

VIEgram – Analysis and Visualization of Intracardiac Electrograms on Patient-Specific 3D Atria Model

Sanket Thakare, Siva K. Mulpuru, Henri Roukoz and Elena G. Tolkacheva

Abstract— Over the last few years, the use of cardiac mapping for effective diagnosis and treatment of arrhythmias has increased significantly. In the clinical environment, electroanatomical mapping (EAM) is performed during the electrophysiological procedures using proprietary systems such as CARTO, EnSite Precision, RHYTHMIA, etc. These systems generate the 3D model of patient-specific atria with the electrical activity (i.e., intracardiac electrograms (iEGMs)) displayed on it, for further identification of the sources of arrhythmia and for guiding cardiac ablation therapy. Recently, several novel techniques were developed to perform iEGMs analysis to more accurately identify the arrhythmogenic sites. However, there is a difficulty in incorporating the results of iEGMs analysis back to EAM systems due to their proprietary constraints. This created a hurdle in the further development of novel techniques to help navigate patient-specific clinical ablation therapy. Thus, we developed an open source software, *VIEgram*¹, that allows researchers to visualize the results of the various iEGMs analysis on a patient-specific 3D atria model. It eliminates the dependency of the academic environment on the proprietary EAM systems, thereby making the process of retrospective mapping extremely convenient and time efficient. Here, we demonstrate the features of *VIEgram* such as visual inspection of iEGMs, flexibility in implementing custom iEGMs analysis techniques and interpolation schemes, and spatial analysis.

I. INTRODUCTION

Arrhythmias, which are caused by the irregularities in the electrical activity of the heart, is the number one cause of sudden cardiac death. Atrial fibrillation (AF), the most common sustained arrhythmia, is associated with heart failure, stroke and other heart related complications [1], [2].

In recent years, catheter ablation procedure, in which regions radiating irregular electrical activity is ablated, has become a mainstay of treatment for AF, largely due to the advancements in cardiac mapping technology. Electroanatomical mapping (EAM) is the process of mapping intracardiac electrograms (iEGMs) recorded from endocardial sites during electrophysiological study to the respective spatial sites [3], and it is widely used to guide ablation procedure. In the clinical setting, proprietary EAM systems, such as CARTO, EnSite Precision, RHYTHMIA,

etc., are used to visualize the iEGMs on a patient's 3D atria model and to identify the potential target sites for AF ablation.

The availability of iEGM data from EAM systems has allowed researchers to perform offline analysis of iEGMs in academic environment, and to further develop several novel analysis techniques for more accurate identification of target sites for ablation [4]–[7]. To ensure whether the developed technique has a diagnosing capability, the results of the offline analysis has to be properly visualized on a 3D model of patient's atria. To date, the only way to achieve this goal is to manually input the results of analysis into the proprietary EAM systems that are currently used in clinics. However, this step is extremely time-consuming, and it also requires the use of expensive EAM systems outside of their clinical intended purpose. Thus, there is a need for a software that will allow 3D visualization of the various iEGMs analysis on a patient-specific atria model for all off-site analysis of clinical iEGMs in the academic environment.

Previously, Linton et al. developed a software called Ripple-mapping to visualize the improvised local activation time (LAT) maps [8]. However, the software is only specific to LAT analysis. An open source modular software was developed by Cantwell et al. [9], which allows visualization of a set of pre-defined techniques. Since the software was written in C++, its usage was resisted by researchers as they are used to developing and customizing tools in MATLAB to fit their unique analysis requirements. Recently, Oesterlein et al. developed the visualization software KaPAVIE (Karlsruhe Platform for Analysis and Visualization of Intracardiac Electrograms) [10]. It uses MATLAB for iEGMs analysis, and therefore it is very attractive for research purposes since it allows easy incorporation of the newly developed techniques. However, one of the limitations of the KaPAVIE software is the use of fixed interpolation scheme irrespective of the nature of iEGMs dataset. Indeed, acquired clinical data can be sparse or dense depending on the EAM system used, and the use of the same interpolation scheme may mislead the interpretation of the results, and therefore it further restrains the user from performing localized spatial analysis. Also, KaPAVIE runs solely on MacOS, thus preventing wide use for analysis and visualization of iEGMs.

Here, we present our recently developed open-source software called *VIEgram* to support the analysis of iEGMs and to perform 3D visualization of the analysis results. *VIEgram* integrates the data handling capabilities of Python and powerful algorithm development environment of MATLAB. We present the performance of *VIEgram* using a set of clinically recorded iEGMs from a patient with persistent AF. We believe that *VIEgram* will further facilitate the development of novel iEGMs analysis techniques.

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¹ <https://z.umn.edu/VIEGram>

II. METHODS

A. Clinical Data Collection and Analysis

The clinical iEGMs were collected from a patient with persistent AF during an EP study at the Mayo clinic (Rochester, MN), with prior approval under institutional review board approved protocol. Informed consent was obtained from the patient with persistent AF.

EAM was performed using the CARTO (Biosense Webster, CA, USA) system. The CARTO mapping system has a sensor position accuracy of 0.8 mm and 5°. High resolution PentaRay NAV catheter (Biosense Webster, CA) was used in a sequential scanning approach to fully map both atrial chambers. The 3D geometry of the chamber was reconstructed in real time, and at each point, the system records the unipolar and bipolar iEGMs, sampled at 977 Hz thus allowing the electrophysiological information to be color coded and superimposed on the anatomic map. Ten bipolar electrograms were recorded at each spatial site.

The data were exported from the CARTO system in .txt format, containing 2.5 s iEGMs. A total of 1055 iEGMs were obtained from the patient with 642 iEGMs in the left atrium (LA) and 413 iEGMs in the right atrium (RA). The geometries of LA and RA were obtained in the form of triangulated surface meshes. The exported data also contained the catheter coordinates, i.e. the spatial locations from which the iEGMs were obtained. The iEGMs with high noise corruption and loss of contact while recording was removed from future analysis. The rest of the clean iEGMs were filtered by a digital bandpass filter of 3-30Hz to limit the frequencies to physiological ranges.

B. Software Description

i. Overview

VIEgram was primarily developed using Python (3.7.0) and MATLAB (R2018a), which are easily available in all major operating systems (OS) including Windows and MacOS, thus eliminating OS-dependency of our software. The overview of *VIEgram* is shown in Fig. 1, where academic setting refers to the off-site for analyzing the data collected from EAM systems used in clinics. A custom-built Python script was used for data extraction, while data processing and 3D mapping was done using custom-built MATLAB script. MATLAB App Designer was used to develop the user interface of the *VIEgram* (See Fig. 2).

ii. Python Script

The typical exported data from EAM system is a mix of iEGMs, catheter locations and geometric data. After studying the format and pattern of the names of files generated by CARTO, Python script was developed to extract these different types of data separately. This script allows to choose either LA and/or RA for analysis and the type of iEGMs – unipolar or bipolar. This flexibility allows for separate implementation of the analysis techniques for bipolar and unipolar data. iEGMs and geometric data extracted using Python script serves as an input to the MATLAB script.

iii. MATLAB Script

The MATLAB script was developed to implement different iEGM analysis techniques and to map the results of these techniques on a 3D atria model. As an example, for this manuscript, we implemented multiscale entropy (MSE) [6] and multiscale frequency (MSF) [4] as iEGMs analysis techniques to demonstrate the capability of *VIEgram*. One of the advantages of the MATLAB script is the potential to easily incorporate and perform 3D visualizations of various analysis techniques, per researcher's choice.

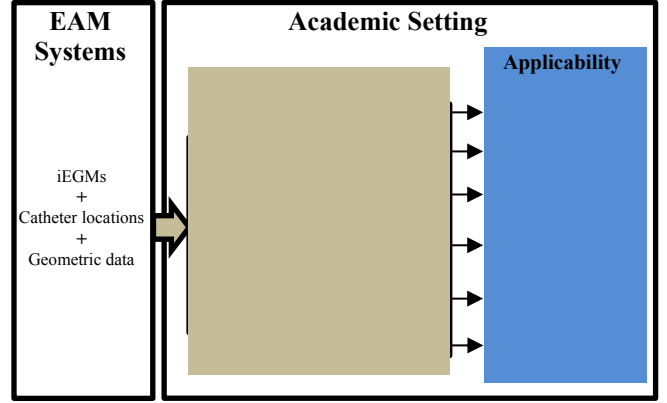


Figure 1. Overview of the open-source software *VIEgram*

iv. Interpolation

For generating 3D maps, a commonly used interpolation scheme called nearest neighbor interpolation was used as a default setting. It is implemented using the following equation:

$$Z_p = \frac{\sum_{i=1}^n \left(\frac{Z_i}{d_i^m} \right)}{\sum_{i=1}^n \frac{1}{d_i^m}} \quad (1)$$

where Z_p is the estimation at point p , Z_i is the value at point i , d_i is the distance between point i and point p , and m is the power parameter. However, the MATLAB script provides the flexibility of implementing *custom interpolation* schemes for better visualization of 3D results.

III. RESULTS

A. *VIEgram* User Interface

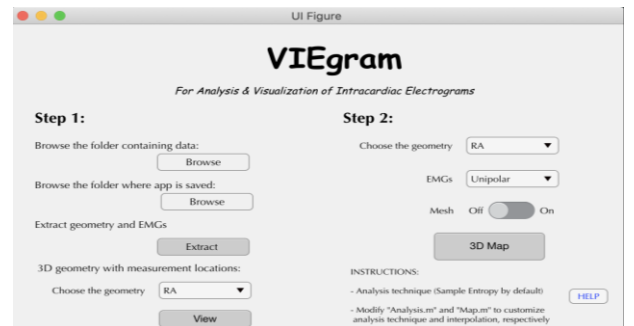


Figure 2. User interface of *VIEgram* software to extract and analyse iEGMs, and to visualize the results on 3D atria model

Fig. 2 shows the user interface of the *VIEgram*. In Step 1, users are able to extract geometry data of atria and

recorded unipolar and bipolar iEGMs with their corresponding locations from EAM systems. Currently, *VIEgram* is compatible with CARTO EAM system, but in the future, extraction modules for other EAM systems can be developed. Extracted data are saved in the “Data” folder of the *VIEgram* in the .csv format. User can also visualize the geometry with the locations of recorded iEGMs highlighted (see Fig. 3 top panel). In Step 2, various analyses of iEGMs are performed (for instance using MSE and MSF), and the results of the analysis is visualized on the 3D geometry of atria. The software includes two user-access files, “Analysis.m” and “Map.m”, which can be modified to add additional iEGMs analysis techniques, and to implement different interpolation schemes, respectively.

B. Patient-Specific 3D Atria Model

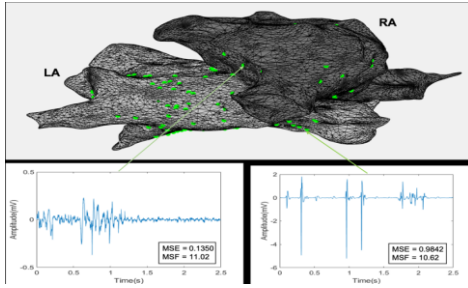


Figure 3. Top panel shows the patient-specific 3D atria model, with LA (light grey) and RA (dark grey). Green dots indicate the location of clinically recorded iEGMs, which examples are shown on the bottom.

Fig. 3 shows the 3D geometrical model of RA (dark grey) and LA (light grey) of the AF patient generated by *VIEgram* based on geometrical data from the CARTO system. The green dots indicate the sites at which iEGMs were recorded. Note that the spatial distribution of the iEGMs is very sparse, and therefore the importance of adequately choosing the interpolation technique and its parameters.

B. 3D Maps

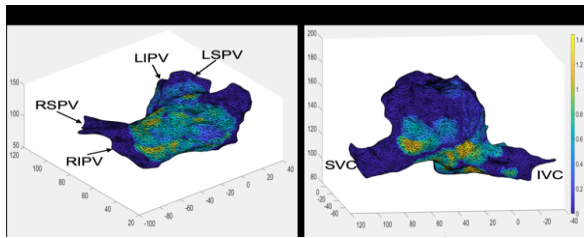


Figure 4. 3D visualization of the MSE analysis on the LA (left panel) and RA (right panel). Several anatomical hallmarks are shown: LSPV – Left Superior Pulmonary Vein (PV), LIPV – Left Inferior PV, RSPV – Left Superior PV, RIPV – Left Inferior PV, SVC – Superior Vena Cava, IVC – Inferior Vena Cava

For testing the *VIEgram* software, MSE and MSF analysis of bipolar iEGMs from both RA and LA were implemented and further visualized (see Figs. 4 and 5, respectively). Spatial sites having greater value, i.e. the brighter color regions, indicate the presence of potential AF active sites. We can see from Figs. 4 and 5 that estimated potential active AF sites appeared to be outside the PV regions for both

MSE and MSF analysis, which is consistent with the current hypothesis [11] for maintaining AF in the case of persistent AF.

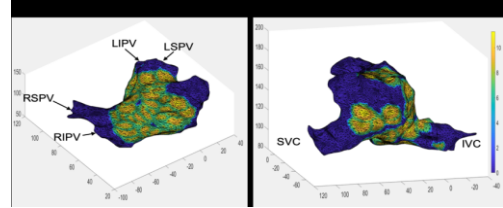


Figure 4. 3D visualization of the MSF analysis on the LA (left panel) and RA (right panel).

C. Customizable Interpolation

For interpolation, nearest neighbor interpolation with power parameter, $m=1$, was implemented as a default scheme (see Fig. 6, left panel). To show the flexibility in modifying or implementing a custom interpolation scheme, nearest neighbor interpolation with $m=4$ was implemented (see Fig. 6, right panel). A significant difference can be noticed between MSE 3D maps with different interpolation. Thus, the choice of interpolation scheme plays a major role in representing the results of analysis.

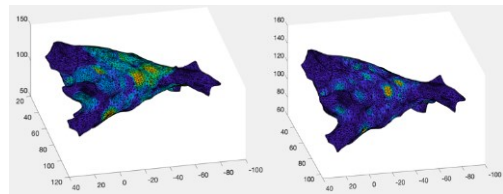


Figure 6. 3D visualization of the MSE analysis using nearest neighbour interpolation scheme (see Eq. (1)) with different power parameter : $m=1$ (left panel) and $m=4$ (right panel).

D. Spatial Analysis of iEGMs

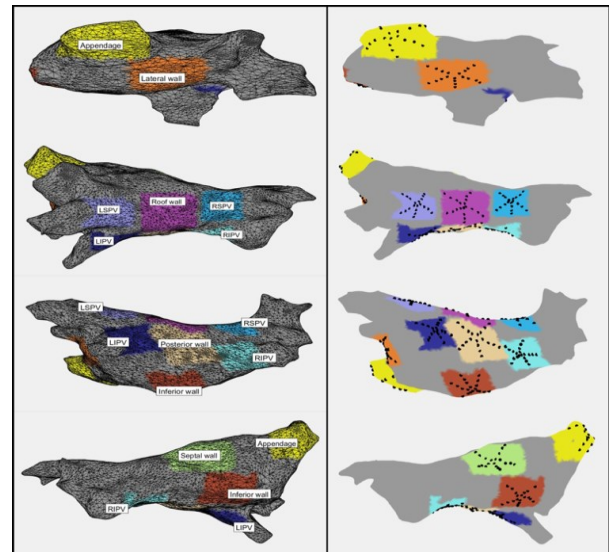


Figure 7. Ten different regions of LA with a mesh structure (left panel) and projection of multi-spline catheter mapped to each of these regions without a mesh structure (right panel).

VIEgram allows to perform spatial analysis of iEGMs. To demonstrate this, LA was divided to 10 different spatial regions (see Fig. 7): LA appendage, lateral wall, roof wall,

posterior wall, inferior wall, septal wall, left superior PV (LSPV), left inferior PV (LIPV), right superior PV (RSPV) and right inferior PV (RIPV). Region growing algorithm using face distance (distance between face vertices) was used to segment different spatial regions. The seed face was manually chosen for each of those 10 spatial regions in LA. The left panel in the Fig. 7 shows the location of these regions from different perspectives. The right panel in Fig. 7 shows the projection of multi-spline catheter mapped on to these regions where black dots indicate the recording sites. This allows the researcher to perform spatial analysis and correlate the performance between different catheters. In addition, *VEgram* allows to enable (left panel) or disable (right panel) the mesh structure for better visualization.

IV. DISCUSSION

In this work, we developed *VEgram*, a MATLAB based software, to analyze and visualize the results of iEGMs analysis on a 3D atria model. The use of MATLAB in developing *VEgram* enables the researchers to easily modify the script, which makes it more customizable for both analysis and visualization. This allows to do the required modifications to suit the acquired iEGM dataset and type of analysis. *VEgram* was demonstrated to perform custom actions such as 1) visual inspection of iEGMs, 2) implement custom iEGMs analysis techniques, 3) mapping analysis results on a patient-specific 3D atrium with customizable interpolation scheme, and 4) spatial analysis of iEGMs. These capabilities make the process of retrospective mapping extremely convenient for academic researchers. Currently, *VEgram* is compatible with the CARTO system, but in the future, additional compatibility with other EAM systems can be easily incorporated by developing the supporting modules.

Previously, several software applications were developed to visualize the results of iEGMs analysis on a patient-specific 3D atria model [8]–[10]. However, they have multiple limitations: 1) no provision for implementing custom analysis techniques, 2) C++ based development environment which makes it difficult for academic researchers to implement their MATLAB developed analysis techniques, 3) operating system dependency, and 4) no control over visualization which precludes the researchers from implementing different interpolation schemes and spatial analysis.

Quantitative evaluation of arrhythmic sites and the utilization of various diagnostic methodologies have become more widely used in clinics. However, one potential problem is that some methods are covered with insurance and some not, thus providing additional burden on clinicians. In addition, the insurance coverage associated with the use of various diagnostic methodologies can be problematic in developing countries. 3D models from *VEgram* can be further integrated with the CT/MRI based 3D models to incorporate fibrosis and scar data. Therefore, *VEgram* can provide an additional support in integrating the results of different cardiac imaging modalities with 3D visualizations for better identification of AF ablation sites. In the future, *VEgram* will equip not only the researchers but also the

clinicians with a tool to study, analyze, and visualize iEGMs.

V. CONCLUSION

We developed new software, *VEgram*, for the analysis and visualization of iEGMs. This software allows researchers to use clinical data from EAM systems to study the iEGM morphology, implement their own iEGMs analysis techniques, generate 3D maps corresponding to those techniques, perform region specific localized analysis, and integrate the generated 3D models with the 3D models generated using CT/MRI scan data to incorporate anatomical and functional information of heart. Altogether, *VEgram* equips the researcher with a tool to study, analyze and visualize iEGMs, thus providing a testing and validation capability prior to clinical implementation.

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