Integrated System for Simultaneous Optical and Electrical Mapping with Experimental Control and Data Logging in Human and Pig Heart Studies

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Abstract

Cardiac diseases are the leading cause of mortality worldwide, necessitating advanced tools for studying arrhythmogenic mechanisms. Optical mapping offers high-resolution spatial visualization, while electrical mapping provides precise temporal insight into cardiac activity, the complexity of combined setups may increase our knowledge and overcome limitations. This paper presents an integrated platform for simultaneous optical and electrical mapping in suitable for pig and human hearts. The system includes custom whole-heart and epi-endo hardware configurations, alongside a Python-based graphical user interface (GUI) for real-time control, stimulation, logging, and sensor data acquisition. Microcontroller-based coordination ensures synchronization across all subsystems. The GUI enables dynamic pacing protocols, accurate timestamped data logging, and continuous environmental monitoring. The system was validated in large-animal and human heart experiments, demonstrating improved workflow, data quality. This versatile tool enhances experimental cardiac electrophysiology and supports translational research into arrhythmias.

1. Introduction

Cardiovascular diseases (CVDs) remain the leading cause of death globally, responsible for approximately 17.9 million deaths per year [1]. These conditions include arrhythmias, which often result from abnormal electrical conduction in the heart and can lead to severe complications such as stroke or sudden cardiac death [2]. Understanding the electrophysiological basis of these disorders is critical for developing effective treatments and diagnostics.

Optical mapping has emerged as a valuable technique in cardiac electrophysiology, allowing high-resolution visualization of action potential propagation and calcium transients across myocardial surfaces [3]. This technique uses fluorescent dyes and high-speed cameras to provide detailed spatial data, making it indispensable for identifying reentrant arrhythmias, conduction block, and electrical heterogeneity [4]. However, optical mapping alone often lacks the temporal precision and depth needed to fully characterize electrophysiological events and is not used in clinical settings.

Electrical mapping, on the other hand, offers high temporal resolution and direct recordings of transmembrane or extracellular potentials. It is routinely used in both clinical and experimental settings to investigate signal morphology, wavefront propagation and conduction velocity [5]. While each technique has its strengths, their limitations necessitate a combined approach to fully capture the dynamics of cardiac excitation.

Simultaneous optical and electrical mapping enables the integration of high-resolution spatial and temporal information, yielding a more complete understanding of arrhythmogenic mechanisms. Studies in large animal models, such as pigs, provide anatomical and physiological relevance to human hearts, facilitating translational research [6]. Additionally, research using ex vivo human hearts offers a rare opportunity to study disease-specific mechanisms under controlled conditions [7].

To support such complex experimentation, reliable systems for synchronized acquisition, precise stimulation, and environmental monitoring are essential. This paper introduces an integrated platform that combines custom hardware for optical and electrical mapping with a Python-based graphical user interface for real-time control, logging, and sensor data acquisition.

2. Methodology

2.1. Experimental Procedure and Tissue Preparation

All porcine hearts used for this research were donated from a surgery training facility (35-40 kg, 4 months old). Euthanasia was done with KCl. The human hearts were provided by VCU Heart Transplant Program. The IRB protocol number HM11452 has been approved by the VCU Institutional Review Boards (IRB). Protocol approval ensures adherence to ethical standards for research involving human subjects. Hearts were surgically extracted by the cardiac surgery team during transplantation.

The following procedure was applied to both pig and

human hearts. Immediately upon removal, the hearts were perfused with ice-cold cardioplegic solution administered via both left and right coronary arteries to maintain myocardial integrity and minimize ischemic injury during transport to the laboratory.

For whole-heart studies (Fig 1A), independent perfusion of the left and right coronary arteries was required using a Langendorff technique and maintained in a vertical position with a 3D-printed hexagonal holder. For endo-epicardial studies of ventricular free wall electrophysiology of the right ventricle (Fig 1B), the ventricle was dissected to allow simultaneous imaging of the epicardium and endocardium in a wedge configuration. The marginal artery was cannulated and secured with a surgical silk ligature, and any leakage from the preparation was controlled by clamping the tissue surrounding the excised regions to ensure proper sealing.

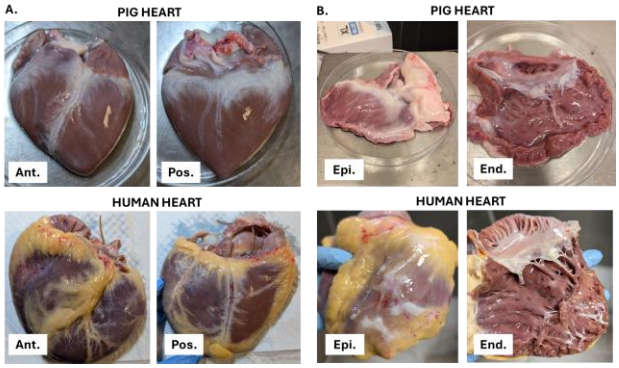

Figure 1. Anatomical Characterization of Pig and Human Hearts; A) At the top the anterior (Ant.) and posterior (Pos.) views of a representative whole pig heart, at the bottom the anterior (Ant.) and posterior (Pos.) views of a representative human heart; B) At the top the isolated RV in its epicardial (Epi) and endocardial (End) side of a pig heart, at the bottom the isolated RV in its epicardial (Epi) and endocardial (End) side of a representative human.

2.2. Experimental Setup

The developed GUI was designed to work with two distinct but complementary setups: a whole-heart configuration (Fig. 2B) and an epi-endo configuration (Fig. 2C), both designed to support simultaneous optical and non-contact and contact electrical recordings.

Whole-heart setup: The heart is located in the middle of a transparent hexagonal tank filled with solution used to transmit electrical signals and keep the heart at a stable temperature (Fig. 2A). A 3D-printed rotatable support structure secures the heart and allows image acquisition from multiple angles, the heart was suspended using multiple threads secured to the rotatable support. For electrical mapping, transparent PET-based printed circuit boards (PCBs) were developed with 15 silver-coated electrodes (10 mm diameter) on each face of the tank, providing spatially distributed electrical contact. A dual optical mapping has an excitation source composes for four red LEDs (660 nm). Image acquisition was performed using two high-speed cameras CAM 1 and CAM 2 (Fig 2B) with a sampling frequency of 500 Hz.

Epi-endo setup: Electrical signals were acquired using two costumed Micro Electrode Arrays (MEAs) with 16 iridium electrodes on each side of the heart, plus four custom-made unipolar needle electrodes, positioned strategically across the heart tissue to record unipolar electrograms (UEGs). In this case cameras were located one above the endocardium (CAM 1), and the other placed on the side of the tank (CAM 2) and a mirror positioned at a 45-degree angle relative to the table helps to record the epicardium. MEA electrical signals were recorded passing through an Intan 64-channel headstage to convert the analogical to digital signals and an Intan RHD recording system and visualized in the Intan RHX Data Acquisition Software. The electrogram signals were recorded via a PowerLab 16/30 system and visualized in real-time using LabChart 8 software.

2.3. Sensors Integration

Environmental and physiological data were continuously recorded using an integrated network of sensors. An Arduino Nano collected data from SLF3S-4000B flow sensors (which also provide temperature readings) and Honeywell pressure sensors (HSCMRNV160MG2A3). These data were transmitted wirelessly via nRF24l01 modules to an ESP32-S3, which forwarded the information to the GUI. Digital outputs from each sensor were also sent through a digital-to-analog converter Adafruit MCP4728 to the PowerLab system for synchronized recording (Fig 2D).

2.4. Graphical User Interface (GUI)

The GUI, developed in Python using libraries such as Tkinter and PySerial, serves as the central hub for experimental control, data acquisition, and logging. The interface enables:

Synchronization: The system synchronizes optical mapping cameras, LED illumination, and electrical recording systems. The GUI adjusts camera frame rate and LED duty cycle and sends trigger pulses to the Intan RHD recording system. It also manipulates the StreamPix software for synchronized video capture.

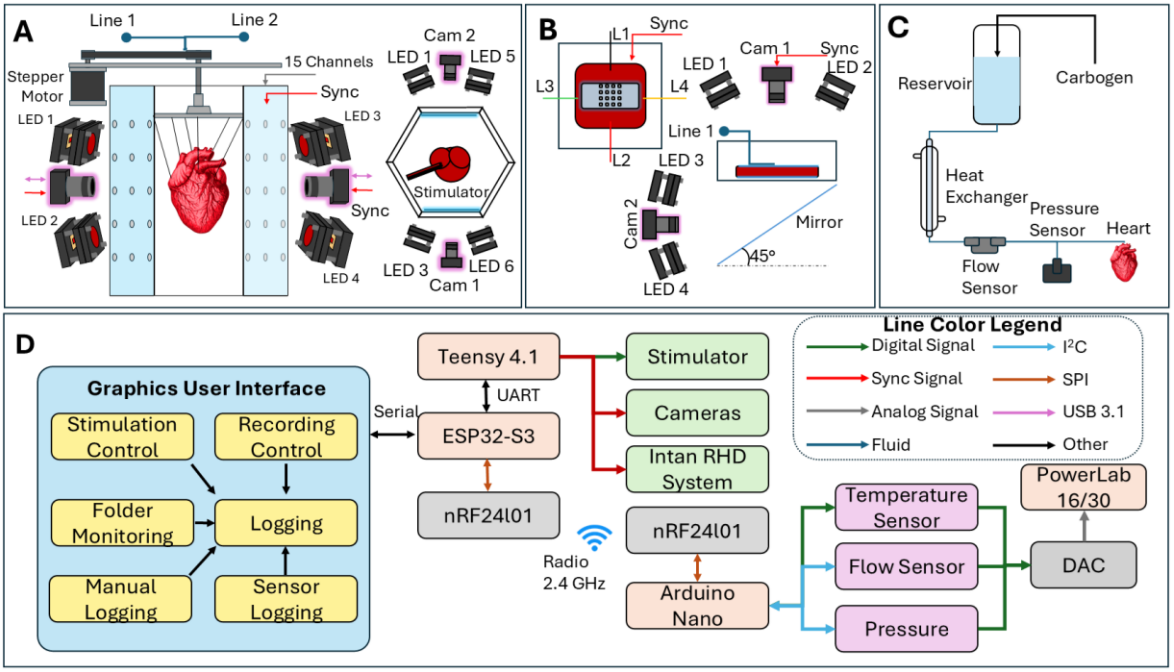

Figure 2. A) Whole-heart optical and non-contact electrical setup; B) Endo-epi optical and contact electrical setup; C) Single line of the Langendorff perfusion system with sensors used during experiments, the pressure sensor line is kept at the same height as the heart, each line is cannulated in one of the coronaries; D) Block diagram of the GUI interaction with boards, equipment and sensors, different colored arrows represent different communication/transmission standards.

Sensor Data Management: The GUI receives real-time environmental data from the ESP32 and stores it in timestamped files for post-processing. This ensures that flow rates, pressure, and temperature are available for correlation with electrophysiological data.

3. Results and Discussion

The integrated system was evaluated through a series of experiments using both pig and human hearts across epi-endo and whole-heart configurations. The graphical user interface (GUI), shown in Figure 3B, effectively managed all aspects of the experiment. Area A of the Figure 3 displays real-time sensor data for two perfusion lines, including tank temperature, flow rate, flow temperature, and pressure; area B shows the GUI and includes controls for serial communication, stimulation protocols, recording, logging, and sensor monitoring, all color-coded in the figure for clarity. The GUI allowed researchers to configure stimulation modes dynamically, and control the recordings without disrupting ongoing data acquisition.

During testing, the GUI reliably executed both continuous and burst stimulation protocols with sub-millisecond synchronization between optical and electrical recordings. Real-time environmental data—flow, pressure, and temperature—were collected at a sampling rate of 4 Hz and accurately integrated into digital and analog systems for simultaneous monitoring and recording (Figure 3A and 3B). These features proved especially valuable for maintaining perfusion stability during extended experiments.

The combination of microcontroller coordination and GUI-based operation minimized latency, supported seamless transitions between protocols, and enhanced experimental reproducibility. One noted limitation was the redundant logging of file changes introduced by StreamPix and the lack of streamlined results tracking. Future improvements will focus on optimizing file system efficiency and refining the logging mechanism to remove non-essential entries.

Overall, the system demonstrated reliable and consistent performance across experimental models. Its integration of control, monitoring, and data acquisition components within a single interface significantly improves workflow efficiency and supports high-quality, reproducible data collection for cardiac electrophysiology research.

4. Conclusion

This work presents a fully integrated system for simultaneous optical and electrical mapping in human and pig heart studies. By combining custom hardware with a flexible, Python-based GUI, the platform offers precise control over stimulation, synchronized data acquisition, real-time logging, and environmental monitoring. These features significantly improve workflow efficiency and data quality in cardiac electrophysiology research.

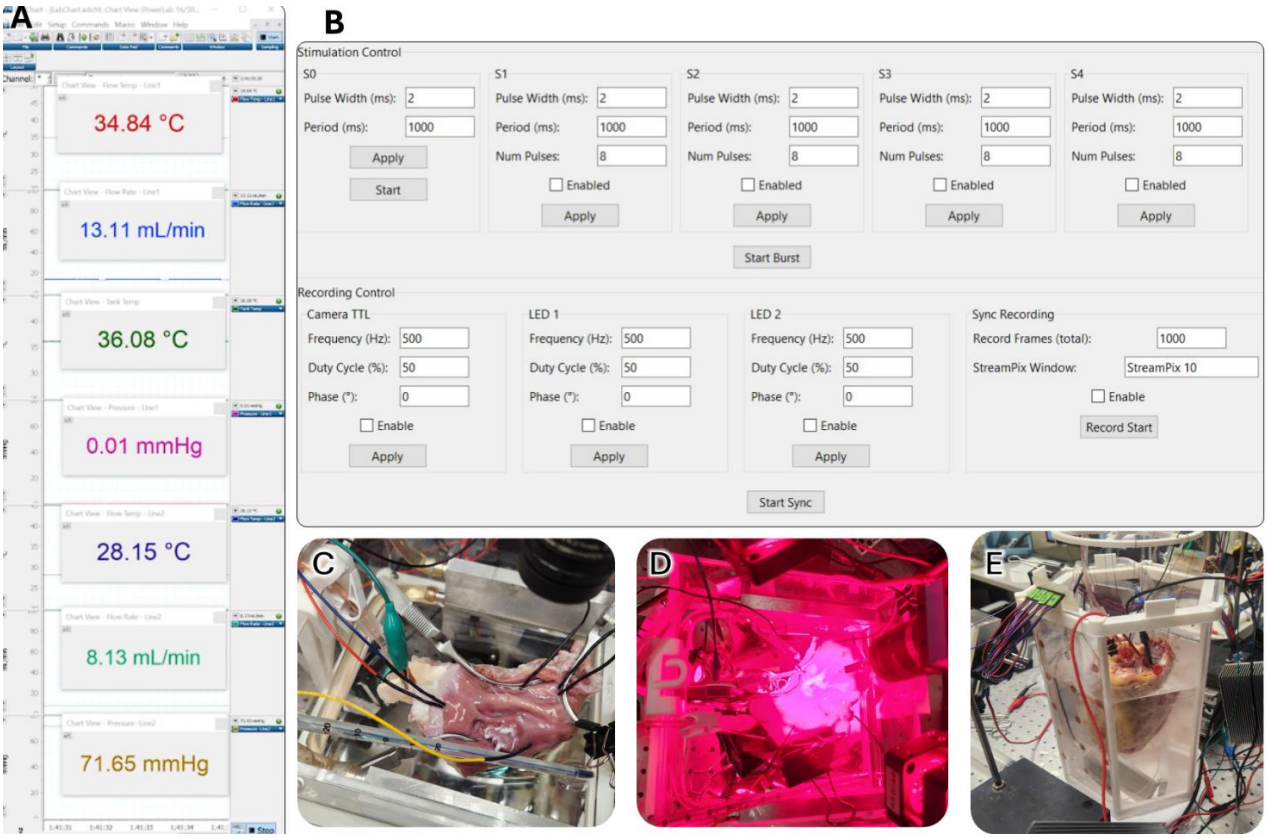

Figure 3. A) LabChart Interface showing sensor values for lines 1 and 2, from top to bottom, tank temperature, line 1 flow rate, line 1 flow temperature, line 1 pressure, line 2 flow temperature, line 2 flow rate, line 2 pressure; B) Section of the GUI interface highlighting different the Stimulation Control and Recording Control sections. C and D) Epi-Endo setup during an experiment. E) Whole heart setup during a whole heart experiment using green LEDs.

The system's successful application in both human and animal models underscores its value for translational arrhythmia research. Future developments may include expanded sensor networks, higher-resolution imaging, and semi-automated analysis tools, further advancing the field of experimental cardiology.

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