Development of a Low-Cost, Ear-Contactless Electronic Stethoscope Powered by Raspberry Pi for Auscultation of Patients with COVID-19: an Exploratory Pilot Study

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Abstract

Background: In the battle against COVID-19, auscultation examination was essential, especially to patients with poor respiratory conditions, such as severe pneumonia, respiratory dysfunction, and intensive cases who were intubated and assisted with ventilators. However, auscultation was hard to be accomplished on the infected patients due to the safety concern and unavailability for medical workers wearing personal protective suits.

Objective: The objective of our study was to design and develop an electronic stethoscope with the characteristics of ear-contactless auscultation, low-cost property, and digital storage for further analysis. An assessment of its clinical feasibility should also be made with the comparison to the electronic stethoscope currently in use.

Methods: We developed a prototype of the electronic stethoscope without ear-contact, Auscul Pi, powered by Raspberry Pi and Python, which can make real-time auscultation sounds played with a micro-speaker instead of ear pieces, and it can also store data files for further analysis. We utilized this stethoscope to assess the feasibility by detecting abnormal heart and breath sounds from 8 patients by comparing it with 3M Littmann electronic stethoscope, and 2 healthy volunteers were included for controls. We then plotted the phonocardiography of heart sounds for visualization for the comparisons.

Results: We were able to operate Auscul Pi conveniently and record the auscultation sounds precisely in practice from the aspects of ergonomics and information technology. A total of 10 participants were recruited to receive auscultation examination with Auscul Pi and 3M Littmann electronic stethoscope. In terms of the real-time playout and recorded audio of heart sounds and breath sounds, the Auscul Pi showed consistency to 3M Littmann. As for the heart sounds, we also plotted phonocardiograph based on the data generated by Auscul Pi and 3M Littmann, and aligned them with the cardiac cycle of ECG respectively. The phonocardiography showed good conformity between Auscul Pi and 3M Littmann according to the waveforms.

Conclusions: Auscul Pi is feasible to perform the auscultation in clinical practice by applying real-time ear-contactless playout and later quantified analysis of auscultation sounds. So, it is expected to benefit the patients with COVID-19 examined by medical employees wearing protective suits and having difficulties in auscultation. Clinical Trial: ChiCTR.org.cn ChiCTR2000033830; http://www.chictr.org.cn/showproj.aspx?proj=54971

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Abstract

Background: Chest examination by auscultation is essential in patients with coronavirus disease (COVID-19), especially those with poor respiratory conditions, such as severe pneumonia, respiratory dysfunction, and intensive cases who are intubated and assisted with ventilators. However, proper auscultation of such patients is difficult when medical workers wear personal protective equipment and when contact with patients is to be minimized.

Objective: The objective of our study was to design and develop a low-cost electronic stethoscope allowing ear-contactless auscultation, and digital storage for further analysis. The clinical feasibility of our device was assessed, in comparison to a standard electronic stethoscope.

Methods: We developed a prototype of the ear-contactless electronic stethoscope, called Auscul Pi, powered by Raspberry Pi and Python. Our device allows real-time capture of auscultation sounds with a micro-speaker instead of ear pieces, and it can store data files for later analysis. We assessed the feasibility of using this stethoscope by detecting abnormal heart and respiratory sounds from eight patients with heart failure or structural heart diseases and two healthy volunteers, and by comparing the results with those from a 3M Littmann electronic stethoscope.

Results: We were able to conveniently operate Auscul Pi and precisely record the patients' auscultation sounds. Auscul Pi showed real-time recording and playback performances as the 3M Littmann stethoscope. Phonocardiogram of data obtained with the two stethoscopes were consistent and could be aligned with cardiac cycle of electrocardiogram. Pearson's correlation analysis of amplitude data from the two types of phonocardiogram showed that the Auscul Pi was correlated with 3M Littmann with the coefficient of 0.3245-0.5570 for healthy subjects ($P<.001$) and 0.3449-0.5138 among four patients ($P<.001$).

Conclusions: Auscul Pi can be used for auscultation in the clinical practice by applying real-time ear-contactless playback followed by quantitative analysis. Auscul Pi may allow accurate auscultation when medical workers are wearing protective suits and have difficulties in examining

COVID-19.

Trial Registration: This study was registered in the Chinese Clinical Trial Registry (http://www.chictr.org.cn/showproj.aspx?proj=54971, ChiCTR2000033830).

Keywords: stethoscope; auscultation; COVID-19; Raspberry Pi; Python; ear-contactless; low-cost; phonocardiogram; digital health

Introduction

Since the outbreak of coronavirus disease (COVID-19), more and more physicians and nurses have been on the front lines treating patients all over the world. Many healthcare workers have been exposed to coronavirus at work, and some of them have become infected due to high rates of nosocomial transmission [1-5]. Many medical professionals have emphasized the importance of safety measures during the management of critical patients [5, 6].

The stethoscope is a useful instrument for physicians, nurses, anesthetists, and other health professionals who examine, diagnose, and evaluate the respiratory status of COVID-19 patients. Nearly all critically ill patients with COVID-19 present severe and acute respiratory conditions [7]. Auscultation is important for these patients, in particular those with severe pneumonia or respiratory dysfunction and those who are intubated and assisted with ventilators, in order to ensure accurate diagnosis and to assess disease severity and treatment efficacy [8, 9]. In addition, auscultation has been shown to act as an emotional bridge between health staffs and the patient, who are isolated and separated from their loved ones [10].

However, some researchers have found that stethoscopes could spread infection between patients and healthcare professionals [11, 12] and that stethoscopes are not cleaned sufficiently often by medical

staff [13]. As a consequence, the safety of stethoscope implementation for chest auscultation during the COVID-19 pandemic has been questioned [14]. Furthermore, inside the quarantine wards in hospitals, medical staff wearing protective clothing are unable to use conventional stethoscopes because the protective clothing covers the ears [9, 15] (Figure 1). As a safer alternative, some experts have suggested less stethoscope and more ultrasound [16], while other experts stressed the necessity of stethoscope and auscultation in COVID-19 treatment [9].

Figure 1. A medical staff from our department, Mr. Jiguo Gu, nursing a patient with COVID-19 in Wuhan, China. Such protective clothing prevents the use of a conventional stethoscope.

Electronic stethoscopes can transmit auscultation sounds via Bluetooth and allow users to store and replay the sounds through a personal computer or other device. For example, the 3M Littmann 3200 electronic stethoscope has higher sensitivity and specificity than the classic acoustic stethoscope for diagnosis of patients with heart vascular disease [17]. Although the electronic stethoscope has these benefits, it still requires contact listening via the ears of medical staff, which is unsafe when working with COVID-19 patients. Furthermore, electronic stethoscopes are expensive, with prices over $350, which limits their use in low-resource settings. During the COVID-19 pandemic, many medical facilities encountered a critical care crisis due to the limited medical capacity, shortage of personnel [18-20], and the shortage and increasing cost of healthcare products, including ventilators and other medical devices [21, 22].

Some manufacturers and researchers have integrated the stethoscope into a smartphone, such as the Eko Core Digital Stethoscope (Eko Devices, Berkeley, CA, USA) [23]. However, this kind of stethoscope can only transfer the auscultation data to a smartphone, tablet, or a personal computer, so real-time playback to other medical staff is difficult. Furthermore, the smartphone is inconvenient for use in an intensive care unit for COVID-19. One proposed solution is to capture and analyze heart sounds using only a smartphone [24]. In that study, researchers recorded normal and pathological heart sounds using three different smartphones, and diagnosis was performed using machine learning. That device and procedure were designed for intelligent diagnosis and not for application during management of COVID-19 patients, in addition to the abovementioned difficulties of using the smartphone in an isolated intensive care unit. Stethoscopes and devices on the market or published in the literature require ear contact, which is not feasible for staff wearing personal protective equipment.

As medical staff participating in the front-line treatment of COVID-19 patients in Wuhan, China, our team realized the need for a stethoscope that did not require ear contact for auscultation. Here we describe the design and development of an electronic stethoscope (Auscul Pi) based on a low-cost, single-board computer the size of a credit-card (Raspberry Pi) for ear-contactless recording and archiving of auscultation results. We explored the usability and advantages of the new stethoscope in an exploratory sample of patients and healthy volunteers, in comparison with the 3M Littmann 3200 electronic stethoscope.

Methods

Development

Design

The Auscul Pi electronic stethoscope protype was designed and developed using Raspberry Pi hardware, the open-source Python programming language and other modified components. We evaluated the prototype for use with COVID-19 patients in terms of seven dimensions: disinfectability, ease of use, safety for patients and health professionals, auscultation performance, affordability, digitalization, and compatibility with the wearing of personal protective suit. The prototype was compared with conventional stethoscope and a 3M Littmann digital stethoscope (Figure 2).

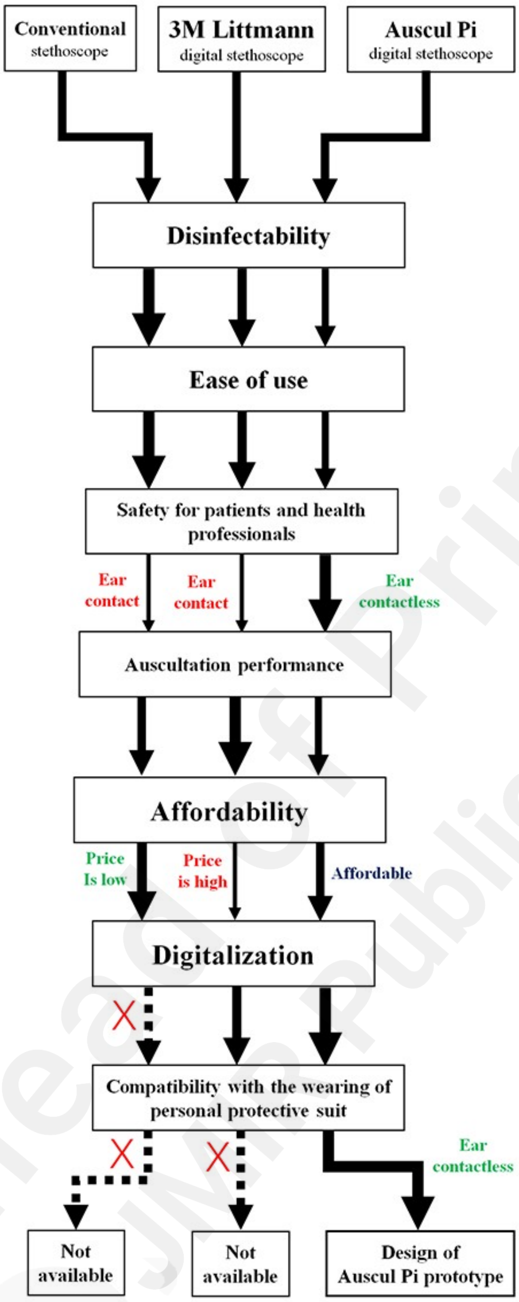


Figure 2. Flow chart of Auscul Pi design based on evaluation of seven dimensions in comparison with a conventional stethoscope and 3M Littmann digital stethoscope. Thick solid arrows indicate that the stethoscope performed satisfactorily on the indicated dimension; dashed arrows indicate that it did not.

Hardware

Raspberry Pi computers were developed by the Raspberry Pi Foundation in 2009 with the original purpose of computer science education [25]. This small single-board computer (up to the size of a credit card) consists of system-on-a-chip hardware including a quad-core ARM processor, 1GB of memory, and a graphic processing unit. Wi-Fi, Bluetooth, Ethernet and other modules are also built-in. The components we used for this project, all of which are generic and can easily be purchased online, are listed in Table 1.

Table 1. Auscul Pi components.

Item	Model	Manufacturer	Qty	Price in RMB	Price USD [a]
Raspberry Pi 3 Model B+	3 Model B+	Raspberry Pi Foundation	1	280	39.27
microSD card, SanDisk	64G	SanDisk	1	59	8.27
Micro USB Power Supply		MingXing	1	5.88	0.82
UPS Battery Expansion Board	5V Output	YDSM	1	132	18.51
18650 Rechargeable Batteries	INR19860-30Q 3000MA	YDSM	2	48	6.73
Microphone	USB collar microphone	QianBaiXiang	1	29	4.07
Speaker	Inserted Micro-Speaker	Yayusi	1	56.9	7.98
Touch Screen	3.5-inch touch screen	Mumu	1	59	8.25
Total				**0**	**$0**

Abbreviations: UPS, uninterruptible power supply.

[a] Based on an exchange rate of 7.13 RMB = 1 USD

We installed the operating system on the Raspberry Pi and initiated it [26], then connected the components mentioned above. Raspberry Pi can use potentially any kind of sensor to record data and hand it over to the software program. We used an ordinary USB collar microphone as a transducer from the modified chest piece of a stethoscope to collect sound wave signals and transform them to electronic signals via USB port. Then, the Python-coded program (Auscul Pi Console) received the digital information, processed it, and sent it back to the micro-speaker. Figure 3 illustrates the connections of each component and Raspberry Pi.

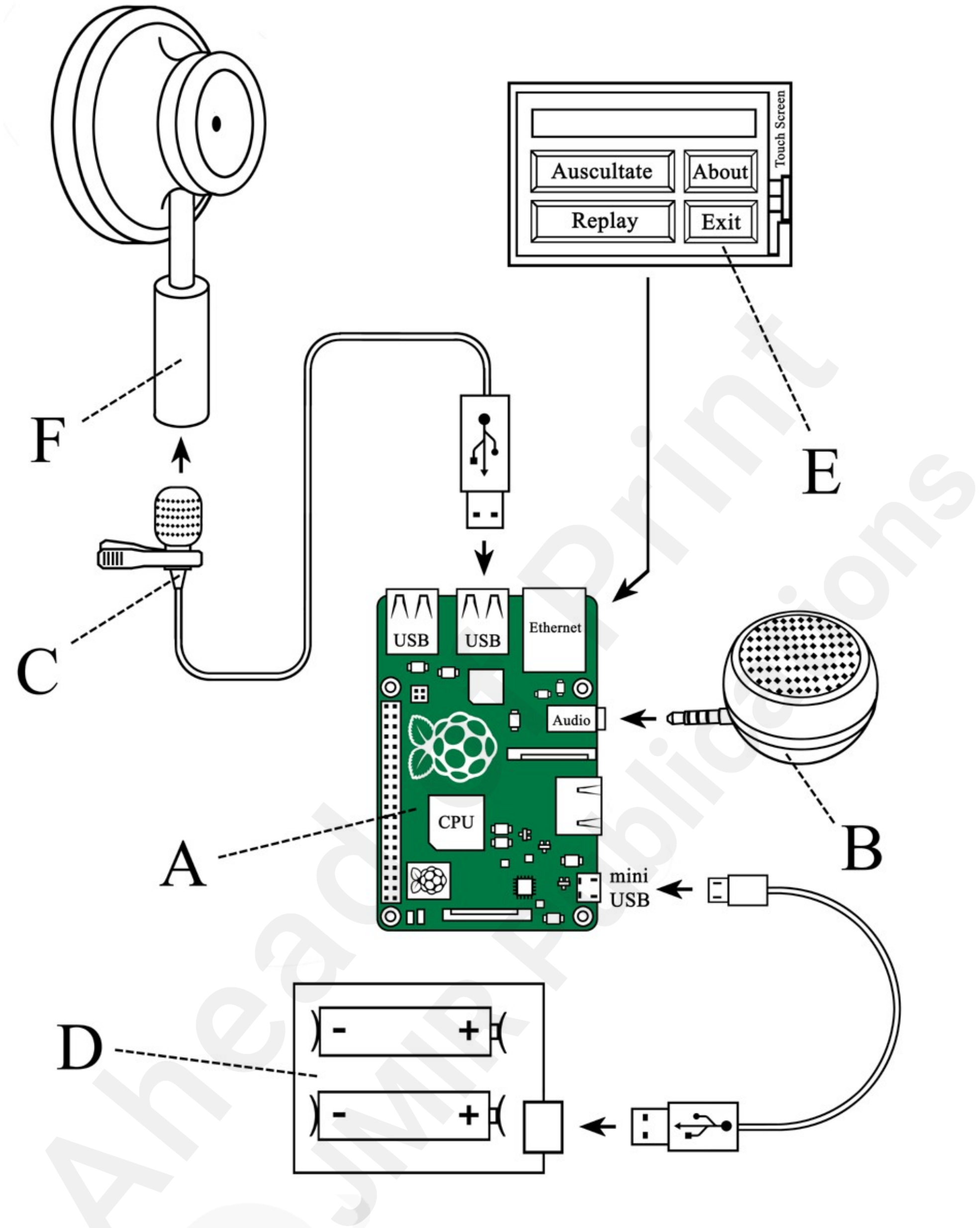
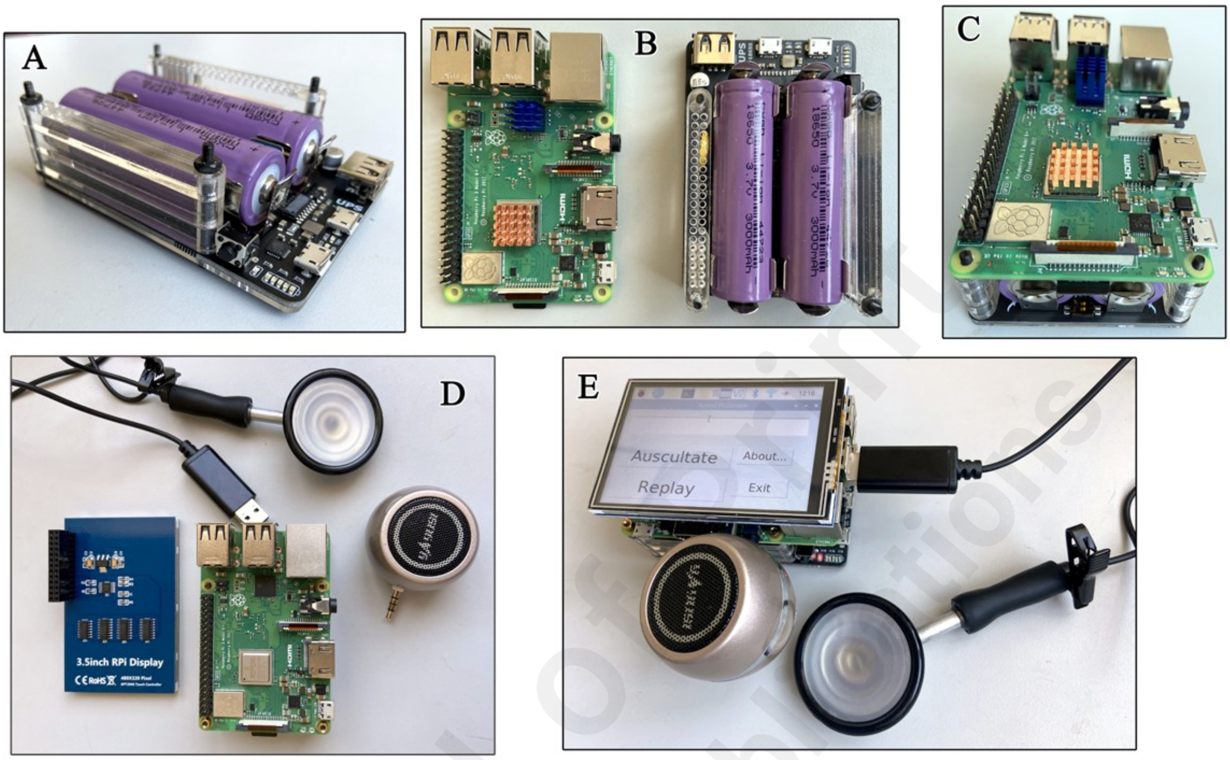


Figure 3. Schematic diagram of connections within Auscul Pi. (A) Raspberry Pi 3 Model B+. (B) Micro-speaker. (C) USB collar microphone. (D) Uninterruptible power supply battery expansion board with two rechargeable batteries (18650). (E) 3·5-inch touch screen. (F) Chest piece from a conventional stethoscope.

Since the goal was to design an electronic stethoscope for use in a quarantine zone or intensive care unit, its operation had to be as simple as possible. We added a touch screen to initiate the auscultation



and allow playback of the recorded sound. Figure 4 shows an image of the components of the Auscul Pi device.

Figure 4. Photographs of the Auscul Pi prototype. (A) The uninterruptible power supply. (B) Raspberry Pi system (left) and uninterruptible power supply (right). (C) Combination of Raspberry Pi and the power supply. (D) A microphone connected to the chest piece from a conventional stethoscope, 3·5-inch touch screen, Raspberry Pi with power supply, and micro-speaker. (E) Fully assembled device containing the components in D.

Software

We used the Python programming language to code our software. Python is one of the most popular programming languages [27], not only because of its simplicity, excellent readability, and powerful functionality, but also because third-party professionals from diverse fields are using it to develop new packages and modules, which are uploaded to a shared repository called the Python package index (PyPI) [28]. Thus, Python is a “glue language” that can join different packages and modules together to construct code with desired functions.

The Pyaudio package is a third-party package developed for audio processing [29], which can be downloaded from the GitHub repository [30] or installed by Linux command [Multimedia Appendix 10]. After importing the Pyaudio and other packages, we wrote our code. Our application program, Auscul Pi Console, was run on Raspberry Pi in a graphical user interface (GUI) using *tkinter* [31]. When the Auscul Pi Console runs, it is possible to hear the auscultation sound played via the micro-speaker. The program generates a sound wave file (.wav) and digital Numpy array file (.npy) [32] bearing the date and time of the measurement (Figure 5).

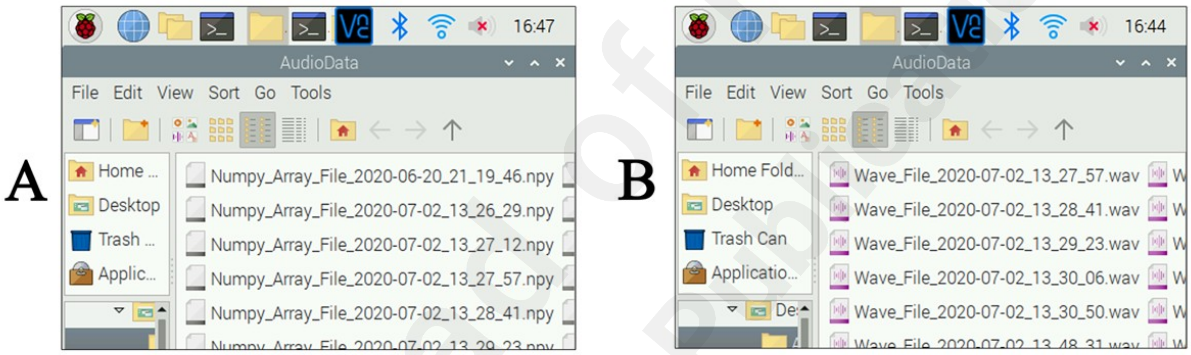


Figure 5. (A) Digital Numpy files (.npy) and (B) audio files (.wav) generated by Auscul Pi. The filenames indicate the date and time of the measurement.

Finally, we converted the Python code file *AusculPiConsole.py* to frozen binary code using PyInstaller [33][Multimedia Appendix 12]. This process allowed the program to be run on another Raspberry Pi simply by double-tapping the icon, without the need for a Python interpreter. The entire source code of Auscul Pi Console is available at our GitHub repository [34] and in Multimedia Appendix 11, and it can be re-used according to the terms of the MIT License.

This touch screen provides a GUI to activate the auscultation process. The “Auscultate” button is pushed, which initiates 30-sec recording and simultaneous broadcast of the auscultation. The last recorded auscultation can be played back by pressing the button “Replay” button (Figure 6). The

Auscul Pi Console program interface is user-friendly and can be operated interactively. All healthcare users in the present study were able to begin using the prototype quickly and were able to use it without touching the study subjects.

Figure 6. The graphical user interface on the touch screen of Auscul Pi. (A) The desktop display. The users can double-tab the Auscul Pi icon to run the program. The recorded data are stored in the folder AudioData. (B) The manipulation interface of Auscul Pi Console after double-tapping the Auscul Pi Console icon. The user can control the auscultation and replay by tapping the "Auscultate" and "Replay" buttons respectively.

Data storage and communication

The audio files and digital array files can be shared and transferred through the Wi-Fi signal for further study and analysis. For instance, we used VNC Viewer [35] or PuTTY terminal [36] to transfer the generated files to a personal computer. Phonocardiogram (PCG) records the occurrence of heart sounds in the cardiac cycle generated from the mechanical activity of the heart [37]. Our prototype includes a Python-coded parser program, which is also provided in our GitHub repository [38] that plots a PCG based on the auscultation data in the digital Numpy array file (.npy). PCG were generated from the 3M Littmann data using 3M StethAssist software.

Clinical study

After the installation of the hardware and the software, we applied this portable device in a pilot clinical study, which was approved by the Medical Ethical Committee of Shengjing Hospital of China Medical University (approval No. 2020PS525K), but no application has been filed for commercial use to the regulatory agencies. Our pilot study (ChiCTR.org.cn Identifier ChiCTR2000033830) aimed to investigate the usability and advantages of Auscul Pi in comparison with the 3M Littmann 3200 electronic stethoscope. To assess the auscultation performance of heart sounds and respiratory sounds with Auscul Pi, we included eight patients with structural heart disease or heart failure and two healthy volunteers, who were examined face-to-face with the device in clinic or in-patient department. None of the subjects had been diagnosed with SARS-CoV-2 infection. Patients and volunteers gave written informed consent in this study.

Patient's inclusion criteria were: (1) heart failure of New York Heart Association (NYHA) class IV, from whom rale sounds, including moist crackles and wheezes, could be heard in lung auscultation. (2) any kind of structural heart diseases, e.g. congenital heart disease, valvular heart disease, from which murmurs could be heard. Patients were excluded if they had weak heart sounds caused by pericardial effusion, pleural effusion and/or pneumothorax. Two healthy volunteers were also included.

We divided the participants into three groups according to the inclusion criteria: (1) the respiratory sound group (rale group) contained patients with heart failures; the (2) heart sound group (murmur group) contained patients with structural heart disease; and the (3) healthy group (normal respiratory sound and heart sound group) contained healthy volunteers. The auscultation procedure was different for each group. To collect respiratory sound from the patients with heart failure in the rale group, we auscultated their left and right lung in the regions of 7^{th}-9^{th} intercostal space (7ICS-9ICS) along the midaxillary line. We first performed auscultation with Asucul Pi by pressing the "Auscultate" button on the touch screen to initiate the 30-sec recording and broadcast. We checked the respiratory sounds from the micro-speaker without ear contact. During that time, we assessed whether we could clearly hear the moist crackles and/or wheezes at the bedsides. Then we repeated the procedure using the 3M Littmann stethoscope.

Before auscultation of patients with structural heart diseases in the murmur group, we checked the echocardiogram to locate the main origin of the murmurs, then we focused on the corresponding site for auscultation. For example, the echocardiogram of one patient with valvular heart disease showed mild mitral regurgitation. Therefore we ausculated at the apex site, located around the 5^{th} intercostal space (5ICS) in the midclavicular line, in order to hear the loudest murmurs from the mitral valve. In one patient with congenital heart disease, the echocardiogram showed a ventricular septal defect. We ausculated in the 3rd intercostal space (3ICS) and 4th intercostal space (4ICS) to the left border of the sternum in order to hear the loudest murmurs. We listened carefully to the output from the micro-speaker of Auscul Pi to assess the presence and clearness of murmurs. Next we checked healthy volunteers with both stethoscopes to evaluate normal heart sounds and respiratory sounds.

After auscultation, we transferred data from the two stethoscopes onto a personal computer via Wi-Fi (Auscul Pi) or Bluetooth (3M Littmann 3200). First, we listened to the sound files (.wav) from both stethoscopes and compared the respiratory and heart sounds and quality. Second, we compared the PCGs generated from the each stethoscope with each other and with an electrocardiogram (ECG) showing the cardiac cycles. To quantify the consistency of the two PCGs, we evaluated the relationship of the waveforms between Auscul Pi and 3M Littmann by assessing whether they had similar simultaneous ups and downs in the waveform, and whether they showed similar S1, S2, and murmur timings.

For the analysis of respiratory sound auscultation, we used the audio data collected from the patients with heart failure, and we listened to the audio file from our Auscul Pi stethoscope to evaluate the consistency with the results obtained from the 3M Littmann stethoscope. For heart sound auscultation analysis, we not only listened to the audio, but we also compared the PCGs plotted from digital array files from each stethoscope for the morphologies of waveforms by Dr Wei Zhang, MD, Dr. Xinzhong Zhang, MD, and Dr. Sicong Guo, MD. Furthermore, a Pearson's correlation analysis was performed to assess the consistency of the results obtained with the two stethoscopes. We first processed the PCG data by extracting the wave amplitude values at every time point as a data series. Then the correlation between the two data series was implemented to evaluate the peak and trough synchronizations of S1, S2, and murmurs using Python code, and we also opened the source code in our GitHub repository [39].

Results

Development

Auscul Pi is modular to allow construction of the entire device in a short time. It took us four weeks to design, purchase, assembly the hardware, code, debug, and optimize the software of Auscul Pi after we had the initial idea. Its size (10 cm x 6 cm x 5 cm) and light weight mean that it can be carried with a single hand, while the other hand holds the chest piece of the stethoscope for auscultation. The stand-by time of the batteries was 2.5 hours during the auscultation examination, and the batteries can be fully recharged in 2 hours via the mini-USB port on the uninterruptible power supply extension board. We found that we could operate it conveniently and record the information precisely in our clinical practice when considering the aspects of ergonomics and information technology.

To make data-based decisions about the prototype design, we evaluated the Auscul Pi performance based on the seven dimensions mentioned in Methods. We involved a scoring system with five levels of satisfaction that was each scored from one to five, with five being the strongest (most satisfactory) and one being the weakest (least satisfactory). The evaluators were Dr. Wei Zhang, MD, Dr. Xinzhong Zhang, MD, and Dr. Sicong Guo, MD, who gave the scores. All scores were weighted by the importance to make the total scores. The total score of Auscul Pi was 104, which was higher than that of the conventional stethoscope (87) and the 3M Littmann (82). (Table 2)

Table 2. Engineering design matrix

Dimension	Importance	Conventional stethoscope	3M Littman digital stethoscope	Ascul Pi digital sethoscope
Size	2	5	4	3

Disinfectability	3	5	4	3
Ease of use	3	5	4	3
Affordability	3	5	3	4
Digitalization	3	1	3	5
Safety for patient	4	2	2	2
Safety for health professional	4	1	1	4
Ability to detect auscultation sound	3	4	5	3
Usability in isolation in the intensive care unit	5	1	1	4
Total		**87**	**82**	**104**

Clinical study

This pilot study included eight patients and two healthy volunteers (Table 3). No patient was excluded from the study. First, we auscultated the two healthy volunteers to acquire normal heart sounds (Multimedia Appendix 1, Multimedia Appendix 2) and normal respiratory sounds (Multimedia Appendix 3, Multimedia Appendix 4). The audios of respiratory and heart sounds obtained with Auscul Pi were clear and recognizable in both real-time play and recorded archives. The digital Numpy array files of the corresponding sounds were used to plot PCGs (Figure 7). The audios and PCGs generated by Auscul Pi were consistent with those obtained from the 3M Littmann stethoscope by the evaluations of the three physicians mentioned in Methods. To quantify the consistency of the two PCGs, we evaluated the relationship of the waveforms between Auscul Pi and 3M Littmann by assessing whether they had similar ups and downs in waveform simultaneously, especially whether they had good synchronization of S1, S2 and murmur timings. We firstly processed the PCG data by extracting the wave amplitude values of every time point. Then we performed the Pearson's correlation of the two data series also with Python [39][Multimedia Appendix 13]. For the two healthy volunteers, no. 9 had a correlation coefficient of 0.5570 (*P*<.001), and the correlation coefficient of no 10 was 0.3245 (*P*<.001).

Table 3. Demographic characteristics of patients and volunteers in the pilot study.

No	Sex	Age	Group	Diagnosis 1	Diagnosis 2	Auscultation site	Abnormalities
1	M	64	Respiratory sound	Heart failure	Atrial fibrillation	7ICS-9ICS along the midaxillary line	Wheezes
2	M	79	Respiratory sound	Heart failure	Atrial fibrillation	7ICS-9ICS along the midaxillary line	Moist crackles
3	M	43	Respiratory sound	Heart failure	Ischemic cardiomyopathy	7ICS-9ICS along the midaxillary line	Moist crackles
4	M	66	Respiratory sound	Heart failure	Atrial fibrillation	7ICS-9ICS along the midaxillary line	Moist crackles
5	M	68	Heart sound	Valvular heart disease	Mitral regurgitation	Apex (5ICS in the midclavicular line)	Mild holosystolic murmurs
6	F	72	Heart sound	Valvular heart disease	Aortic stenosis	2ICS to the right border of the sternum	Mild holosystolic murmurs
7	M	69	Heart sound	Valvular heart disease	Aortic stenosis	2ICS to the right border of the sternum	Mild holosystolic murmurs
8	M	4	Heart sound	Congenital heart disease	Ventricular septal defect	3ICS and 4ICS to the left border of the sternum	Loud holosystolic murmurs
9	M	40	Healthy			Apex (5ICS in the midclavicular line)	None
10	M	22	Healthy			Apex (5ICS in the midclavicular line)	None

Abbreviations: M, male; F, female; ICS, intercostal spaces.

Figure 7. Electrocardiogram (ECG) and phonocardiograms of healthy volunteer no. 9 generated by the 3M Littmann and Auscul Pi stethoscopes, showing normal sinus rhythm and normal heart sounds. S1: first heart sounds; S2: second heart sounds.

In the respiratory sound group (patient 1-4), all patients complained of dyspnea at first when presented at the hospital, and we heard rales in all patients. They all received anti-heart failure therapies. They were all cured and discharged several days later. Patient no. 1 was an presented atrial fibrillation and heart failure. At the beginning of the treatment period, we performed auscultation on him with both stethoscopes. We could hear clear wheezes in both inspiratory and expiratory phases. During the examination, we checked respiratory sounds simultaneously played by the micro-speaker, from which the wheezes were clear and obvious. Then, we replayed the wheezing sounds in the computer when away from the patient, and the wheeze sound quality and recognizability were better than when we broadcast the sound during recording (Multimedia Appendix 5). The qualities of respiratory sounds were good for the other three patients in the group (no. 2-4) during recording the playback.

For the patients in the heart sound group (no. 5-8), we examined and easily detected the murmurs at the corresponding auscultation sites of culprit valves or defects. For example, patient no. 8, who was suffering from congenital heart disease, had two intraventricular septal defects. When we auscultated him at 3ICS and 4ICS to the left border of the sternum, a loud holosystolic murmur was clearly detected with Auscul Pi (Multimedia Appendix 6). The acoustic characteristics and timings of the murmurs were quite similar to the murmurs heard with the 3M Littmann stethoscope (Multimedia Appendix 7). This patient underwent surgical ventricular septal repair. Post-surgery auscultation with Auscul Pi (Multimedia Appendix 8) and 3M Littmann stethoscope (Multimedia Appendix 9) showed that the murmurs had disappeared.

The alignments of PCGs with ECGs showed good visual consistency between Auscul Pi and the 3M Littmann stethoscope (Figure 8). We also performed the same correlation analysis respectively to evaluate the consistency by using the data series extracted from PCG numpy data. The correlation coefficient of Auscul Pi and 3M Littmann results before surgery was 0.3436 (P<.001), and the coefficient after surgery was 0.5138 (P<0.001). The correlation coefficients of the other 3 patients were from 0.3449 to 0.4797 (P<.001) (Table 4).

Table 4. Pearson's correlation coefficients between phonograms obtained using the Auscul Pi and 3M Littmann stethoscopes

Patient or volunteer	Correlation coeffient	*P*
9	0.5570	<.001
10	0.3245	<.001
5	0.3449	<.001
6	0.4797	<.001
7	0.4134	<.001
8, pre-surgery	0.3436	<.001
8, post-surgery	0.5138	<.001

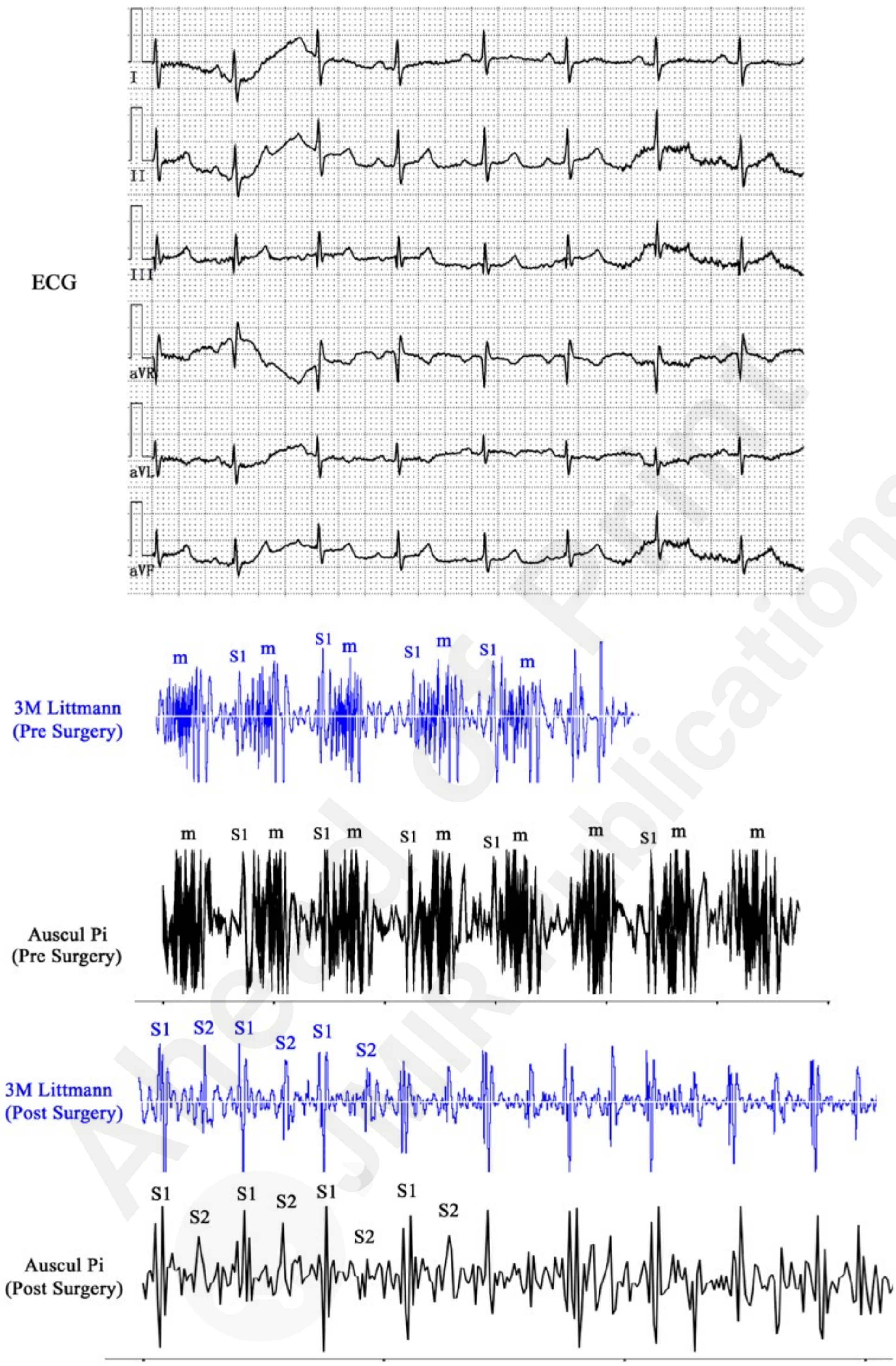


Figure 8. Electrocardiogram (ECG) and phonocardiograms of patient no 8, showing systolic murmurs before cardiac surgery to treat a ventricular septal defect but no murmurs after the surgery. S1: first heart sounds; S2: second heart sounds; m: murmurs.

Discussion

Principal results

In this work, we present the development of Auscul Pi, an innovative electronic stethoscope that we evaluated in a pilot study in patients with cardiovascular diseases. Our results show that Auscul Pi can be applied for the examination of cardiovascular diseases since it clearly plays and records heart and respiratory sounds. The consistency between the results obtained by Auscul Pi and a typical electronic stethoscope was dependable based on qualitative analysis of audio files and statistical analysis of PCGs.

Our team found that Auscul Pi had several advantages over traditional stethoscopes in clinical practice. First, the contactless design of the stethoscope allowed no contact with the medical staff's ears. The device can be used by physicians and nurses wearing a protective suit, eye protector, and face shield when auscultation is essential in clinical work, for example to treat COVID-19 patients. The stethoscope can reproduce respiratory and heart sounds with the micro-speaker, allowing medical staff nearby to hear well from the broadcast as if touching their ear to the stethoscope earpieces.

Second, the components are quite inexpensive, and component assembly and software installation are quite easy, so the do-it-yourself protocol can be followed by medical staff in a quite short time. The price of the entire device is about $94, of which $35 correspond to Raspberry Pi, which is much lower than the price of a 3M Littman stethoscope. This makes the device accessible to most medical facilities, hospitals, and emergency rooms all over the world. Besides, Raspberry Pi is a popular project worldwide. It can be easily ordered online, and its small size makes shipment fast.

Third, besides its low-cost, Raspberry Pi has versatility that has allowed it to be applied in many medical projects, ranging from assistance with medical imaging [40] to cervical cancer prevention [41], and from building computational microscopy [42] to ventilator building-up during the pandemic of COVID-19 [42, 43]. Moreover, Raspberry Pi uses Linux as a routine operating system, which is open-source, generic, and freely downloadable. Besides, many software packages developed by third-party developers use Python, which is one of the most popular programming languages works well with Raspberry Pi.

Fourth, the recorded respiratory and heart sound data can be stored in the Raspberry Pi, then transferred to a personal computer for further analysis if the hospital, emergency room, intensive care unit, or ward has a Wi-Fi signal.

Finally, Auscul Pi can quantify and visualize auscultation: the system simultaneously records and broadcasts the signal, and the resulting computer files can be transferred using Wi-Fi for off-line analysis. PCGs can also be plotted based on the Numpy array files for easy visualization and analysis. These data can also be used in the future for research related to diagnosis and prognosis, such as using machine learning algorithms [24, 44]. The device may also have educational value as a teaching aid for medical students.

While dealing with COVID-19 patients in Wuhan, we developed the Auscul Pi to solve the problems of auscultation. In a long-term perspective, this innovation may not be limited to the COVID-19 examination, and it may be applied to other infectious diseases to reduce the risk of infection of medical workers. Although we do not envisage that Auscul Pi will become a commercial medical product in a large market, we believe it may inspire biomedical engineers, bioinformatics researchers, clinicians, and computer scientists to create low-cost engineering technologies to benefit patients ravaged by COVID-19. Low-cost portable medical devices based on Raspberry Pi and the Python programming language may even become useful as tools for self-monitoring and assessment by COVID-19 patients under quarantine[45], especially in the low-resource areas.

Limitations

The auscultation sounds recorded and broadcast by Auscul Pi inevitably contain some noises due to background and electricity, such as tiny click and pop sounds, that nevertheless do not cover up the main auscultation sounds. Future work should allow much or all of this background noise to be filtered out. Our clinical research was a small pilot study to explore the feasibility to utilize the device in patients, but we have planned a randomized clinical trial involving more medical professionals as device users and more patients with auscultatory abnormalities. We will also use questionnaires and unstructured interviews to ask the professionals about device usability and reliability.

Conclusions

The low-cost electronic stethoscope, Auscul Pi, allows auscultation without ear-contact. The device allows real-time broadcast of the auscultation sounds and simultaneous digital storage for off-line analysis. Auscul Pi may allow accurate auscultation of patients with COVID-19 by medical workers wearing protective suits, thereby helping to minimize risk of infection.

Acknowledgments

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Conflict of Interest

The hardware part (Auscul Pi) and the software part (Auscul Pi Console) of this project were developed by Dr. CY and Mr. ZP, both of whom have filed a patent (202021055264.4) through Shengjing Hospital of China Medical University. None of the other authors have conflicts of interest to declare.

Multimedia Appendix

Multimedia Appendix 1: Heart sounds of healthy volunteer no. 9 with Auscul Pi.

Multimedia Appendix 2: Heart sounds of healthy volunteer no. 9 with 3M Littmann.

Multimedia Appendix 3: Respiratory sounds of healthy volunteer no. 9 with Auscul Pi.

Multimedia Appendix 4: Respiratory sounds of healthy volunteer no. 9 with 3M Littmann.

Multimedia Appendix 5: Respiratory sounds of patient no. 1 with heart failure patient by Auscul Pi. Clear wheezes were heard.

Multimedia Appendix 6: Heart sounds of patients no. 8 with congenital heart disease (VSD) before surgery by Auscul Pi. We can hear Loud holosystolic murmurs.

Multimedia Appendix 7: Heart sounds of patients no. 8 before surgery by 3M Littmann. The murmurs can also be heard.

Multimedia Appendix 8: Heart sounds of patients no. 8 after surgery by Auscul Pi. The murmurs disappeared.

Multimedia Appendix 9: Heart sounds of patients no. 8 after surgery by 3M Littmann. The murmurs disappeared.

Multimedia Appendix 10: Pyaudio installation.

Multimedia Appendix 11: Source code of Auscul Pi Console.

Multimedia Appendix 12: The conversion to frozen binary code.

Multimedia Appendix 13: The source code of PCG processing and correlation analysis.

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Abbreviations

PCG: phonocardiogram

ECG: electrocardiogram

GUI: graphical user interface

ICS: intercostal space

PyPI: Python package index

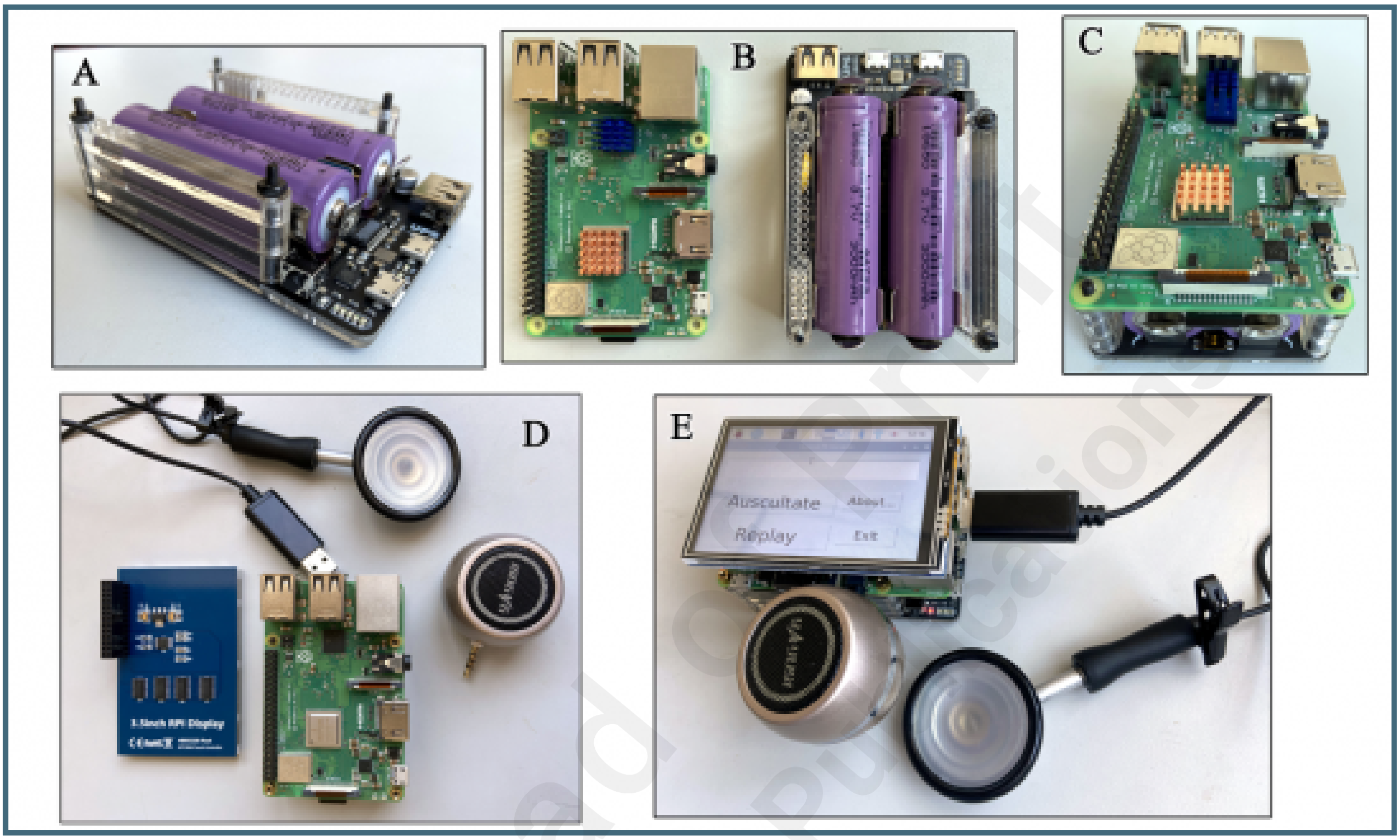
ICU: intensive care unit

Supplementary Files

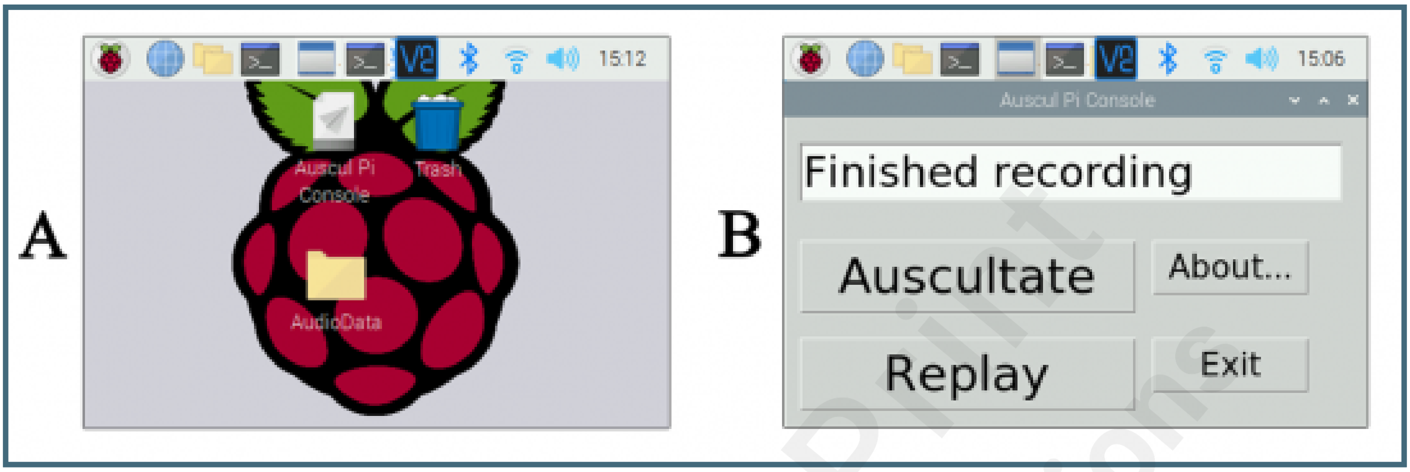
Figures

A medical staff from our department, Mr. Jiguo Gu, nursing a patient with COVID-19 in Wuhan, China. Such protective clothing prevents the use of a conventional stethoscope.

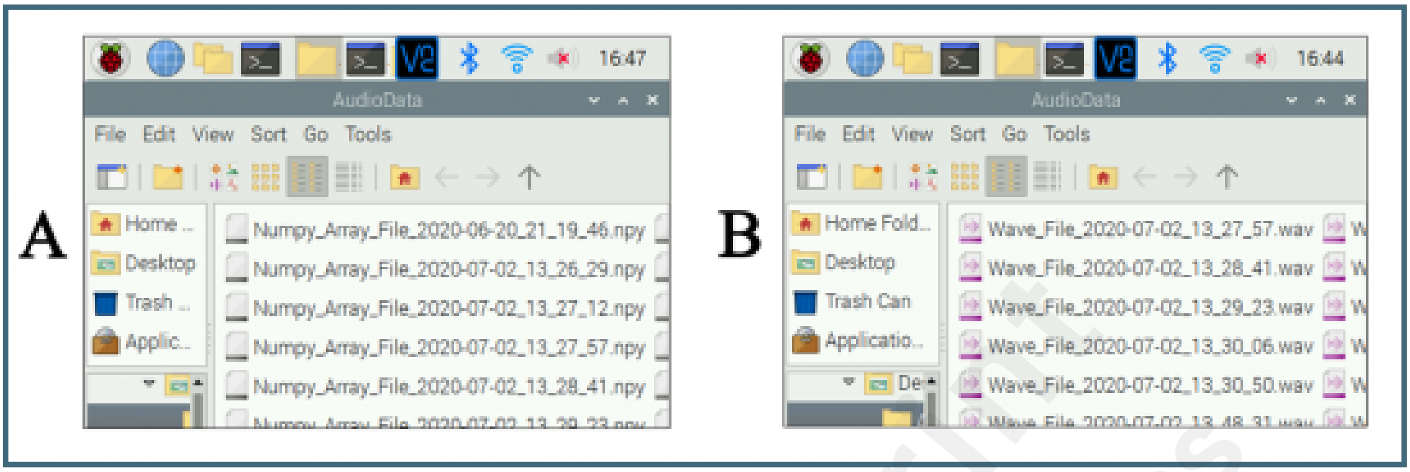
Photographs of the Auscul Pi prototype. (A) The uninterruptible power supply. (B) Raspberry Pi system (left) and uninterruptible power supply (right). (C) Combination of Raspberry Pi and the power supply. (D) A microphone connected to the chest piece from a conventional stethoscope, 3·5-inch touch screen, Raspberry Pi with power supply, and micro-speaker. (E) Fully assembled device containing the components in D.



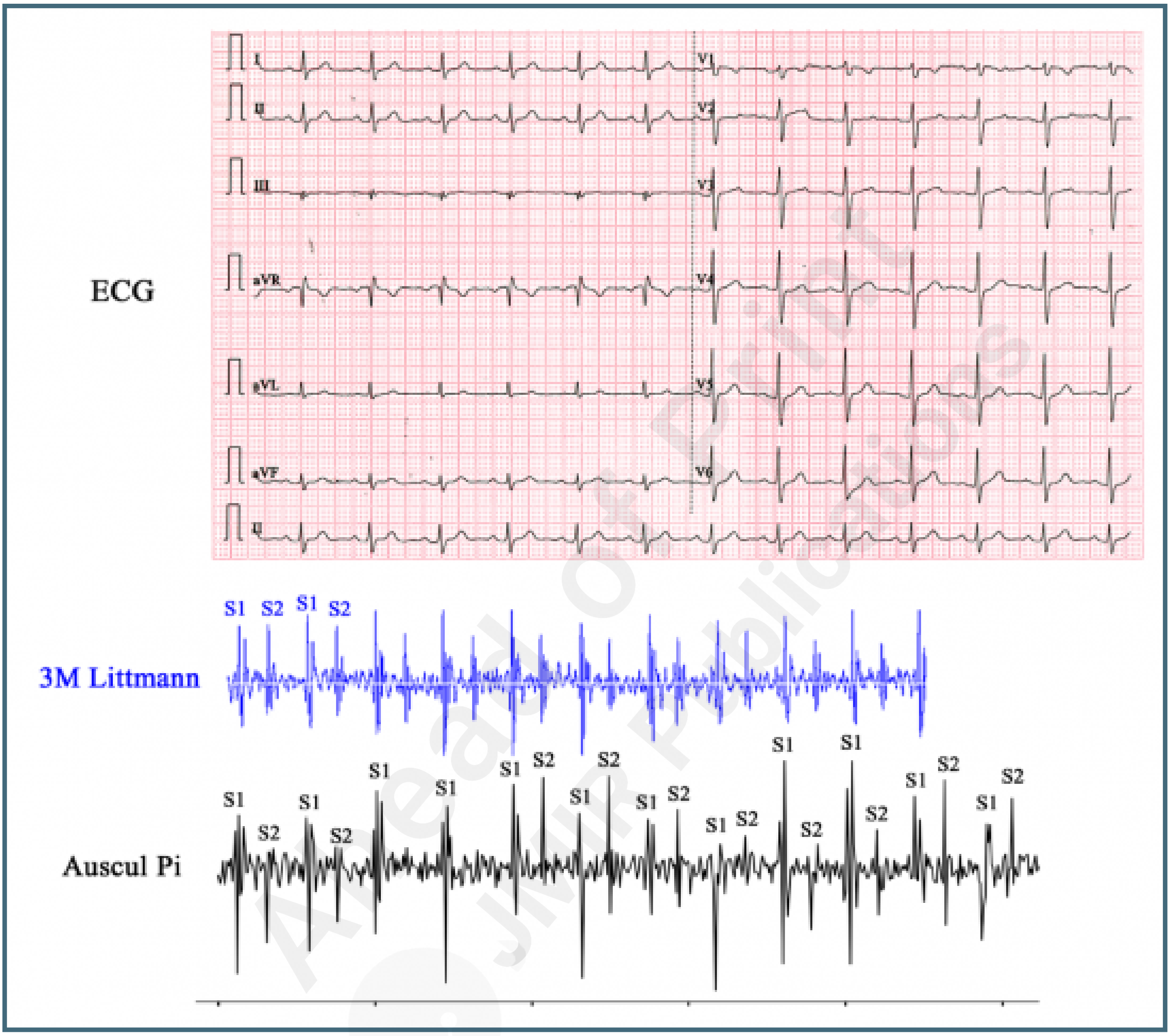
The graphical user interface on the touch screen of Auscul Pi. (A) The desktop display. The users can double-tab the Auscul Pi icon to run the program. The recorded data are stored in the folder AudioData. (B) The manipulation interface of Auscul Pi Console after double-tapping the Auscul Pi Console icon. The user can control the auscultation and replay by tapping the "Auscultate" and "Replay" buttons respectively.



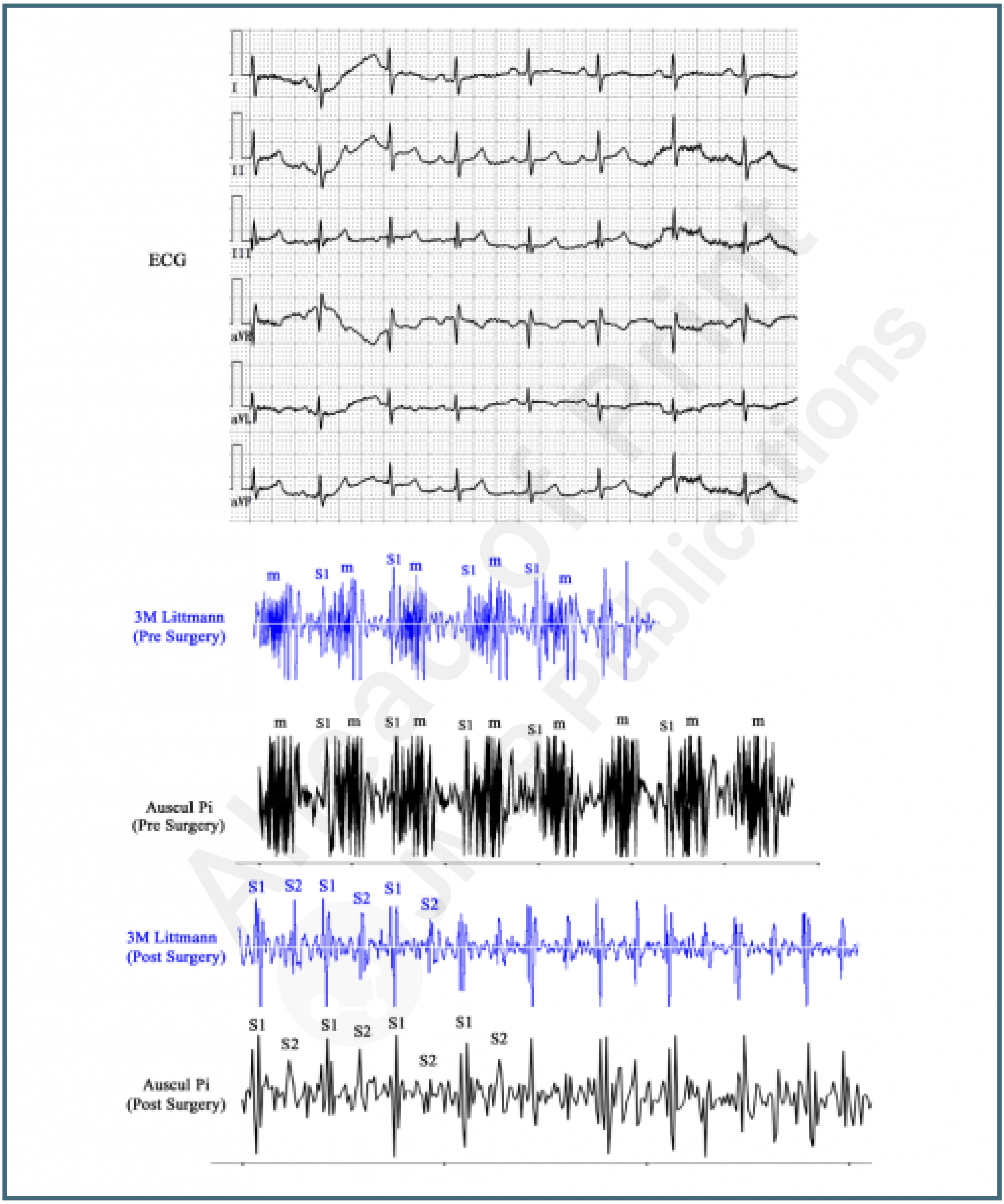
(A) Digital Numpy files (.npy) and (B) audio files (.wav) generated by Auscul Pi. The filenames indicate the date and time of the measurement.



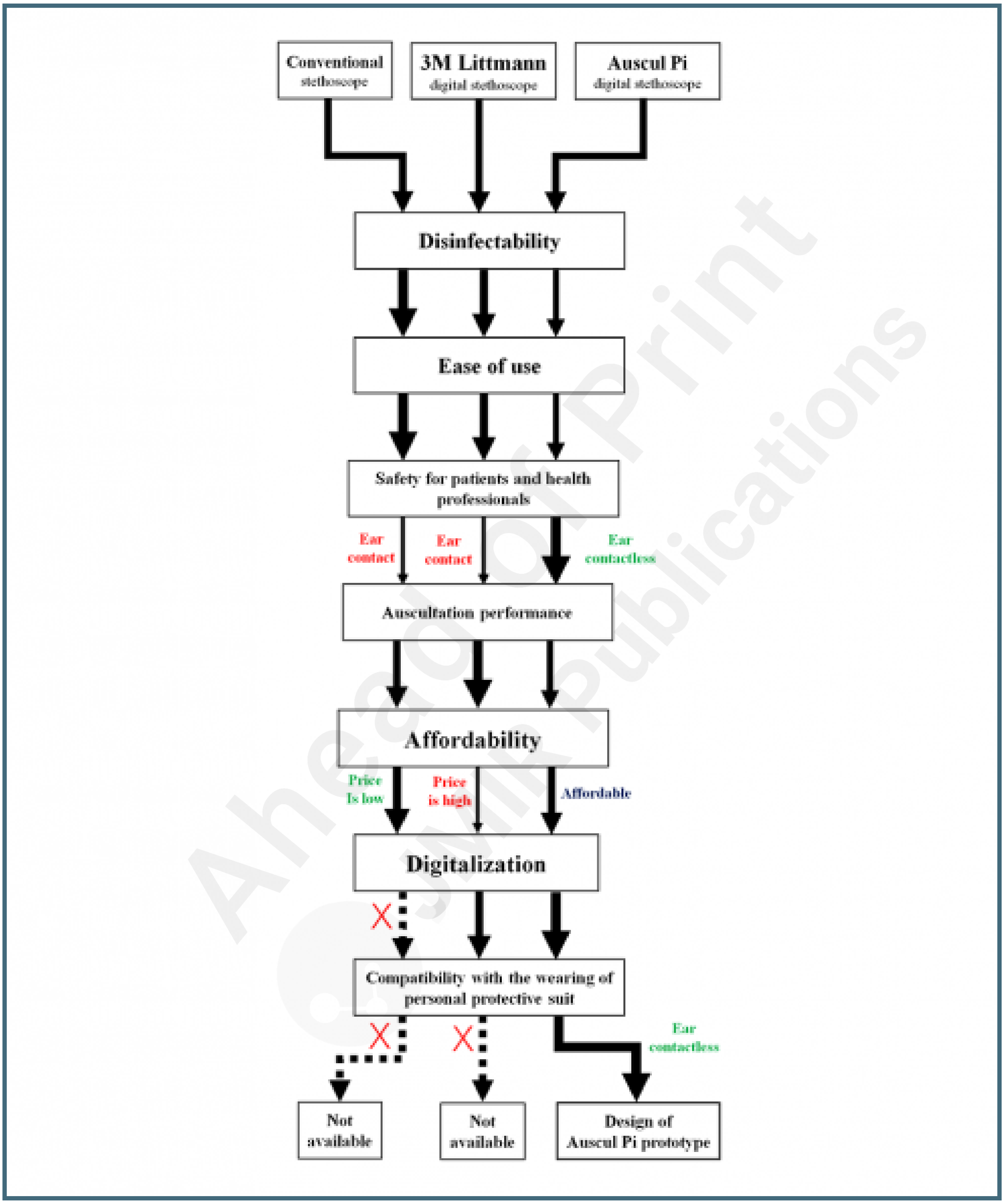
Electrocardiogram (ECG) and phonocardiograms of healthy volunteer no. 9 generated by the 3M Littmann and Auscul Pi stethoscopes, showing normal sinus rhythm and normal heart sounds. S1: first heart sounds; S2: second heart sounds.



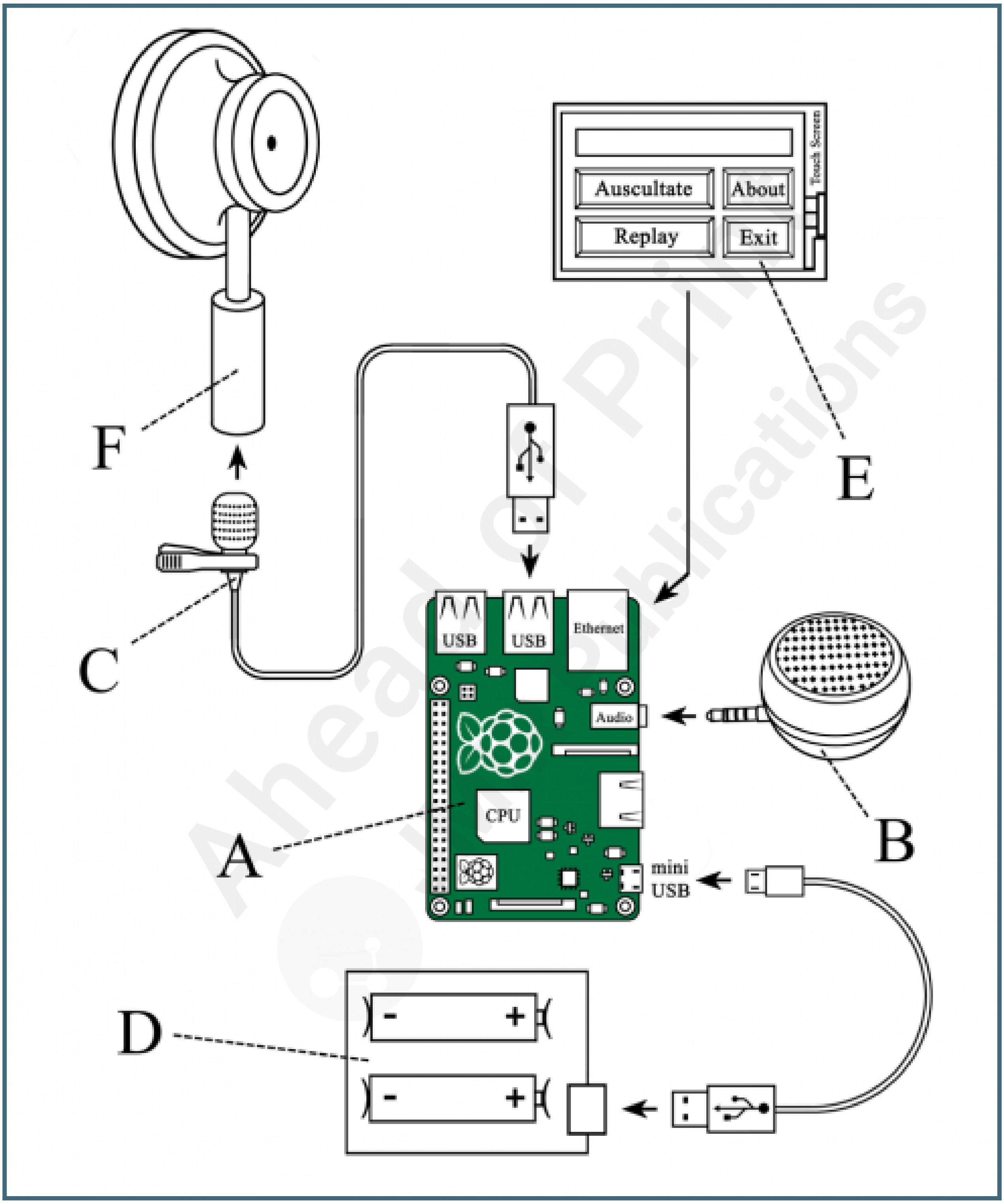
Electrocardiogram (ECG) and phonocardiograms of patient no 8, showing systolic murmurs before cardiac surgery to treat a ventricular septal defect but no murmurs after the surgery. S1: first heart sounds; S2: second heart sounds; m: murmurs.



Flow chart of Auscul Pi design based on evaluation of seven dimensions in comparison with a conventional stethoscope and 3M Littmann digital stethoscope. Thick solid arrows indicate that the stethoscope performed satisfactorily on the indicated dimension; dashed arrows indicate that it did not.



Schematic diagram of connections within Auscul Pi. (A) Raspberry Pi 3 Model B+. (B) Micro-speaker. (C) USB collar microphone. (D) Uninterruptible power supply battery expansion board with two rechargeable batteries (18650). (E) 3·5-inch touch screen. (F) Chest piece from a conventional stethoscope.



Multimedia Appendixes

Heart sounds of patients no. 8 after surgery by 3M Littmann. The murmurs disappeared.
URL: https://asset.jmir.pub/assets/f5cef16518221515fce4ec93a534bd80.mp4

The source code of the PCG processing and the correlation analysis.
URL: https://asset.jmir.pub/assets/5063ca99daf5cc9da5f18d982e33ef07.pdf

The conversion to frozen binary code.
URL: https://asset.jmir.pub/assets/fcc6b7c70e2f98c62e3cc7b5b7813a6f.pdf

Source code of Auscul Pi Console.
URL: https://asset.jmir.pub/assets/1a3d95db3687854ca9d9d6010c7f8a9a.pdf

Pyaudio installation.
URL: https://asset.jmir.pub/assets/14937d4e09a4e1c744080a1029ffd061.pdf

Heart sounds of patients no. 8 with congenital heart disease (VSD) before surgery by Auscul Pi. We can hear Loud holosystolic murmurs.
URL: https://asset.jmir.pub/assets/72851cd4277166f6c11afb4f6392e332.mp4

Heart sounds of patients no. 8 after surgery by Auscul Pi. The murmurs disappeared.
URL: https://asset.jmir.pub/assets/ef1b6f572831e99b3c1eaf394885d5ba.mp4

Heart sounds of patients no. 8 before surgery by 3M Littmann. The murmurs can also be heard.
URL: https://asset.jmir.pub/assets/e51ca05478df4c178902ac86d3917ac6.mp4

Respiratory sounds of patient no. 1 with heart failure patient by Auscul Pi. Clear wheezes were heard.
URL: https://asset.jmir.pub/assets/861ed6e1150adff659d518002ff2b2b6.mp4

Respiratory sounds of healthy volunteer no. 9 with 3M Littmann.
URL: https://asset.jmir.pub/assets/673c9ddf0d883ffc835c32b5051490c8.mp4

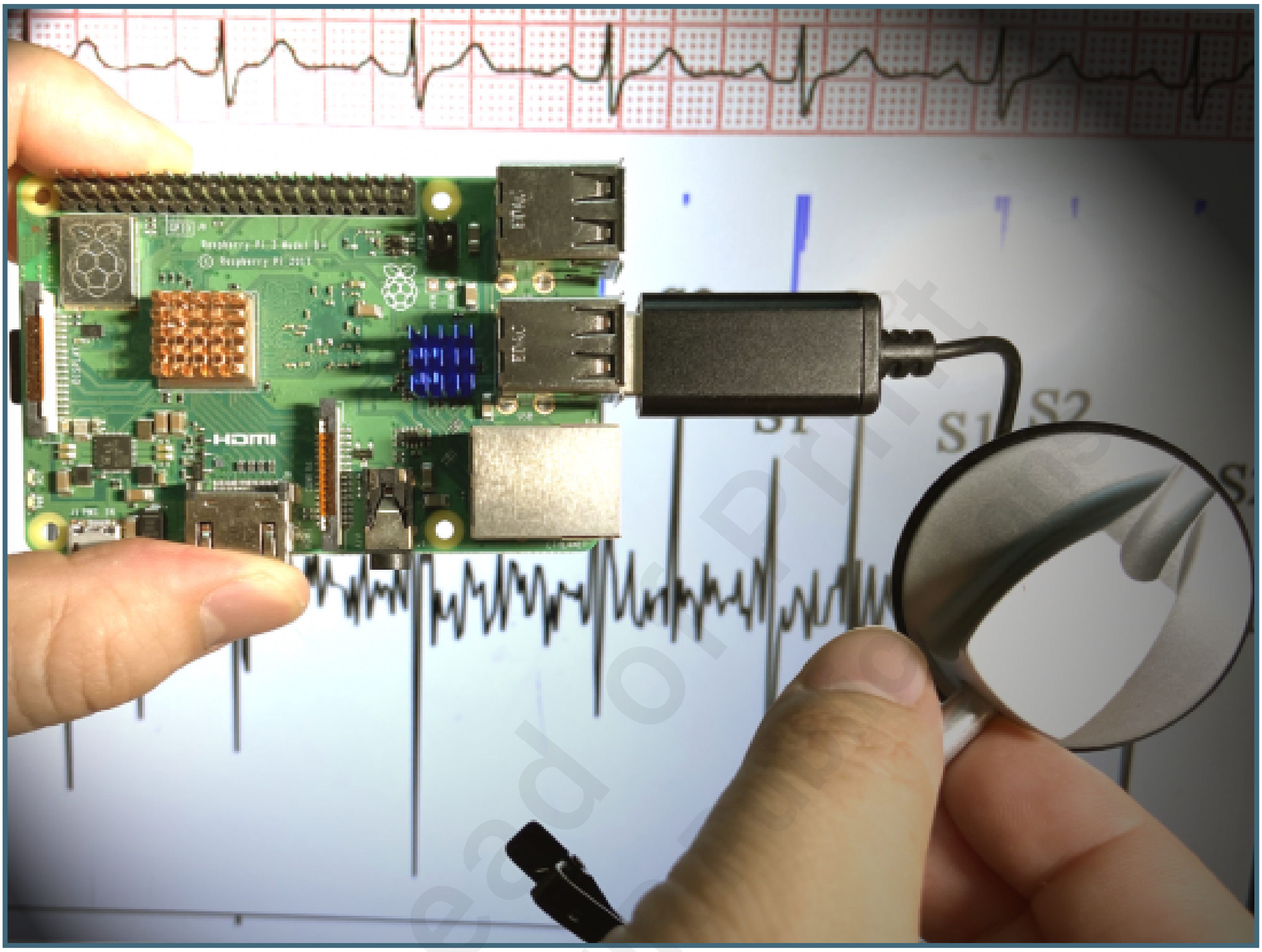
Respiratory sounds of healthy volunteer no. 9 with Auscul Pi.
URL: https://asset.jmir.pub/assets/a2d57b073d98251c633fc264fb6daf98.mp4

Heart sounds of healthy volunteer no. 9 with 3M Littmann.
URL: https://asset.jmir.pub/assets/bcafb111b055a07470c52f11fd7c9746.mp4

Heart sounds of healthy volunteer no. 9 with Auscul Pi.
URL: https://asset.jmir.pub/assets/1c39d7ddf3bf937c12d0d5e3831e8101.mp4

TOC/Feature image for homepages

An electronic stethoscope developed based on Raspberry Pi.



Clinical appearance of Auscul Pi .