



Design and Implementation of a Phonocardiography System Combining ECG and Stethoscope Features

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Abstract— Cardiovascular diseases (CVDs) remain the leading cause of global mortality, underscoring the need for cost-effective and reliable diagnostic and monitoring systems. Conventional stethoscopes and single-lead electrocardiogram (ECG) devices, still prevalent in clinical settings, lack digital storage and analytical capabilities, thereby limiting both diagnostic accuracy and educational value. In this study, we present the design and implementation of an integrated phonocardiography (PCG)–ECG system that combines the functional features of a stethoscope and an ECG within a single portable device. The system employs an ESP32-WROOM-32 microcontroller for synchronous acquisition of cardiac sound and ECG signals at 1 kHz, incorporating front-end microphone modules, an AD8232 analog front end, and a custom battery management subsystem. Signal conditioning was achieved through band-pass and notch filtering, with subsequent R-peak detection and S1–S2 heart sound identification. Data were transmitted to a remote server via a REST API, enabling secure storage, labeling, and server-side analysis. Experimental results demonstrated high-fidelity detection of S1 and S2 heart sounds from the PCG signal and robust R-peak detection from the ECG signal, with strong temporal alignment between electromechanical cardiac events. These findings confirm the feasibility of the proposed device for real-time monitoring, clinical education, and potential telemedicine applications, offering a locally developed and export-capable solution to current gaps in digital stethoscope technology.

Keywords—Phonocardiography (PCG), Electrocardiogram (ECG), Biomedical Signal Processing, Digital Stethoscope, Wearable Health Monitoring, IoT-based Medical Devices

I. INTRODUCTION

Cardiovascular diseases (CVDs) remain among the leading causes of mortality worldwide, accounting for approximately 18 million deaths annually, according to data from the World Health Organization (WHO) [1]. In 2017, an estimated 126.5 million individuals were living with heart disease, and this number is projected to rise substantially, with annual deaths expected to reach 23 million by 2030 [2]. CVD prevalence is particularly high in regions such as the United States, Central Europe, North Africa, and the Middle East, posing a significant public health challenge that demands both urgent medical intervention and continuous patient monitoring [3]. In Türkiye, factors such as demographic growth, increased health tourism, and improvements in healthcare accessibility have placed considerable strain on cardiology clinics and emergency departments, creating challenges in resource allocation and service delivery [4].

Despite significant advances in healthcare technology, many existing diagnostic and monitoring systems still exhibit critical limitations. These include the inability to effectively utilize multiple data types simultaneously and the lack of advanced algorithms capable of interpreting complex signals that integrate mechanical and electrical cardiac activity [5]. Conventional stethoscopes and electrocardiogram (ECG) devices, still widely used in clinical practice, are predominantly analog and typically lack data storage capability. As a result, valuable clinical information is often lost, as these devices rely heavily on subjective interpretation by healthcare professionals. This limitation not only affects clinical diagnostics but also hinders medical education, where the ability to review and analyze recorded data is essential [6].

In response to these challenges, recent research has emphasized the development of innovative systems integrating phonocardiography (PCG) and ECG measurements into a single platform. Such systems enable the simultaneous monitoring of mechanical heart sounds and electrical cardiac activity, generating digital data that can be stored, analyzed, and utilized for both real-time clinical decision-making and educational purposes. These advancements have the potential to improve rapid diagnosis, continuous patient monitoring, data management, and the quality of training provided to medical students and healthcare professionals [7–8].

A notable example is a 2025 study introducing a portable, integrated PCG–ECG system that demonstrated significant improvements in signal-to-noise ratio (SNR) and enhanced extraction of electromechanical parameters critical for cardiac health assessment. This device represents a step forward in wearable cardiac health monitoring, combining high-fidelity data acquisition with user-friendly portability [9]. Furthermore, these developments align with national strategies to strengthen healthcare infrastructure through domestic innovation. The proposed integrated system offers a unique, locally produced solution with high export potential, addressing gaps in current digital stethoscope technologies and contributing significantly to Türkiye's healthcare capabilities [9, 10, 11].

Current study began with research analyzing the performance of various digital and analog microphones used in medical applications. The scope then expanded to include the acquisition of single-channel electrocardiogram (ECG) signals. A circuit model was developed to synchronously acquire both signals at a sampling frequency of 1 kHz. Using an ESP32

Wroom-32 microcontroller, basic signal processing algorithms were applied to the acquired signals to produce clean, noise-reduced data. Subsequently, R-peak detection was performed on the ECG signal, followed by the acquisition of S1, S2, S3, and S4 heart sounds. Through the developed interface, these signals can be processed and statistically evaluated, with the aim of enabling their use in the detection of specific cardiological conditions.

This study, unlike previous works in the literature, integrates a stethoscope with a three-channel ECG device to enable the simultaneous acquisition of both signal and sound at the same sampling frequency. In this way, it is demonstrated that clinical data collection in experimental studies can be facilitated with the help of a lower-cost device. Furthermore, the development stages of a cost-effective design using modern electronic systems are also presented in this study.

II. MATERIALS AND METHODS

A. Microphone Configurations Integrated into the Device Hardware

A microphone transduces ambient acoustic pressure into an electrical signal. The preamplifier conditions this signal and feeds it to the microcontroller, whose digital output reflects amplitude variations of the surrounding sound; higher digital values indicate higher sound pressure, and lower values indicate lower sound pressure.

To characterize front-end options, we procured and evaluated multiple microphone types commonly used in medical applications, including MAX-series modules, INMP-series digital MEMS microphones, analog electret capsules, MEMS devices, and SMD-package microphones employed in industrial medical equipment. The signal performance of each was examined. The analog electret capsule is shown in Fig. 1(a). The MAX4466 pre-amplified microphone module (Fig. 1(b))—selected based on datasheet sensitivity and noise specifications—has been widely used in prior medical prototypes. The MAX9814 module with AGC is shown in Fig. 1(c). A 12-bit microcontroller ADC was programmed to acquire analog outputs from these modules, and recordings were obtained in both quiet and noisy environments. The INMP441 digital MEMS microphone (Fig. 1(d)) was interfaced via the microcontroller's I²S peripheral. Figures 1(e)–1(f) depict an SMD digital microphone IC (MAX81650) of the type also found in industrial medical devices (e.g., Masimo and Philips systems). Sampling rates of 800 Hz and 1 kHz were employed for preliminary trials.

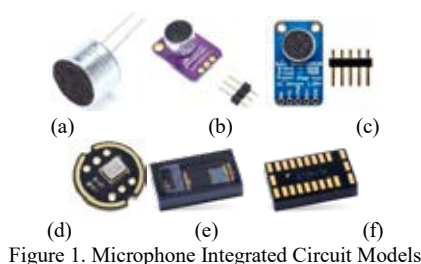


Figure 1. Microphone Integrated Circuit Models

B. Cardiac Sound Bandwidth and Sampling Method

Typical phonocardiographic frequency content is concentrated in the low-frequency range, S1: 20–45 Hz, S2: 50–70 Hz and S4: < 20 Hz

By the Nyquist criterion, the sampling frequency must satisfy $f_s \geq 2f_{max}$, with $f_{max} = 70$ Hz, the minimum is $f_s \geq 140$ Hz. For clinical studies, a practical margin of 4x or 5x the maximum frequency is preferred. In practice: 500 Hz adequately captures S1, S2, and S4, 1,000 Hz yields clearer clinical recordings, and 2,000 Hz allows detection of higher-frequency phenomena (e.g., murmurs).

During stethoscope-based acquisition, the desired signal is often contaminated by hand-borne vibrations and ambient acoustic noise. To mitigate these effects, signals were filtered using a combination of band-pass and notch responses. Specifically, the filter configuration passes 0–48 Hz and 52–98 Hz (implemented in 4 Hz passband segments) to suppress the 50 Hz mains component while preserving cardiac sound content.

C. Single-Lead ECG Acquisition and Microprocessor

ECG signals were acquired in a single-lead configuration using the AD8232 analog front end, and R-peak detection was implemented for heart rate estimation. A compact PCB layout was designed by integrating the AD8232 with the ESP32-WROOM-32U module. While initial data transfer was performed via USB serial communication, the design objective was to enable wireless connectivity by linking the device to a local network. The ESP32-WROOM-32U supports both Wi-Fi and Bluetooth RF interfaces; to ensure reliable transmission and avoid data loss, the Transmission Control Protocol (TCP) was selected at the transport layer for Wi-Fi communication.



Figure 2. AD8232 Single-Lead ECG Sensor

D. Battery Management System

Following signal acquisition studies, the battery control and charging subsystem was implemented. The TP4056 integrated circuit was employed as the charge controller, ensuring proper charging of the battery with the correct voltage and current levels. The TP4056 is one of the most widely used ICs for single-cell battery systems in commercial applications.

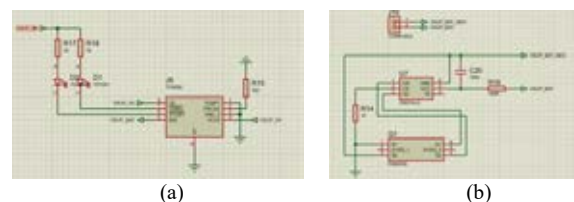


Figure 3. (a) Battery Charge Circuit, (b) Battery Protection Circuit

For battery protection, the DW01A integrated circuit was selected. Specifically designed for Li-ion cell protection, this IC functions primarily as a voltage comparator. When the battery voltage drops to a level that may cause damage, the DW01A disables its output, thereby preventing current draw from the circuit. Current interruption at the output is achieved through the integrated FS8205A dual MOSFET.

E. Data Base Management

Data recording operations were implemented in Kotlin and can be performed at varying time intervals. During each session, the device buffers sensor data locally and, upon completion, transmits the data to a remote server via a REST API. Each record is stored with mandatory patient information entered through the user interface, along with a timestamp of the recording date, and is displayed accordingly. When previously recorded data are accessed, the user can trigger server-side analysis by selecting the *Analyze* option within the application. The resulting analysis files are stored with an appended “-analyzed” suffix and timestamp, and results are immediately displayed to the user. The same file can be revisited at later times, with the analysis data preserved. The analysis process includes labeling of S1–S2 heart sounds and ECG R-waves sequentially within the dataset, after which results are transmitted back to the Kotlin application. All communication through the REST API is carried out using JSON objects. On the server side, JSON-formatted records are stored on a dedicated secondary virtual disk provisioned specifically for data storage.

III. RESULT AND DISCUSSION

An electret microphone was selected due to its analog output capability. Measurements performed with amplifier circuits commonly used in MAX-series microphone modules are shown in Figure 4. These analog values were digitized by the microcontroller and subsequently converted into voltage levels. The analog-to-digital conversion (ADC) outputs were transformed to corresponding voltage amplitudes using the formula provided in Equation (1), where the reference voltage of the ESP32-WROOM-32 microcontroller is specified.

$$V_{Out} = \left(\frac{ADC\ Value}{2^{12}-1} \right) \cdot V_{ref} \quad (1)$$

To enhance the quality of the acquired acoustic signals and suppress noise, an operational amplifier (op-amp)-based filtering stage was proposed. Low-pass and high-pass filters were designed to remove unwanted frequency components: the low-pass filter attenuates high-frequency noise, while the high-pass filter suppresses low-frequency interference.

Some recordings contain PCG2, AUX1, and AUX2 channels, which generally exhibit signals of very low amplitude—at or near the quantization noise level. However, when these channels are audibly monitored and visually inspected, they are observed to capture weak background sounds and electronic device noise present in the environment.

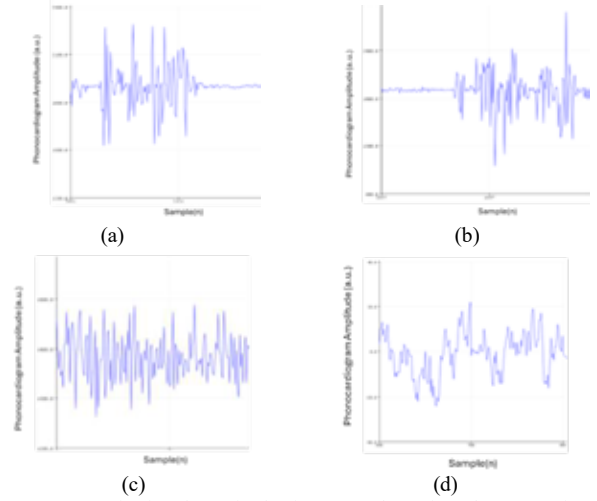


Figure 4. Acoustic signal acquired using an analog microphone (a), signal acquired using the MAX4466 microphone (b), noise signal acquired in a quiet environment using the MAX9814 microphone (c), and noise signal acquired in a quiet environment using the INMP441 microphone (d).

Although not directly usable for primary analysis, these channels may still be of interest to researchers working in signal processing. Specifically, they can serve as auxiliary data for the design of adaptive noise cancellation systems or multi-channel blind/partially blind source separation algorithms.

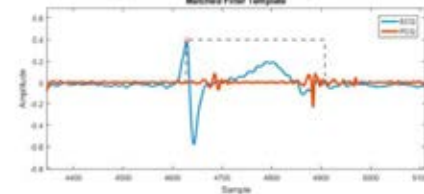


Figure 5. Matched filter template selection based on R-peak position.

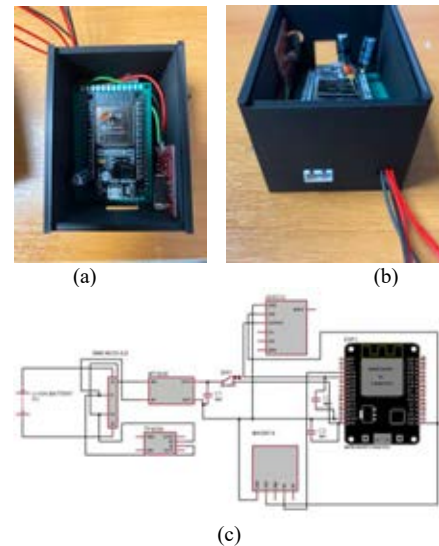


Figure 6. Placement of the controller, phonocardiography module, and single-lead ECG system (a); battery slot positioned on the system (b); and block diagram of the complete system (c).

The developed integrated PCG–ECG monitoring system was successfully assembled and tested. The electronic components were enclosed within a custom-designed housing, ensuring proper placement of all modules and protection of the system.

Internal wiring and system integration were carried out in accordance with the design schematic, in which the ESP32 development board was employed as the central processing unit.

The power supply was provided by three 3.7 V Li-Po batteries connected through a BMS module, enabling portability and stable operation. Following assembly, the system was tested using ECG and heart sound measurements. The electronic wiring diagram was followed to ensure correct connections and maintain stable sensor performance. The test results demonstrated that S1 and S2 heart sounds were accurately detected from the PCG signal, and R-peaks were reliably identified from the ECG signal. Figure 7 presents the block representation of the system along with sample signals acquired from the device.



Figure 7. Critical System Design

The acquired waveforms demonstrated high signal integrity and temporal alignment between mechanical (PCG) and electrical (ECG) cardiac events, thereby confirming the system's real-time monitoring capability.

In Figure 8 simultaneously acquired phonocardiogram and ECG signals are presented. The R-peaks, along with the S1 and S2 heart sounds, are clearly identified on the synchronized waveforms.



Figure 8. Synchronously acquired heart sounds and ECG signals

IV. CONCLUSION AND FUTURE WORKS

Single-channel ECG and heart sound signals, synchronously acquired at a 1 kHz sampling frequency, were tested on different subjects to observe the performance of the study. The device's LVD and EMC test performance was also tested and verified by an independent testing institution. At this stage, the interface and database performance tests will be monitored

together with clinical trials. With the data to be obtained thereafter, studies on automated prediction and disease diagnosis will be scientifically investigated. It should be noted that the AD8232 sensor used in this study provides research-grade ECG results rather than clinical-grade accuracy. Therefore, in future works, alternative acquisition methods and advanced sensor technologies will be considered to improve signal quality and reliability for clinical applications.

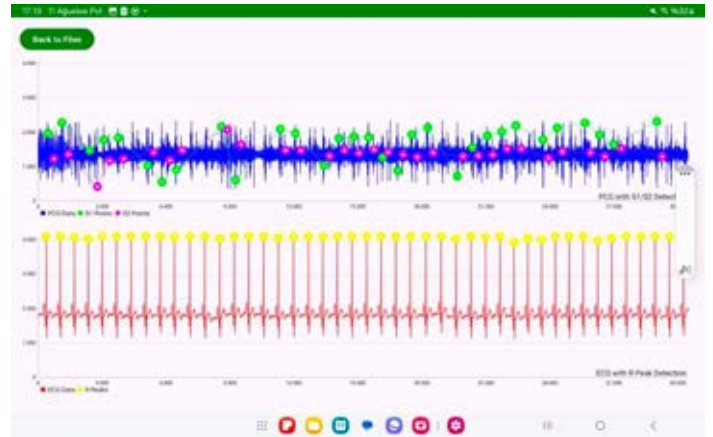


Figure 9. Other Participant Scores

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