A Wireless Digital Stethoscope Design

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***Abstract*—This paper presents a design and implementation of a digital stethoscope using a mobile device and wireless transmission. Our goal is to develop a smart digital stethoscope that adopts modern electronics and computing technologies to provide accurate information to assist cardiac auscultation. A signal conditioning circuit was designed to process an auscultation signal measured by a microphone. An Arduino processor board was used to convert the processed signal to a digital format. A Bluetooth module was employed to allow communication between the Arduino computer and an Android mobile phone. A mobile signal processing app was developed and implemented in Java. The current mobile app can store and retrieve uploaded heart sound signals for display; it also engages further analysis to identify the first and second heart sounds, and thus the systole and the diastole. The mobile app was implemented and validated using different clinical heart sound episodes.**

Keywords—heart sounds and murmurs, wireless transmission; mobile computing;

I. Introduction

Heart murmurs are auditory vibrations within a heart cycle that are often caused by abnormal cardiovascular alternations such as damaged heart valves. The heart cycle consists of two heart sounds. The first heart sound (S_1) is generated by the closure of atrioventricular valves, mitral and tricuspid valves. The second heart sound (S_2) is caused by the closure of semilunar valves, aortic and pulmonic valves. The systole represents the time interval between S_1 and S_2; the diastole represents the time interval between S_2 and the next S_1. When diagnosing a heart murmur, a doctor usually determines firstly if it is systolic or diastolic, which requires the detection and classification of systole and diastole [1] - [3].

Heart diseases are of primary concern for patients of all ages. The most widely used bedside diagnostic tool, the stethoscope, was first invented more than 200 years ago and, to date, the practice of auscultation still follows the same original design. Despite the fact that cardiac auscultation is the primary method of initial heart murmur diagnosis, it is a very subjective, and therefore inaccurate method that relies on the hearing ability and experience level of an individual medical practitioner [2]. As such, a high percentage of misdiagnoses occurs.

Most medical diagnostic equipment and tools nowadays are embedded with complicated electronics and fast computing microprocessors, yet medical professionals still rely on the century-old classical stethoscope. The goal of this research is to develop a smart digital stethoscope that is equipped with modern electronics and computing technologies to provide accurate information to assist cardiac auscultation. With the recent popularity of AI and machine learning, it becomes more imperative to develop a smart digital stethoscope that takes on fast computing technologies and modern digital signal processing tools to significantly reduce cardiac auscultation misdiagnoses.

Our solution to this involves a mobile Bluetooth app that can wirelessly collect data from the digital stethoscope. All smartphones have Bluetooth, which enables easy pairing with peripheral devices such as a digital stethoscope. Bluetooth pairing also has the capacity for pin protection, allowing for medical information security. This app can graphically display heart sounds, toggle the display of indicators like systole and diastole labels generated through artificial intelligence, and store and replay previously generated data. With this mobile implementation, physicians can now utilize an additional visual aspect to make more accurate heart murmur diagnoses. A mobile app that can connect to a digital stethoscope, collect and analyze the detected heart sound data, and display the results on a medical practitioner's smartphone would make automatic cardiac auscultation more accessible to medical professionals and assist information sharing when the laws allow.

The digital stethoscope design was implemented using a microphone to replace the hearing function of human ears. An Arduino processor was included in the design to perform data acquisition. An Android mobile phone (6.0 Marshmallow) connects to the Arduino board through a Bluetooth module in order to maintain communication and wireless data transmission. A mobile signal processing app was developed and implemented in Java in order to allow the Android phone user to instantiate data transfer as well as data analysis. The app's signal processing performance was validated using different heart sound episodes.

The 16 heart sound episodes examined were taken from the PhysioNet CINC Challenge 2016 training set database [12]. The recordings were collected in clinical and nonclinical environments, from both healthy subjects and pathological patients. The typical locations on the body at which these heart sounds were collected were the aortic area, pulmonic area, tricuspid area and mitral area. All recordings were resampled to

2000 Hertz and saved as .wav format. In the 16 heart signal recordings used, there were 1106 instances of S1 or S2 of which the signal processing algorithm correctly identified 1086, for a raw accuracy of ~98%.

II. Methods

A. *Signal Conditioning and Data Acquisiion*

Heart sounds and murmurs exhibit repeated characteristics, where the first and second heart sounds repeat with the same frequency of a cardiac cycle, generally less than 1.5 to 2 Hertz. On the other hand, heart murmurs (e.g., early systolic murmurs) may have a high pitch near 400-500 Hertz. The heart sounds and murmurs picked up by an analog stethoscope must be converted to digital format in order to take advantage of the modern computing technologies.

The project designed and built a digital stethoscope with a built-in microphone to replace the typical tube and ear pieces. The microphone converts the sound pressure wave to an electrical voltage potential with a dynamic range no more than 15 millivolts. A circuit was designed and built with an amplifier and low pass filter in order to remove any frequency components higher than 1000 Hertz. To ensure the analog heart sounds and murmurs were properly converted to digital format, we chose a sampling frequency of 2000 Hertz. Analog to digital conversion was implemented using an Arduino microcontroller.

B. *Wireless Transmission using Bluetooth*

For the convenience of data storage, retrieval, and processing using mobile devices, digitized heart sounds and murmurs were transmitted via Bluetooth to an Android smartphone. We developed the following steps to implement wireless data transfer:

- The Arduino board used in sampling and digitization is connected to a Bluetooth Serial Port Protocol module (HC-05) through a serial communication port and prepared to transmit data.
- An Android smartphone instantiates the pair-up connection by performing a Service Discovery Protocol (SDP) look up of the peripheral device, i.e., HC-05, with the correct Universally Unique Identifier (UUID). Once connected, the smartphone and the Arduino can maintain connection through Bluetooth.
- The Arduino/HC-05 begins sending a stream of data for the smartphone to receive. After data reception, an in-house developed mobile Android app will allow users to display recorded heart sound signals, store them, or retrieve previously stored heart sound signals (Fig. 1).

C. *Mobile Signal Processing*

Heart sound signals uploaded to the mobile device (an Android smartphone in this study) can be processed per a user's needs. In our mobile computing, we developed an

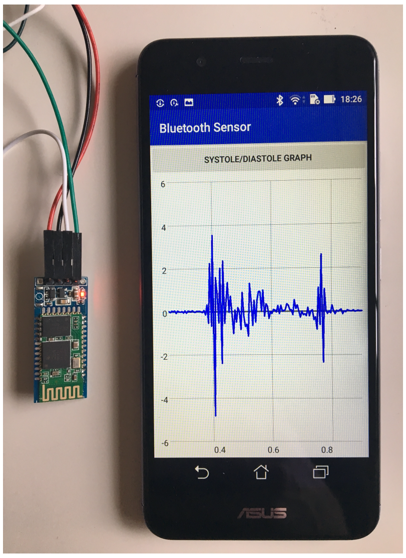

Figure 1 An Android smartphone displaying the heart sound signal uploaded via Bluetooth

effective algorithm that can quickly identify the first and second heart sounds (S_1 and S_2). This heart sound identification algorithm functions on the following assumptions: that the patient has a resting heartbeat rate of approximately 60-90 beats per minute and that the diastole duration lasts longer than the systole duration, which is the case for most heart sound episodes. The identification algorithm is summarized as follows:

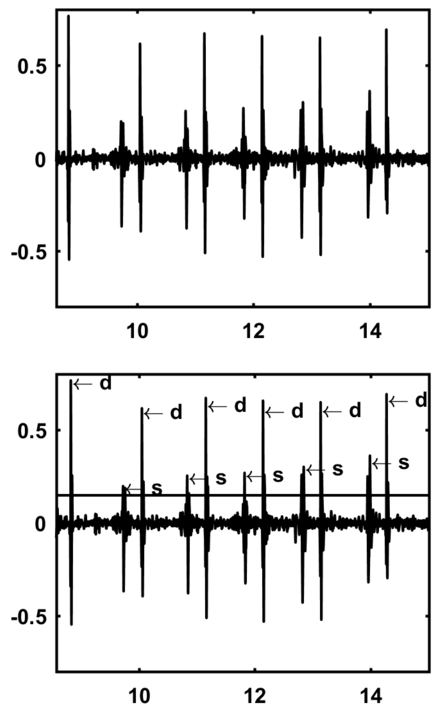

Figure 2 Normal heart sound signal-1 (top plot); detected onsets of systole (s) and diastole (d) are shown, respectively, in the bottom plot

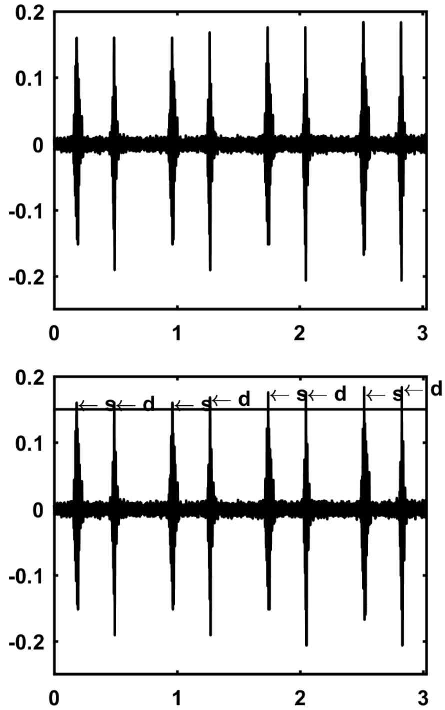

Figure 3 Normal heart sound signal-2 (top plot); detected onsets of systole (s) and diastole (d) are shown, respectively, in the bottom plot.

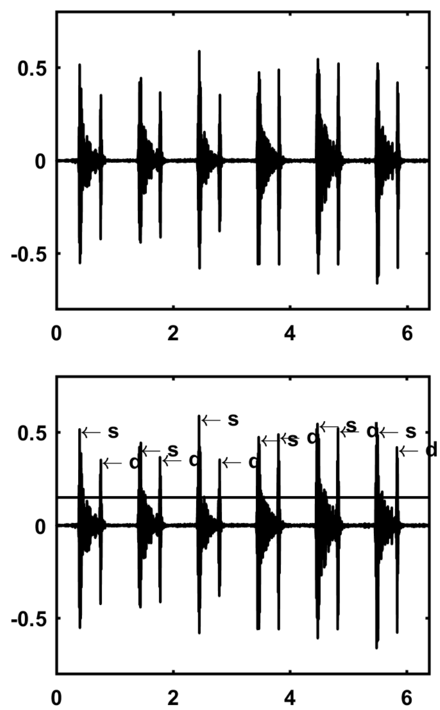

Figure 4 Early systolic murmurs (top plot); detected onsets of systole (s) and diastole (d) are shown, respectively, in the bottom plot.

- Divide and uploaded heart sound signal into short segments less than half a second.
- Apply a threshold to detect meaningful signal peaks.
- Filter clicks and other noise not caught by the y-axis threshold using an adaptive time threshold. Based on previous time intervals between significant heart sounds, clicks that do not fall in the expected range are removed.
- Examine the time interval from the previous peak to the current peak. If it exceeds the time interval to the next peak, the current peak is identified as the first heart sound (S_1), indicating closure of mitral and tricuspid valves. On the other hand, if the time interval to the next peak exceeds the time interval from the previous peak, the current peak is identified as the second heart sound (S_2), indicating closure of aortic and pulmonic valves.
- Label the onset of systole (S_1) and the onset of diastole (S_2) in the heart sound plot with "s" and "d" markers respectively. Significant signal energy may suggest a potential murmur in systole and/or diastole.

It should be noted that the current mobile signal processing app can be expanded to include additional signal processing algorithms. For example, with added algorithms to extract features from detected heart murmurs, the app could be further developed to identify heart murmur characteristics to assist

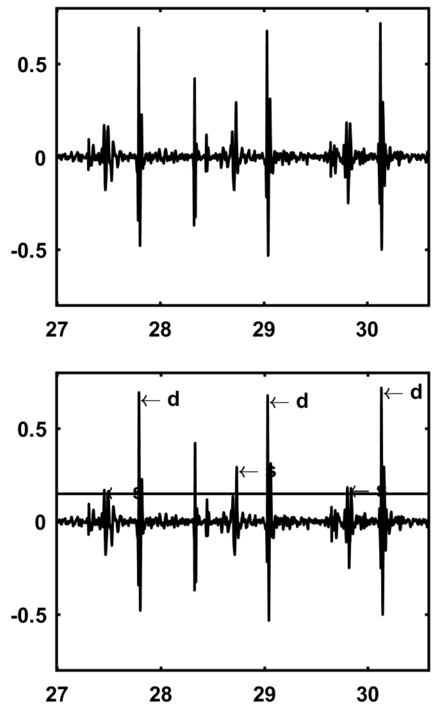

Figure 5 Heart sound signal with diastolic clicks (top plot); detected onsets of systole (s) and diastole (d) are indicated in the bottom plot.

cardiovascular disease diagnosis. The mobile signal processing algorithm was implemented using Java programming.

III. Results and Discussion

We examined the accuracy of the heart sound identification mobile app with clinical heart sounds and murmurs, including both healthy heart sounds and those with murmurs and abnormal clicks. Figures 2 and 3 (top plots) exemplify two clinical heart sound signals which are deemed normal/healthy. Though both are normal, we can observe the differences; Figure 2 shows quite different dynamic ranges of signal intensity between S_1 and S_2, where the peak intensity of S_2 is three times that of S_1. The heart sound signal shown in Fig. 3, on the other hand, exhibits that the peak intensity for S_1 and S_2 are identical. Though there is a difference in S_1 and S_2 intensities, the mobile signal processing algorithm previously described was able to accurately identify S_1 and S_2, as shown in the bottom plots in Figures 2 and 3, where "s" was labeled in the plot to indicate the onset of the systole cycle and "d" the onset of the diastole cycle.

Figure 4 demonstrates the effectiveness of the algorithm to identify the first and the second heart sounds in a heart sound episode of early systolic murmurs. Figure 5 shows a heart sound episode similar to Fig. 2 except it displays occasional diastolic clicks. The clicks, or extra peak intensities other than S_1 and S_2, are overlooked due to the adaptive threshold algorithm.

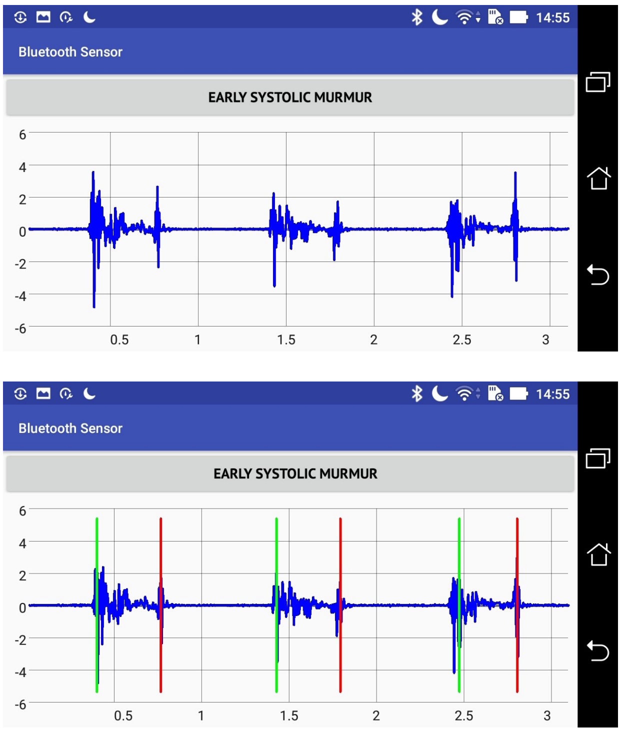

Figure 6 An early systolic murmur signal being retrieved for display. The first heart sound S_1 (green) and the second heart sound S_2 (red) were identified.

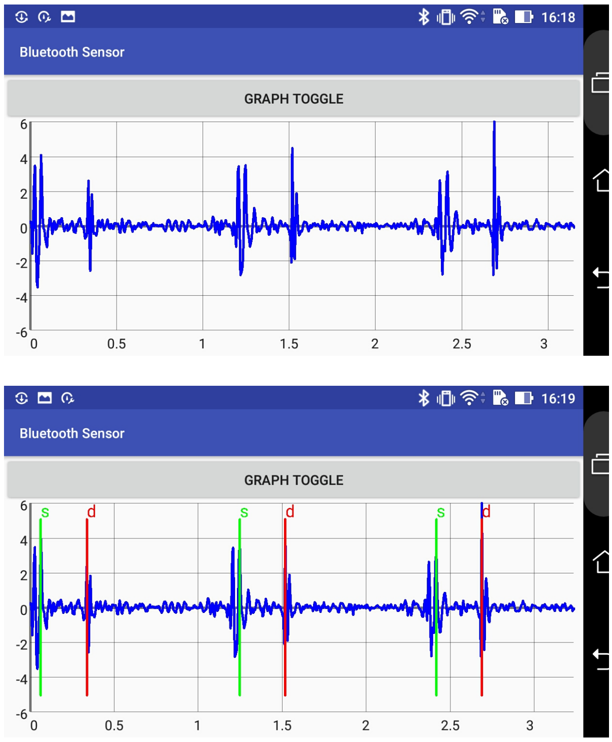

Figure 7 A normal heart signal retrieved for display and analysis using mobile app. The onset of systole (s) and diastole (d) were identified.

To validate the underlying approach, a total of 16 clinical heart sound episodes were examined. These heart sound

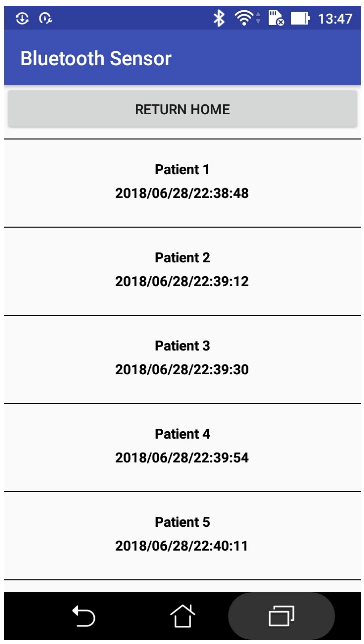

Figure 8 List of previously stored heart sound data that can be selected for display or analysis. Each entry has a filename and time stamp.

signals varied in amplitudes of S_1 and S_2, duration of heart sounds, and presence of murmurs and noise. They are, however, visually distinguishable. There are a total of 553 cardiac cycles (or 1106 heart sounds S_1 and S_2) contained in these 16 files. Our signal processing algorithm correctly identified 1086 heart sounds (S_1 and S_2), i.e., an accuracy of 98%. The confidence interval of the accuracy was evaluated using a Wilson Score Interval, which is a common method for assessing machine learning and artificial intelligence algorithms [11]. The 98% accuracy falls within the significant confidence range in a Wilson Score Interval of [0.974, 0.99]. Using the t-test, we also obtained a small p-value near 0.016 (≤ 0.05).

The Bluetooth wireless data transfer was set up and ran smoothly with an Android smartphone (Fig. 1). After heart sound signals are transmitted to a mobile device, they can be retrieved for display or further analysis. The top plot in Fig. 6 shows an early systolic murmur signal being retrieved for display. The bottom plot in Fig. 6 exhibits the result after the onsets of systole and diastole have been identified and labeled. Figure 7 displays another heart sound signal being retrieved for display and analyzed with the onsets of systole and diastole being correctly identified.

The Android app user can also choose to save the recorded heart sound data under any given filename. The database is implemented using Android's Room Persistence Library, and a list of its previously recorded heart sound signals is also made available in the app (Fig. 8). By clicking on a heart sound entry in the list, marked by its given file name and the exact date and time that it was saved, the user can once again retrieve the data for display and analysis. In the future, this database could be adapted for secure data sharing between medical practitioners, allowing for ease of second opinion.

IV. CONCLUSION

The underlying research has shown a promising development of a digital stethoscope equipped with mobile signal processing that utilizes modern computing technologies. With this mobile implementation, physicians can now utilize an additional visual aspect to detect heart diseases. In addition, mobile devices can engage in complicated processing tasks to provide further analyses which are not possible with human ears nor eyes. The underlying effort can assist physicians and make cardiac auscultation more accessible to medical professionals.

REFERENCES

[1] S. Mandal, R. J. Martis, K. Mandana, R. U. Acharya, J. Chatterjee and A. K. Ray, "Practice of Cardiac Auscultation: Clinical perspectives and its implications on computer aided diagnosis." bioRxiv, 2014.

[2] Division for Heart Disease and Stroke Prevention, "Heart Disease Fact Sheet." Centers for Disease Control and Prevention, 2017.

[3] R. O. Bonow, B. A. Carabello, K. Chatterjee, A. C. de Leon Jr, D. P. Faxon, M. D. Freed, W. H. Gaasch, B. W. Lytle, R. A. Nishimura, P. T. O'Gara and R.A. O'Rourke. "ACC/AHA Practice Guide-lines." *Circulation*, 114: 84-231, 2006.

[4] T. Ning, L. Cheng and K. Hsieh, "Identification and Features Extraction of Systolic and Diastolic Murmurs," The 13th IEEE International Conference on Signal Processing, Nov. 6-10, 2016.

[5] Android Studio User Guide. Google and Open Handset Alliance. https://developer.android.com/studio/intro

[6] Android Bluetooth Developer Guide. *Google and Open Handset Alliance*.https://developer.android.com/guide/topics/connectivity/bluetooth

[7] Android Room Persistence Library Guide. *Google and Open Handset Alliance*. https://developer.android.com/training/data-storage/room

[8] Konev, S., Stus, A., Kasyanenko, E., & Dolgov, V. (2017). Bluetooth API Implementation into Android. *MATEC Web of Conferences, 132*, 04025. doi: 10.1051/matecconf/201713204025

[9] E. Alpaydin, "Machine learning: the new AI." MIT press, Cambridge, MA, US, 2016.

[10] D. Mason, Listening to the Heart: A Comprehensive Collection of Heart sounds and Murmurs. F.A. Davis Company, Philadelphia, 2000.

[11] Wilson, E.B. (1927). Probable Interference, the Law of Succession and Statistical Inference. *Jounral of the American Statisical Associatoin*, 22, 209-212.

[12] Goldberger A.L., Amaral L.A.N., Glass L., Hausdorff J.M., Ivanov P.Ch., Mark R.G., Mietus J.E., Moody G.B., Peng C-K., Stanley H.E. PhysioBank, PhysioToolkit, and PhysioNet: Components of a New Research Resource for Coplect Physiologic Signals. *Circulation* 101(23):e215-e220 [Circulation Electronic Pages; http://circ.ahajournals.org/cgi/content/full/101/23/e215 [http://circ.ahajournals.org/cgi/content/full/101/e215]]; 2000 (June 13).

[13] University of Michigan, University of Michigan Heart Sound and Murmur Library. University of Michigan Medical School, 2017