# An Intelligent Stethoscope with ECG and Heart Sound Synchronous Display

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***Abstract*—This study presents an intelligent stethoscope that can visualize heart sound signals and can simultaneously measure human's electrocardiogram (ECG) and heart sounds. The proposed stethoscope can be used in hospitals and telemedicine through an internet of things (IoT) system and a cloud database. The proposed stethoscope includes three parts, namely, a front-end device for ECG and heart sound measurement, a smart device application (APP), and a cloud server. The ECG-measuring device is designed for single lead measurement and has low power consumption and IoT-based design, which can send real-time ECG data to the smart device APP. Simultaneously, the heart-sound-measuring device combined with a traditional stethoscope head is used to measure heart sound signals. This device includes an analog front-end circuit and a microphone to filter environmental noises and to record heart sound signals. Heart sound signals are transmitted to the APP by using a Bluetooth Low Energy module. The smart device APP can display synchronized and real-time signals, including ECG and heart sounds. Meanwhile, those signals are recorded in smart devices and are uploaded to the cloud server, where doctors and users can diagnose and monitor healthcare anytime. The cloud server can store previous signals and can realize telemedicine through a web user interface. The proposed intelligent stethoscope is applied on human trials in the National Cheng Kung University Hospital.**

***Keywords—electrocardiogram, heart sound, synchronous display, artificial intelligence of things, wearable device, smartphone application, cloud server.***

## I. Introduction

Today, young doctors cannot precisely distinguish first heart sound (S1) and second heart sound (S2) by using a traditional stethoscope because auscultation relatively relies on their experience. Heart murmurs or other abnormal heart sounds cannot be easily identified when doctors cannot distinguish S1 and S2.

Doctors can diagnose several cardiac diseases, such as atrial or ventricular septal defect, valvular stenosis, valve regurgitation, valve cleft, arteriovenous malformation, and hypertension, with the discrimination of heart murmurs. According to statics [1], that prevalence of valvular heart diseases increases with age, which is from 3.7% in 18–74 years old to 13.3% in 75 years and older group. Moreover, the incidence of congenital valvular defect is approximately 10% of congenital heart disease [2]. However, only experienced doctors can well diagnose the above symptoms by auscultation. Heart sound auscultation is a subjective method, and heart sound patterns are difficult to verbally describe. Doctors who are not cardiologists and trained medical students face an immense challenge when they conduct heart sound auscultation.


Fig 1. Association of ECG and Heart Sound

The visualization and quantization of heart sound signals can provide doctors a specific diagnosis reference. This concept reduces the burden of cardiologists and aids medical students and inexperienced doctors in heart sound auscultation training.

## II. System Overview

Although several digital stethoscopes have been proposed [3] [4] [5], all of them lack electrocardiogram (ECG) measurement, in which they cannot confirm the accuracy of heart sound signals. In other words, the accuracy of S1 and S2 cannot be guaranteed by only displaying heart sound signals. The pattern of heart sounds cannot be defined when the locations of S1 and S2 are not identified. To address this problem, this study combines a synchronized ECG signal with a heart sound signal. The peak value of sound near the R peak of ECG is labeled as S1, and the peak value of sound near the T wave of ECG is labeled as S2, as shown in Fig. 1. Heart sounds can be easily identified based on the synchronized ECG signal.

To verify the suitability of the proposed intelligent stethoscope, a traditional stethoscope head is adopted, where the stethoscope line is replaced by an analog front-end device with a microphone and a Bluetooth Low Energy (BLE) module. Furthermore, this study proposes a system where ECG and heart sound signals can be independently measured and can be simultaneously displayed on a smartphone, as shown in Fig. 2. The proposed system can collect ECG and heart sound signals and can also realize telemedicine based on internet of things (IoT) and cloud server.

### *A. Heart sound measuring device*

Fig. 3 shows the system block of a heart-sound-measuring device based on IoT. The system block includes a traditional stethoscope head, an analog front-end circuit with microphone, a micro-controller unit (MCU), and a BLE module. A 3M™ Littmann® Master Cardiology™ Stethoscope's head is used to ensure sound source quality. The analog front-end includes an electret microphone, a

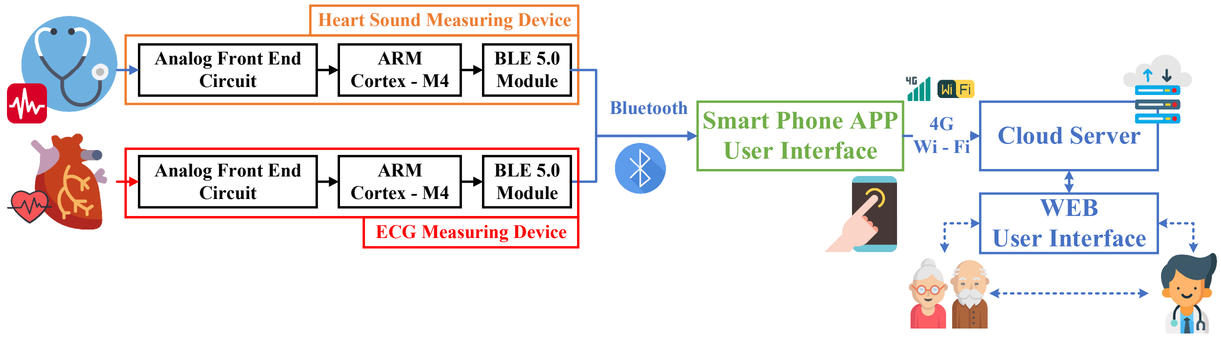



Fig 2. System block of intelligent stethoscope

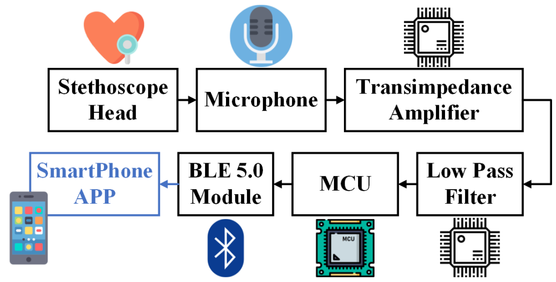



Fig. 3. System block of heart sound measuring device

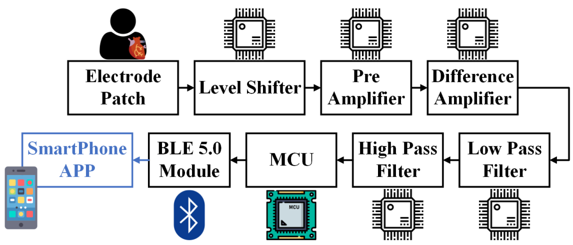



Fig. 4. System block of ECG measuring device

transimpedance amplifier (TIA), a second-order low pass filter, and a low-dropout (LDO) regulator.

The electret microphone is used due to its sensitivity, environmental noise interference, and heart sound frequency. First, heart sounds are mainly produced by the heart's valves and are transmitted through human's thoracic cavity. To amplify small heart sounds, stethoscope heads are designed with a special diaphragm structure that can enhance the vibration of heart sounds.

However, enhanced heart sounds are still relatively lower than that of normal sounds in our daily life. First, an electret microphone, such as an electromagnetic microphone, is adopted rather than a common microphone to accurately collect heart sounds. Second, a tight tube is used to connect the stethoscope head and electret microphone to maintain clean and original heart sounds. The junction between the microphone and tube is complete sealed to prevent the microphone from collecting environmental noises. Third, heart sound frequency is set to 20–200 Hz [5]. Compared with microelectromechanical system microphones, the electret microphone does not require a high-pass filter in circuit design. The TIA can transform the output current from the microphone into voltage, which is easily operated by the following signal processing and is recorded by using an analog-to-digital converter (ADC). The low-pass filter applies a second-order

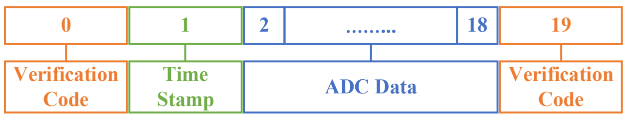



Fig. 5. Packet format with ECG and heart sound synchronization

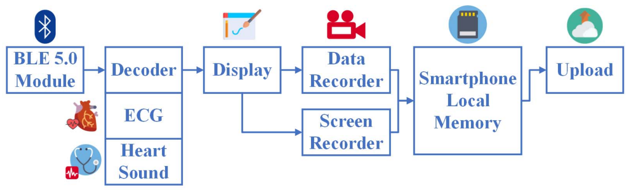



Fig. 6. APP structure in the smart device

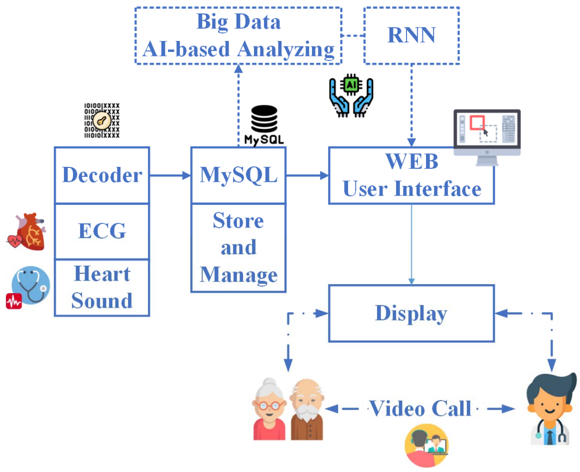
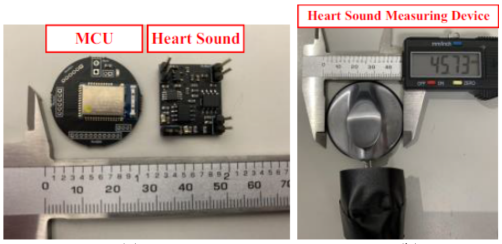



Fig. 7. Cloud server structure

Butterworth filter with the cutoff frequency of 200 Hz. The circuit is difficult to realize on a small printed circuit board (PCB) when the filter order is high. Moreover, the values of resistors and capacitors should be large because the cutoff frequency is set at 200 Hz, which is lower than that of many applications. On this basis, a high-order filter may cause signal distortion at low-frequencies (approximately 20–100 Hz). As previously mentioned, a second-order filter is used. A 3.3 V LDO is used for the power management of the entire system.

The MCU is an ARM Cortex M4, and heart sound signals are recorded by using a 12-bit ADC with sample rate of 1 kHz. Subsequently, heart sound signals are added with timestamps and are encoded by MCU. Data are transmitted to smart devices by using the BLE module.

### *B. ECG masuring device*



(a) (b)

Fig. 8. (a) MCU and heart sound PCBs of heart sound measuring device (b) The proposed heart sound measuring device

The ECG-measuring device is an IoT-based design, as shown in Fig. 4. This device includes an analog front-end circuit, an MCU, and a BLE module. The analog front-end circuit consists of level shift units, pre-amplifiers, a differential amplifier, a low-pass filter, a high-pass filter, and an LDO.

Level shift units are used to control ECG signals to a positive level. The differential amplifier behind the pre-amplifier is used to remove the common mode noise from the human body and to increase the signal-to-noise ratio (SNR). High-pass and low-pass filters are adopted to remove undesired noises caused by motion artifact and electromyogram signal.

Considering power consumption and PCB size, the ready-made operational amplifier with ultra-low power consumption and a second-order filter are used in this study. The MCU is an ARM Cortex M4, and ECG signals are recorded by using a 12-bit ADC with sample rate of 1 kHz. Furthermore, ECG signals are added with timestamps and are encoded by the MCU. Data are transmitted to smart devices by using the BLE module.

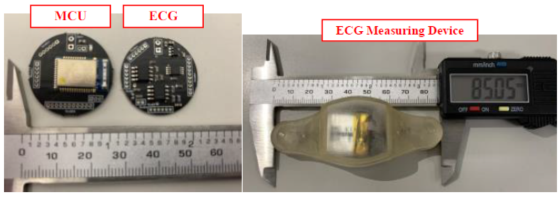
### C. *Encoding method of heart sound and ECG signals*

This study presents an encoding method with timestamps to synchronize ECG and heart sound signals, as shown in Fig. 5. Each packet is encoded in 20 bytes, which includes the first and last bytes for verification, the second byte for timestamp, and the remaining 17 bytes for recording the output voltage from ADC. The safety and accuracy of signals are considered in the encoding method. Moreover, the proposed method is designed to collect ECG and heart sound signals when the two devices are connected in the APP.

### D. *Smart device's APP*

The smart device's APP is a user interface based on an iOS system, as shown in Fig. 6. The APP has five main functions, namely, decoding, digital filtering, signal display, data storage, and uploading.

A decoder is used to decode the data transmitted from the MCU. The decoder aligns the data based on the timestamps after verifying the verification code, and the data are processed by the digital filter. A 50th-order finite impulse response filter is implemented to compensate the insufficient rejection of the analog front-end filter, which can completely remove noises. Real-time ECG and heart sound signals are shown by APP's displaying function. The recording function can record the data through screen recording or raw data storage. Users can separately record heart sound signals at four auscultatory sites, namely, aortic, pulmonic, tricuspid, and mitral areas. Users can observe the visualized heart sound signals and can hear heart sounds through headphones or speakers from the smart phone. Meanwhile, all the data are encrypted and uploaded to the cloud database via mobile internet or Wi-Fi.



(a) (b)

Fig. 9. (a) MCU and ECG PCBs of ECG measuring device (b) The proposed ECG measuring device

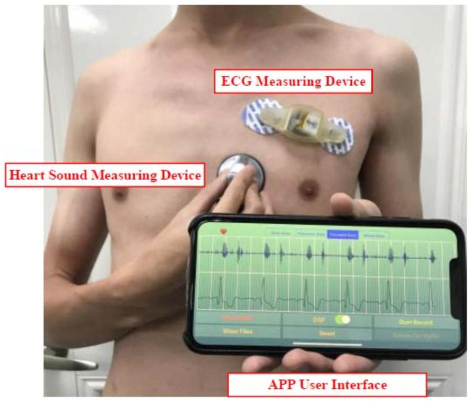


Fig. 10. Actual intelligent stethoscope measurement

### E. *Cloud server*

Fig. 7 shows the cloud server that acts as a database and a telemedicine platform. The cloud server includes a decoder, MySQL, a web user interface, and an artificial intelligence (AI)-based analyzing system for big data.

The decoder is used to decode the data transmitted from the APP. MySQL is used to store and manage the historical data from each user. The web user interface in the cloud server can synchronously display real-time ECG and heart sound signals. Doctors can remotely guide patients in conducting regular auscultation through video chat APPs, such as FaceTime and Skype, and doctors can observe patients' ECG and heart sound signals on the web user interface. The platform can provide important benefits to patients who suffer from chronic diseases. Patients can reduce considerable waiting time in hospitals and can be diagnosed in remote places.

The AI-based analyzing system for big data is still under construction. In the future, a recurrent neural network model will be applied in this system to identify heart murmurs and to aid doctors during their diagnosis.

## III. Experimental Result

The proposed stethoscope is completely developed, and is permitted by the Taiwan Food and Drug Administration (TFDA) of our country to conduct human trials in the National Cheng Kung University Hospital.

### A. *Hardware implementation*

Fig. 8(a) shows the PCBs of the heart sound measuring device, which include a hear sound analog front-end circuit and an MCU. The heart sound size is 21.04 mm*18.63 mm, and the MCU is circular with a diameter of 25.6 mm. Fig.

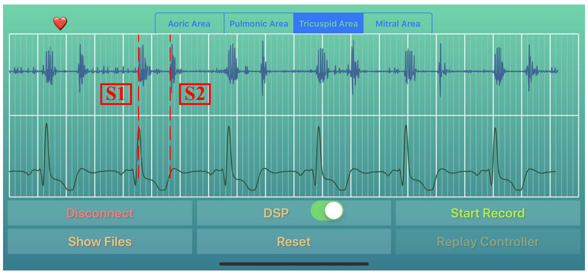



Fig. 11. Actual intelligent stethoscope measurement screenshot

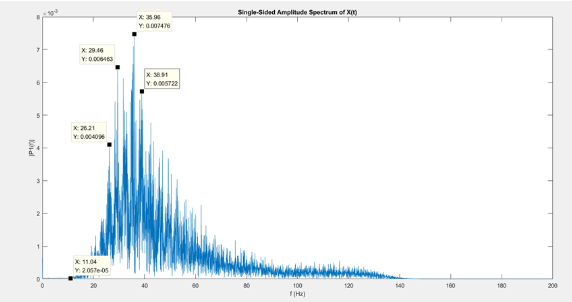



Fig. 12. Frequency analysis of heart sound signals

8(b) shows the assembled heart sound measuring device with a size of 81.69 mm*45.73 mm*23 mm. Fig. 9(a) shows the PCBs of the ECG measuring device, which include an ECG analog front-end circuit and an MCU. The ECG measuring device is circular with a diameter of 25.6 mm. Fig. 9(b) shows the assembled ECG-measuring device with a size of 85.05 mm*30.36 mm*18.55 mm.

Fig. 10 demonstrates the practical measurement on the human body. ECG measurement is a single-lead measurement, and is set on the left-upper part of the chest. Meanwhile, heart sound measurement can freely move among the four auscultatory sites. The measured signals are displayed in the APP, as shown in Fig. 11. The signals can be easily observed, and S1 and S2 can be identified by using R peak and T wave as reference. Fig. 12 shows the frequency analysis of heart sound signals, and the main frequency of heart sounds is located at 20–200 Hz, which meets the practical situation.

### B. *Software development*

Fig. 11 shows the APP user interface, which includes all the above mentioned functions, such as recording signals, replaying historical data, and uploading data. The proposed web user interface in the cloud server can display ECG and heart sound signals, as shown in Fig. 13.


Fig 13. Proposed web interface screenshot

TABLE I. PEFORMANCE COMPARSION

| | This work | 2016[3] | 2015[4] |
|---|---|---|---|
| Measuring | Heart sound and ECG | Heart sound | Heart sound |
| Wireless | Bluetooth | NO | 2.4 G RF |
| User Interface | Smart Phone APP WEB | Smart Phone APP | PC |
| Database | Cloud | N/A | N/A |
| Human trials | Yes | N/A | N/A |

TABLE II. EXISTING PRODUCTS COMPARSION

| | This work | 3M[1] | EKO[2] |
|---|---|---|---|
| Measuring | Heart sound and ECG | Heart sound | Heart sound and ECG |
| Wireless | Bluetooth | Bluetooth | Bluetooth |
| User Interface | Smart Phone APP WEB | PC | Smart Phone APP |
| Database | Cloud | Computer | Smart Phone |
| FDA | No (TFDA) | Yes | Yes |

Tables I and II presents the comparison between this work and other digital stethoscopes. Compared with other studies, this study synchronously completes the measurement of ECG and heart sound signals and utilizes the cloud server and IoT in this system. Compare with traditional digital stethoscopes that only measure heart sound signals, this study adds ECG measurement and provides considerable diagnosis references to doctors.

## IV. CONCLUSION

This study provides three contributions as follows. First, the proposed stethoscope can enhance medical usage efficiency. Doctors in different divisions, such as family medicine, pediatrics or otolaryngology, can perform precise diagnosis by using this intelligent stethoscope. Therefore, this intelligent stethoscope can save medical resources and can detect cardiovascular diseases in advance. Second, doctors and trained medical students can enhance their heart sound auscultation skills by using this intelligent stethoscope. Third, this intelligent stethoscope can be applied in telemedicine, which is a convenient home-care device for elderly people and those who suffer from chronic diseases.

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