Graphics User Interface for Processing and Analyzing Cardiac Optical and Electrical Mapping Recorded During Animal Arrhythmic Models

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Abstract

This study presents a system combining invasive and non-invasive electrical mapping with panoramic optical mapping for cardiac electrophysiology research. A Graphical User Interface (GUI) was developed to process, synchronize, and analyze data from these methods, generating maps such as Local Activation Time, Conduction Velocity, Dominant Frequency, and Phase Maps. These tools help to better understand cardiac dynamics, arrhythmias, and conduction patterns. By improving the integration of optical and electrical data, this system enhances existing electrophysiology research methods and may assist in diagnosing and treating cardiovascular diseases.

1. Introduction

Cardiovascular diseases (CVDs) are the leading cause of mortality worldwide, responsible for nearly a third of all deaths [1]. These conditions disrupt heart function and its electrical patterns, highlighting the critical need for electrophysiological tests to achieve accurate diagnoses. In complex arrhythmias like atrial fibrillation, current commercial systems may distort electrograms, potentially leading to misdiagnoses and a decreased quality of life for patients [2, 3].

While clinical systems predominantly rely on electrical mapping, optical mapping remains the gold standard for cardiac electrophysiology analysis. However, it is not yet suitable for direct patient diagnosis, although it is widely used in research to improve the accuracy of commercial systems [4].

This study implements a comprehensive setup for both invasive and non-invasive electrical mapping, along with panoramic optical mapping. The primary goal is to develop a GUI to process and analyze the optical data generated by this experimental setup. The GUI is designed to produce investigative maps from both electrical and optical data, enabling precise studies of complex arrhythmias and enhancing current electrophysiology systems. The research protocol has been reviewed and approved by the local Committee on Ethics in the Use of Animals (CEUA), ensuring compliance with current legislation (CEUA no. 3947230519).

2. Material and Methods

2.1 Experimental Setup

The setup for analysing cardiac electrophysiology integrates eight distinct subsystems (Fig. 1A): the Langendorff system, panoramic optical mapping, epicardial electrical mapping, non-invasive electrical mapping, AV-node ablation system, stimulator system, synchronization system, and 3D geometry reconstruction.

The Langendorff perfusion system was developed to maintain a temperature of 38°C and a nutrient solution flow of 20-50 mL/min at a constant pressure of 70 mmHg, mimicking the standard physiological state of a living organism.

For epicardial electrical mapping, we employed three Multi-Electrode Arrays (MEAs), each with 16 silver electrodes arranged in a 4x4 grid. One MEA was positioned in the left ventricle, and the others in the left and right atria. The heart and MEAs were submerged in a hexagonal acrylic tank containing 60 electrodes filled with a physiological solution that replicates the electric impedance of the animal's torso.

Analog signals from the MEAs were converted into digital signals via the Intan 64-Channel Headstages and transmitted to the Open Ephys Acquisition Board at a sampling rate of 4 kHz. The panoramic optical mapping system comprises three high-speed GigE cameras, positioned 120° apart around the heart, enabling the capture of panoramic infrared videos.

The system for reconstructing the heart's 3D geometry uses a stepper motor and a custom GUI developed in LabVIEW, allowing controlled heart rotation while capturing images at 3.6° intervals over a complete 360° rotation.

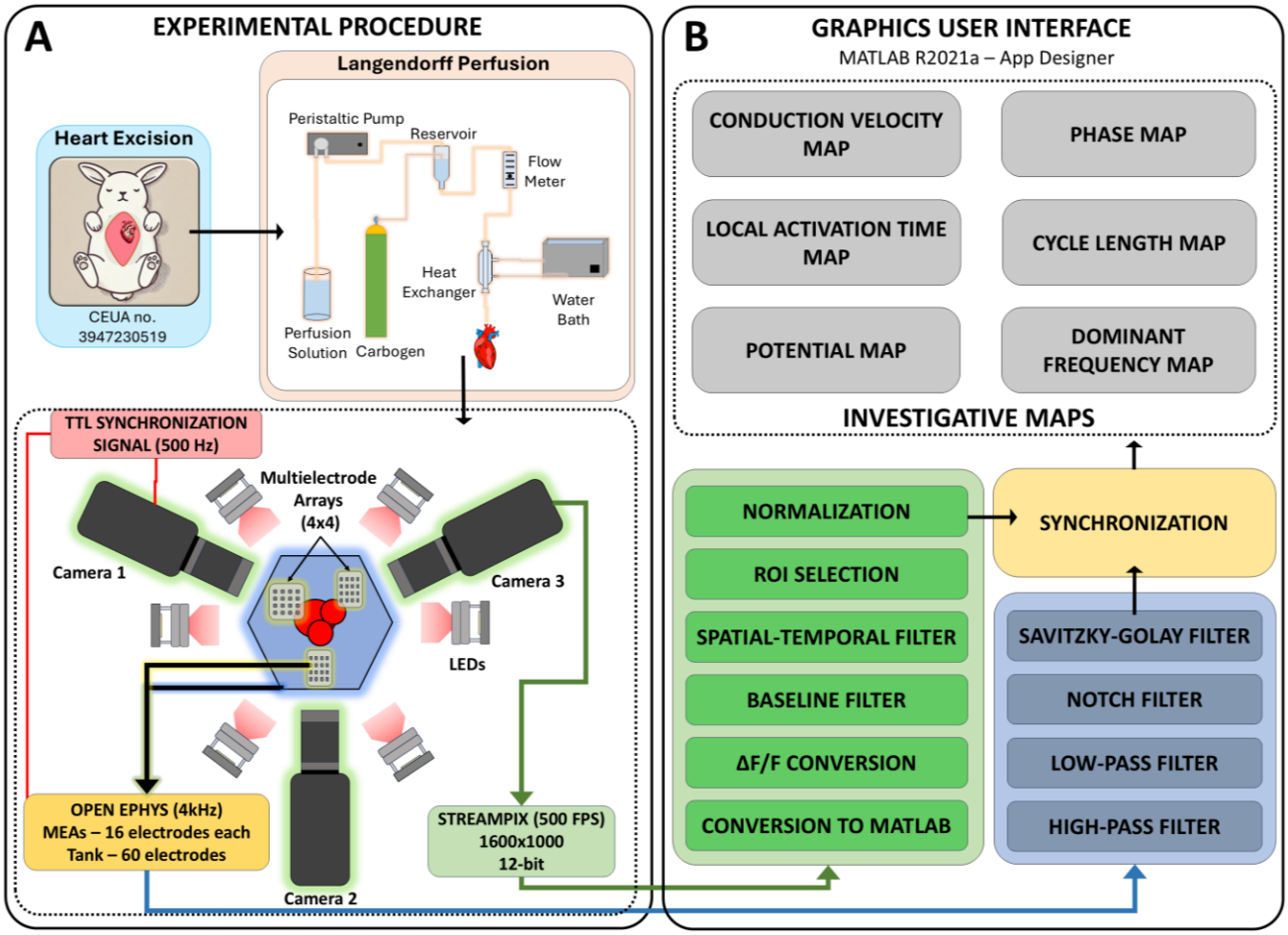

Figure 1. A) Diagram of the experimental procedure, setup and acquisition of optical mapping data, epicardial electrical data, and non-invasive electrical data. B) Block diagram of the Graphics User Interface process.

2.3. Graphics User Interface

The GUI for analysing and processing optical and electrical mapping data was developed using MATLAB R2021a App Designer. It serves as a comprehensive tool for researchers to synchronize optical and electrical data and generate investigative cardiac maps. The GUI allows for the creation of figures and videos from the acquired data, enhancing the visualization and analysis process.

One key feature of the GUI is the synchronization of optical and electrical data, ensuring that both modalities are aligned in time for accurate correlation and analysis. This enables a deeper understanding of cardiac dynamics.

The GUI generates several types of investigative cardiac maps, each providing valuable insights into cardiac electrophysiology:

Local Activation Time Map (LAT): Displays the time taken for electrical activation to propagate across the heart. This map helps identify areas of abnormal conduction and is computed using linear regression between the minimum and maximum values of the signal.

For the optical mapping data, the LAT is calculated based on the mean time value of the depolarization. For the electrical mapping data, it is calculated by measuring the maximum of the derivative of a single action potential in a pixel; the dye used has a linear relation by the fluorescence emitted with the voltage of the cell, as such:

$$LAT = \max\left[\frac{dV_A}{dt}\right] = \max\left[\frac{dF}{dt}\right] \quad [1]$$

Where V_A is the voltage and F is the fluorescence in the area.

Conduction Velocity Map (CV): Illustrates the speed at which electrical impulses travel through cardiac tissue. The Circle Method (CM) is used to calculate conduction velocity by comparing the LAT data at the endpoints of a chord passing through a circle's center.

Dominant Frequency Map (DF): Shows the dominant frequency of electrical signals in various regions of the heart. It is particularly useful for identifying areas prone to arrhythmias.

The DF map is calculated based on the Fast Fourier Transform algorithm by decomposing the electrical signal

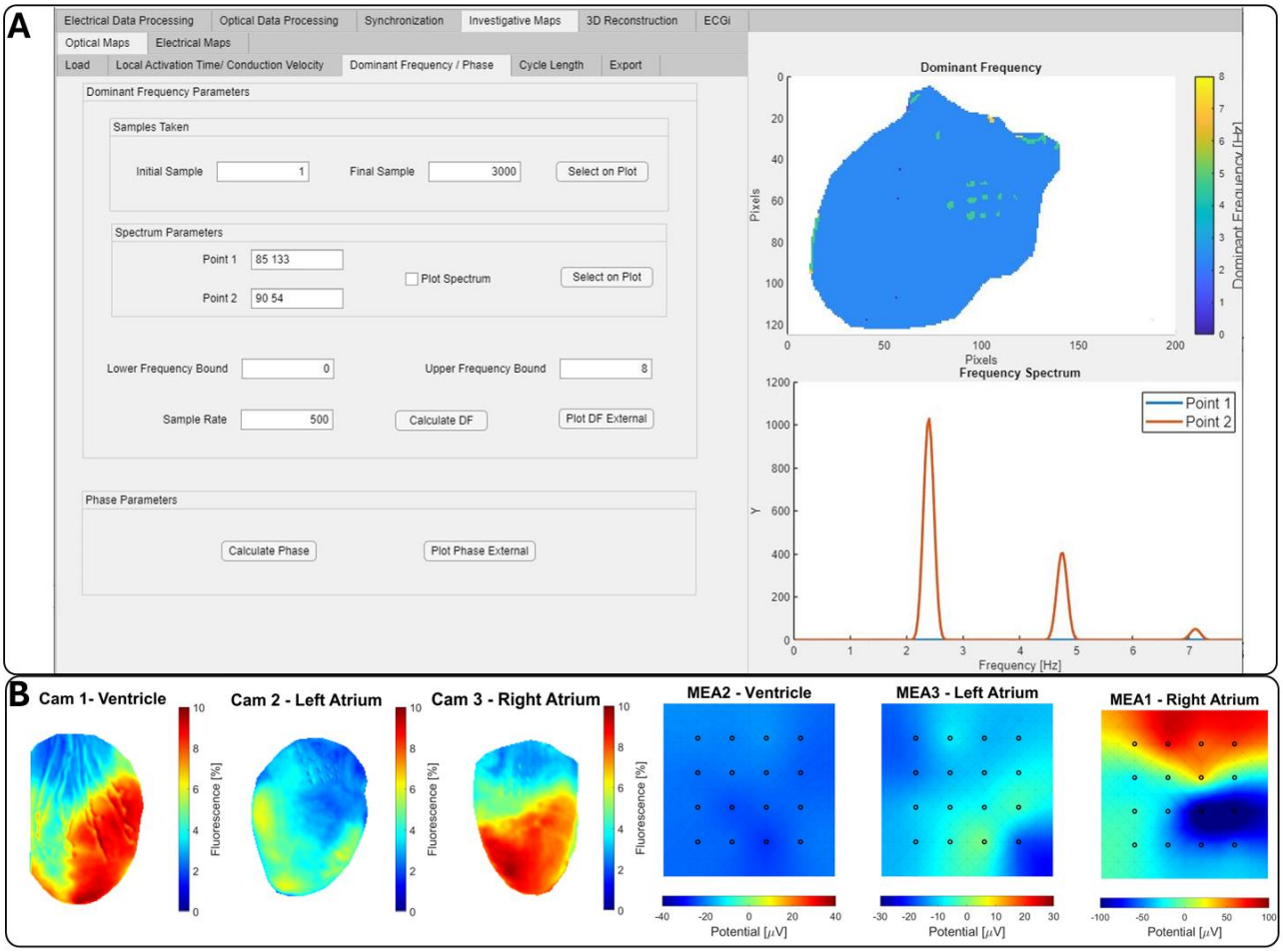

Figure 2 - A) GUI in the Dominant Frequency utility, showing a dominant frequency map and the frequency spectrum. B) Potential maps of the synchronized data captured during an experiment and processed using the GUI.

in its frequency components and taking the value with the highest amplitude, following the formula:

$$F(j\omega) = \sum_{k=0}^{N-1} f[k].e^{-j\omega kT}, K = 0, \dots, N-1 \quad [2]$$

Where $f(t)$ is the source signal with N samples that can be denoted as $f[0], f[1], \dots, f[k], f[N-1]$, ω is frequency evaluated and T is the sample period.

Phase Map: Represents the phase of the cardiac cycle at each heart location, aiding in understanding electrical wavefront propagation patterns.

The phase map is calculated by applying the Hilbert Transform to the signal; the Hilbert Transform of a function $f(t)$ is the convolution of the function with $h(t) = 1/\pi t$, resulting in $\hat{u}(t)$. This can be expressed as $\mathcal{H}\{f(t)\} = \hat{u}(t)$, in such way that $g(t) = f(t) + i \cdot \hat{u}(t)$, so that the phase (θ) can then be calculated by:

$$\theta = \arctan\left[\frac{\hat{u}(x)}{f(x)}\right] \quad [3]$$

Each of these maps plays a crucial role in analysing cardiac electrophysiology and provides valuable insights into arrhythmias and other cardiac disorders.

The program flow within the GUI follows a structured path (Fig. 1B):

Data Acquisition: Optical and electrical data are collected using StreamPix software, capturing high-resolution videos and binary-format electrical data.

Data Conversion: Both optical and electrical data are converted into MATLAB-compatible files for further processing.

Optical Signal Processing: Various filtering techniques are applied to the optical data to improve signal quality: Baseline Filtering: Removes baseline drift and DC offset using a Butterworth filter. Spatial and Temporal Filters: Enhance spatial resolution and remove artifacts using a Gaussian kernel.

Electrical Signal Processing: Electrical data undergo several refinement steps, including baseline filtering, notch filtering (for 60 Hz noise removal), and low-pass filtering. Advanced options such as Savitzky-Golay Filtering and Common Mode Rejection are also available.

Synchronization: Optical data is synchronized with electrical data using TTL signals, ensuring seamless alignment between the two modalities.

Investigative Map Generation: The GUI generates

various investigative cardiac maps, including LAT, CV, DF, and Phase Maps for both electrical and optical data.

Creation of Figures and Videos: Users can generate figures and videos based on the processed data, enabling visual representation of cardiac dynamics.

3. Results

The developed GUI facilitated a comprehensive analysis of optical and electrical mapping data, providing valuable insights into cardiac electrophysiology (Fig 2A). The synchronization of optical and electrical datasets ensured accurate time alignment, allowing for precise correlation between optical signals (representing tissue activity) and electrical signals (capturing corresponding electrical events).

The GUI generated several types of investigative cardiac maps, each offering unique information about the heart's electrophysiological properties:

Local Activation Time Map: Revealed the sequence of electrical activation across the heart, helping to identify abnormal conduction regions, such as delayed activation patterns in the left ventricle.

Conduction Velocity Map: Displayed the speed of electrical impulse propagation, with variations indicating altered tissue properties. Examples of optical and electrical maps highlighted regions of slow conduction in blue and fast conduction in red.

Dominant Frequency Map: Provided insights into the dominant frequencies in different regions of the heart, which is useful for identifying arrhythmia-prone areas.

Phase Map: Represented the cardiac cycle phase at various locations in the heart.

The side-by-side comparison of electrical and optical data (Figure 2B) highlighted the correlation between tissue activity and electrical signals, further demonstrating the GUI's effectiveness in analyzing cardiac mapping data.

4. Conclusion

In conclusion, the developed GUI is a powerful tool for the comprehensive analysis of optical and electrical mapping data in cardiac electrophysiology. By synchronizing optical and electrical datasets, the GUI enabled precise joint analysis, enhancing our understanding of cardiac dynamics.

The GUI-generated investigative maps, including the Local Activation Time Map, Conduction Velocity Map, Dominant Frequency Map, and Phase Map, provided valuable insights into the electrophysiological properties of the heart. These maps visualized the spatial and temporal aspects of electrical activity and facilitated the identification of abnormal conduction patterns and areas of interest for further investigation.

Overall, the GUI proved effective in processing, analyzing, and visualizing complex cardiac mapping data, offering researchers a user-friendly tool for deeper insights into cardiac electrophysiology. Future work will focus on expanding the GUI's capabilities and applying it to further cardiac research and arrhythmia mechanisms.

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