrial focal tachycardia, and (2.34, 1.79, 2.19 $rad^{-1}$) for atrial flutter. Trends were observed for atrial flutter requiring higher bandwidths in all the features. Activation time required more bandwidth, whereas unipolar amplitude required the least. In conclusion, the method allows to analyze the spatial sampling requirements of current SCNS in terms of the arrhythmic substrate.*

## 1. Introduction

Sequential Cardiac Navigation Systems (SCNS) are widely used in cardiac electrophysiology as a help tool for creating spatial maps of the distribution of an informative characteristic in a heart chamber under study (atria or ventricles), by successively sampling the intracardiac electrograms (EGM) inside the heart in a number of locations, whose spatial coordinates are also measured by a catheter system [1]. Post-processed EGM are subsequently used to create feature maps, which show either the spatial distribution of EGM activation times, yielding the depolarization impulse time course and decreased conduction velocity regions, or the maximum EGM voltage amplitudes, showing the regions with normal conduction and with scars. Also, in atrial fibrillation patients, features such as dominant frequency and regularity indices are obtained. These spatial distribution maps are fundamental to help the cardiologist to determine the ablation targets in a variety of arrhythmia management and therapy ablation [2]. SCNS have even been recently proposed as an alternative for substituting the radioscopy in ablation or device implantation procedures. Their evolution has involved the incorporation of virtual anatomical reconstruction of cardiac cavities, previously obtained by means of medical image modalities such as computer tomography (CT) or magnetic resonance (MR), which gives more detailed information about the patient anatomy than the EGM sampling process alone.

However, despite all the clinical results on the usefulness of SNCS, and to the best of our knowledge, there is no clear indication about the number of spatial locations that are necessary for yielding accurate enough maps for the usual cardiac features. Given that the number or acquired EGM is a major determinant of the duration of the clinical ablation procedure, our aim was to propose a simple method suitable for analyzing the spatial sampling rate that is required for obtaining quality spatial maps in a variety of cardiac features.

For this purpose, we propose to analyze feature spatial maps obtained from SNCS in patients using a two steps procedure. In the first stage, the non-uniformly spatially sampled feature maps are processed by using a statistical learning procedure, the k Nearest Neighbors (kNN) algorithm, which allows us to reconstruct the feature map in a two-dimensional, evenly sampled map, in terms of angular coordinates referred to the gravity center of the cavity. In the second stage, simple considerations of the sampling

theorem for two-dimensional images allow us to calculate sampling bandwidths (one per angular coordinate) for each feature under analysis. In this preliminary work, we focused on time-activation (or delay, or latency) maps, and on (bipolar and unipolar EGM) amplitude maps. We analyzed simple, yet well-known, arrhythmia mechanisms, namely, focal atrial activation and atrial flutter.

The paper is structured as follows. In the next section, the proposed method for reinterpolation of the feature map and estimation of its bandwidth is presented. Next, results on examples of right atria maps in patients with atrial focal activation and atrial flutter are presented. Finally, discussion and conclusions are summarized.

## 2. Proposed method

As the cardiac chambers are geometrically asymmetrical, a simplified approach consisted on projecting a given measured feature (activation time, amplitude of unipolar and bipolar EGM), denoted by $m(\rho, \theta, \phi)$, into a 2-dimensional image $m'(\theta, \phi)$, according to the azimuth and elevation coordinates of its spatial location, using the chamber gravity center as coordinate origin.

*Use of kNN Algorithm.* As the set of measurements in the SCNS still represented a non-uniformly sampled image, it was reinterpolated into a uniform image grid, by using a kNN algorithm method, as follows. Be the set of measurements $\{\mathbf{l}_i, i = 1, \ldots, N\}$, where $\mathbf{l}_i = [\theta_i, \phi_i, m_i] = [\mathbf{v}_i^T, m_i]$, with $\mathbf{v}_i$ being the column vector with the angular coordinates and $m_i$ being the measured feature at that angular coordinate. A version of kNN algorithm [3] can be used to reinterpolate the estimated feature $m^{new}$ in a point of an angular spatial grid $\mathbf{v}^{new}$, the estimated measurement being given by

$$\hat{m}^{new} = \sum_{k=1}^{K} w_i m_i^{sort} \tag{1}$$

where $\mathbf{m}^{sort}$ is obtained sorting the measurements according to their distance to the new measurement angular coordinates $\mathbf{v}^{new}$, i.e, to $d_i^2 = \mathbf{v}_i^T \mathbf{v}^{new}$. Also, $\mathbf{v}_i^{sort}$, with $i = 1, \ldots, N$, is the set of angular coordinates of the available points in the feature maps after sorted according to their distance $d_i^{sort}$ to the measurement to be interpolated. In our case, $\mathbf{v}_i^{sort}$ are the angular coordinates of the evenly sampled image to be interpolated from the unevenly sampled data.

The kNN algorithm uses a weighted version of the $K$ closest neighbors to estimate the value of a given feature. As explained in [3], we obtain each weight $w_i$ given by:

$$r_i = \frac{d_i^{sort}}{\sum_{k=1}^{K} d_k^{sort} + \delta} \tag{2}$$

$$v_i = \sum_{k=1}^{K} \frac{1}{r_k + \delta} \tag{3}$$

$$w_i = \frac{1}{(r_i + \delta) v_i} \tag{4}$$

where $r_i$ and $v_i$ are auxiliary variables to calculate weights $w_i$, and $\delta$ is a small regularization constant which has been included for avoid dividing by near to zero in the coordinates from the available data. Hence, $\hat{m}^{new}$ can be readily obtained for the coordinates in the uniform sampling grid.

*Spatial Sampling Bandwidth Estimation.* After reinterpolation of the 2D feature map, the bandwidth can be determined by processing its Fourier Transform. Note that this approach assumes that enough samples have been taken in order to avoid aliasing in the image, hence, the method will be valid to analyze densely sampled maps and to obtain conclusions with respect to the sampling requirements of future maps of a given feature. We denote by $m(\theta, \phi)$ the reinterpolated image depending on its continuous independent variables (angular directions), and we denote its Fourier Transform as $M(\omega_\theta, \omega_\phi)$, where independent variables are angular frequencies. Marginal energies for each angular variable are defined as:

$$M_\theta(\omega_\theta) = \int_0^{2\pi} |M(\omega_\theta, \omega_\phi)| \, d\omega_\phi \tag{5}$$

$$M_\phi(\omega_\phi) = \int_0^{2\pi} |M(\omega_\theta, \omega_\phi)| \, d\omega_\theta \tag{6}$$

Then, an approximated bandwidth for each variable can be obtained, given by

$$BW_\theta = \omega_\theta^h - \omega_\theta^l \tag{7}$$

$$BW_\phi = \omega_\phi^h - \omega_\phi^l \tag{8}$$

where superscripts $h$ and $l$ denote the higher and lower bandwidth limit, respectively. We used a conservative 10 dB bandwidth, in order to keep the map details for the clinical application.

## 3. Results

We analyzed propagation delay, monopolar EGM amplitude, and bipolar EGM amplitude, in maps obtained from 4 available cases of focal tachycardia (2) and flutter (2) in the right atria. Maps were obtained with a Carto$^{TM}$ XP (Johnson&Johnson) SCNS. Figure 1 shows examples of delay maps and activation snapshots for these patients. The number of EGM (or spatial locations) in the maps were 64 and 65 for focal activation (patients $F1$ and $F2$), 71 and 75 for atrial flutter (patients $Fl1$ and $Fl2$). This was

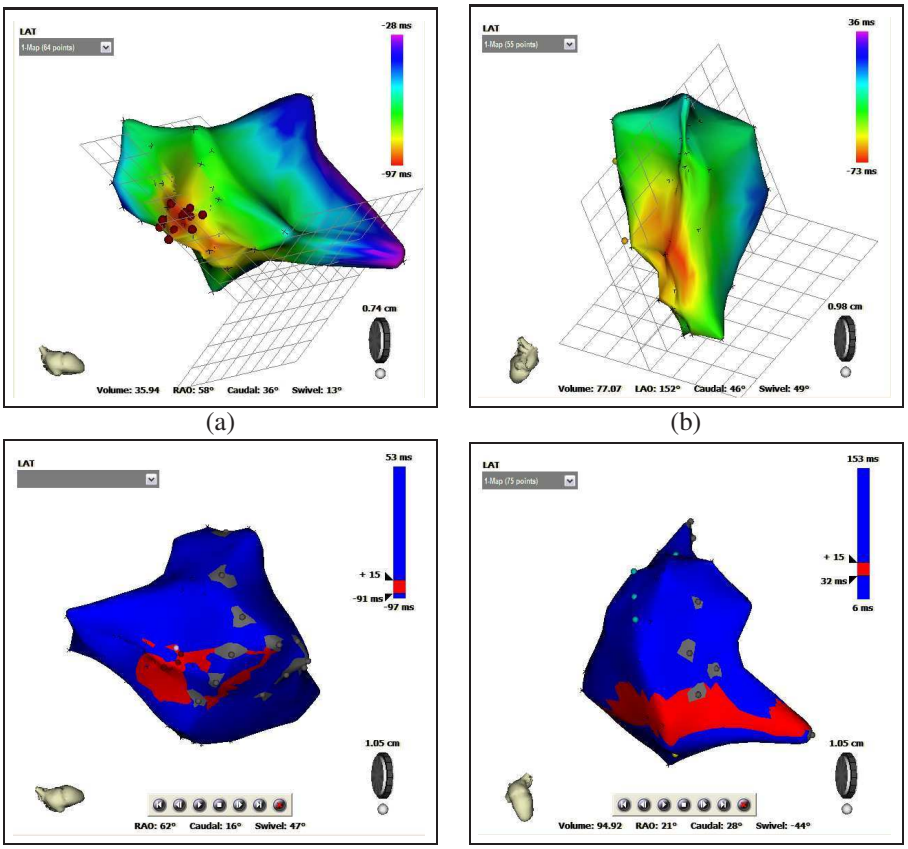


Figure 1. Feature maps for delay in focal activation (a,b), and snapshot of chamber activation in patients with atrial flutter (c,d), in the right atria.

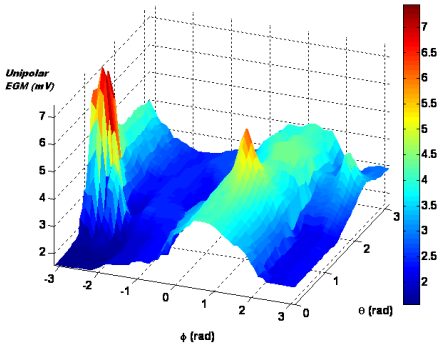


Figure 2. Example of unipolar EGM amplitude map after reinterpolating the SCNS amplitudes to a regular grid using the kNN algorithm.

considered as a high enough number of sampled points for containing all the relevant changes in the map, as both focal tachycardia and atrial flutter have maps with smooth variations.

Figure 2 shows an example of reinterpolated map for the unipolar EGM amplitude in patient $F1$. By following the proposed procedure, we analyzed the 10 dB bandwidth of activation time and voltage maps in the four patients. Table 1 shows the obtained bandwidths for each map in each patient, the averages being 2.19, 1.25, 1.48 rad $^{-1}$ for atrial focal tachycardia, and 2.34, 1.79, 2.19 rad $^{-1}$ for atrial flutter. Trends were observed for atrial flutter requiring higher bandwidths in all the features. Also, activation time maps were the most required bandwidth ones, whereas unipolar maps where the least.

## 4. Discussion and conclusions

A simple method has been proposed to determine the spatial sampling requirements for feature maps obtained in current SNCS. The method makes a simplified 2D image of the cardiac feature under analysis, interpolates its values to a regular spatial sampling grid by using a kNN algorithm, and then obtains the bandwidth required for each angular direction. This represents the first approach to a systematic method which can yield the number of required number of EGM in a SNCS, in terms of the feature under

| | Delay | | Unipolar | | Bipolar | |
|---|---|---|---|---|---|---|
| | $BW_\phi$ | $BW_\theta$ | $BW_\phi$ | $BW_\theta$ | $BW_\phi$ | $BW_\theta$ |
| $F1$ | 1.41 | 2.18 | 1.10 | 1.56 | 1.10 | 1.56 |
| $F2$ | 2.36 | 2.81 | 0.79 | 1.56 | 1.73 | 1.56 |
| $Fl1$ | 2.67 | 4.06 | 1.73 | 2.18 | 2.04 | 2.18 |
| $Fl2$ | 1.10 | 1.56 | 1.10 | 2.18 | 1.73 | 2.81 |

Table 1. Results

analysis and of the underlying mechanism, in representative databases.

There is a growing interest in the relationship and interconnection of electrical and anatomical data in SNCS. The volume measurements using SCNS coordinates of the 3 dimensional map have been compared with the volume given by cardiac MR imaging, showing that their clinical interchangeability may be questioned [4]. In [5], authors propose a system capable of integrating the CT geometry with the set of data points collected in the left atria by a SNCS, in patients undergoing atrial fibrillation (AF) ablation. Maps improved with image geometry used as a support, instead of maps when using the points in the SCNS. In that work, the maps were created without need for detailed mapping, but they did not analyze how many points were necessary for a map to avoid aliasing and ambiguity. In [6], ventricular fibrillation segments were analyzed in terms of the spatiotemporal evolution of the frequency, by means of instantaneous mean frequency instead of dominant frequency for ventricular fibrilation in the left ventricle. The time evolution of dominant frequency spatial maps was analyzed, using a $8 \times 14$ in a polar grid. In [7], authors analyzed the ability of a single electrode to detect activation due to a passing wavefront in a simulation model. They tested the assumption that electrodes are points adequately separated as to not interfere with the tissue or each other in high-density electrode arrays, concluding that electrode array designs in which electrode spacing greatly exceeds electrode diameter are conservative, and that arrays with a spacing ratio of less than 2 may perform successfully in electrophysiological studies. In [8], authors identified critical parts of the ventricular tachycardia reentry circuit without inducing VT, as a goal for VT ablation. They developed a model to predict reentry circuit locations basing on maps of the sinus or paced EGM from the local infarct region, compared with the success in target ablation regions, and they used $63\pm$ 23 sites per patient.

Despite the relevance of this topic, no study has analyzed the required spatial sampling requirements. We conclude that the proposed method allows us to analyze the spatial sampling requirements of maps in current SCNS according to the arrhythmic substrate.

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