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TECHNICAL NOTE

Auscultation Using Modern Mobile Communication

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Abstract This paper presents a relatively simple trial of a method for transmitting audio signals derived through auscultation. Current smartphones are widely used because of the availability of numerous new applications. On the basis of modern wireless communication technologies, such as Bluetooth, modern mobile communication systems, and modern electronic stethoscopes, we developed a real-time mobile-based auscultation (RMA) that can be applied to distant healthcare systems to improve the convenience of performing real-time auscultation on patients. We inserted a small-scale microphone attached to the earset of a smartphone (HTC Desire 626) into the ear tip of a stethoscope (3M Littmann model 3200) to transmit sound through a mobile device when the mobile dials and connects to another phone or mobile. Another smartphone (Samsung Core Prime) was used as a receiver. We investigated the signal of the received versus the signal relayed into the earphone of the transmitter in the forms of original, normalised, and spectrogram in linear scale of the signals, respectively. The respective correlation coefficients were 0.5419, 0.5419, and 0.8461 ($p < 0.01$). The correlation coefficient was higher than 0.85 ($p < 0.01$) when those signals were transmitted in decibels (dB) to the spectrogram. This high-positive correlation supports the feasibility of the RMA. The environmental noise levels ranged from 25 to 40 dB. Achieving this noise level condition by using the RMA is easy.

Keywords Acoustic signal · Lung sound · Heart sound · Mobile · Smartphone · Distant health care

1 Introduction

This study presents a simple trial of a method for transmitting audio signals derived through auscultation. Modern smartphones, such as an iPhone 6 (Apple), Galaxy Note IV (Samsung), and HTC One (HTC) are widely used because numerous new applications (apps) are available for these smartphones. According to modern wireless communication technologies, including Bluetooth, 3G and 4G mobile communication systems, and modern electronic stethoscopes, we developed a real-time mobile-based auscultation (RMA) that can be applied to distant healthcare systems to improve the convenience of performing real-time auscultation on patients.

Real-time distant health care is crucial in examining the heart and lung sounds of patients. Rene Laennec, a French physician, invented the first stethoscope in 1816 [1]. Auscultation involves listening to the internal sounds of the body. The heart, lungs, and gastrointestinal tract are frequently subjected to auscultation. Therefore, auscultation can be used to detect the physiological sounds produced by the circulatory, respiratory, and digestive systems. Doctors generally apply standard auscultation procedures for diagnoses.

Wheezes are continuous and audible, and are caused by airway wall oscillations or the narrowing of the bronchus. Continuous wheezes refer to wheezing sounds with a duration longer than 250 ms and frequency of 200 Hz [2]. According to the Computerised Respiratory Sound Analy-

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sis guidelines, the new definition of a continuous wheeze is a wheezing sound with a dominant frequency greater than 100 Hz and duration of approximately 100 ms [3]. Rhonchi are defined as continuous low-pitched sounds with a dominant frequency of approximately 200 Hz. Several researchers have proposed that the term 'rhonchi' should be abandoned or modified to describe low-pitched wheezes [4,5]. Wheeze-related conditions include bronchospasms, airway thickening caused by mucosal swelling or muscle hypertrophy, inhalation of a foreign object, tumours, secretions, or dynamic airway compression [6]. Wheezes may be monophonic or polyphonic; such wheezes are produced by severe status asthmatic patients.

This study presents the setup and measurement of RMA auscultation, which is verified according to the correlation coefficients of the signals. According to the signal measurement, we propose the helpful RMA as a solution to the real-time distant auscultation.

2 Method

Modern electronic stethoscopes support the powerful function of distant auscultation and can transfer signals to an auscultation centre, which is a functional server for collecting physiological sounds from user auscultations conducted using such stethoscopes. However, the complex settings of such stethoscopes might be a concern to medical staff. According to the promotion of distant auscultation as a 3M distant auscultation centre, we propose a highly convenient method for realising distant healthcare functions. An experienced medical doctor can easily operate this method because applying the method is as easy as dialling on a smartphone.

Figure 1 illustrates a block diagram of the RMA. The input is the electronic stethoscope (3M Littmann Model 3200), which was designed using ambient noise reduction, frictional noise dampening, electronic amplification, and Bluetooth data transfer technologies, as well as an all-new user interface. The detected sound was transferred to a personal computer (Acer, Intel Core2, Quad CPU Q8200 @2.33 GHz, 1 GB RAM, and MS XP OS), on which StethAssist (3M Littmann) was installed, and Bluetooth wireless technology was used to show and store the visualised sound signals. A small-scale earset microphone for a smartphone (HTC Desire 626) was inserted into the ear tip of a stethoscope to transmit sound through the mobile when it dials to another phone or mobile. Another smartphone (Samsung Galaxy Core Prime) was used as a receiver, which functioned as a concurrent recorder when the mobile communication was functional.

Figure 2 shows the devices used in this study. A microphone was inserted into one of the ear tubes of the electronic stethoscope to transmit sound to the mobile. Concurrently, the digitised sound data were transferred to the personal computer, on which StethAssist was installed, to show and store the visualised sound signals in the time domain. The recorder in both smartphones was an automatic call recorder, which has the flexibility of the recorded sound formats (Fig. 3). In this study, we set all the recorded sound in .wav format. The environmental noise levels were recorded using an app called 'Noise Detector', which is a free app for Google's Android operating system (Fig. 4).

Calibration generally entails conducting a comparison between standard values and measured values. However, defining real heart and lung sounds is difficult. Therefore, we used the reliable and widely applied 3M Littmann stethoscope and Bluetooth data transfer technology to define the standard values for the heart and lung sounds. Spectrograms

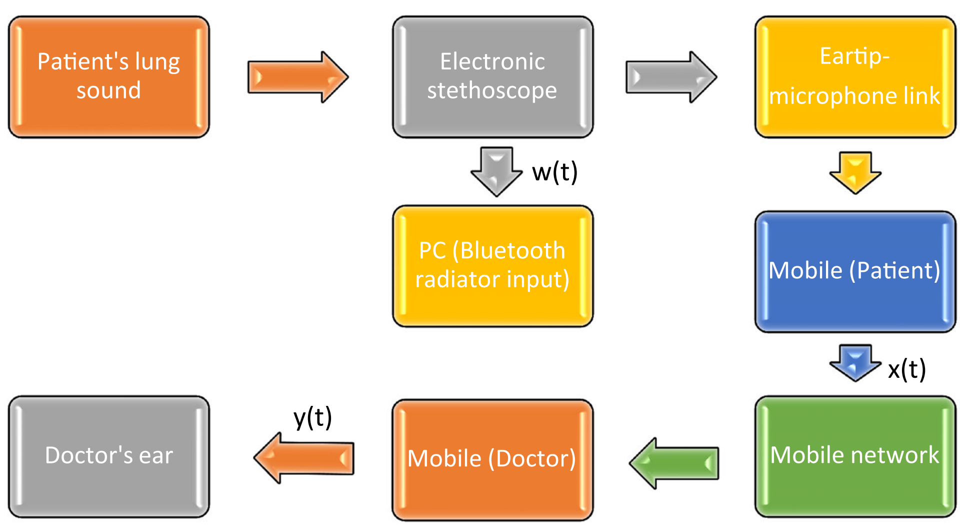

Fig. 1 The block diagram of the RMA

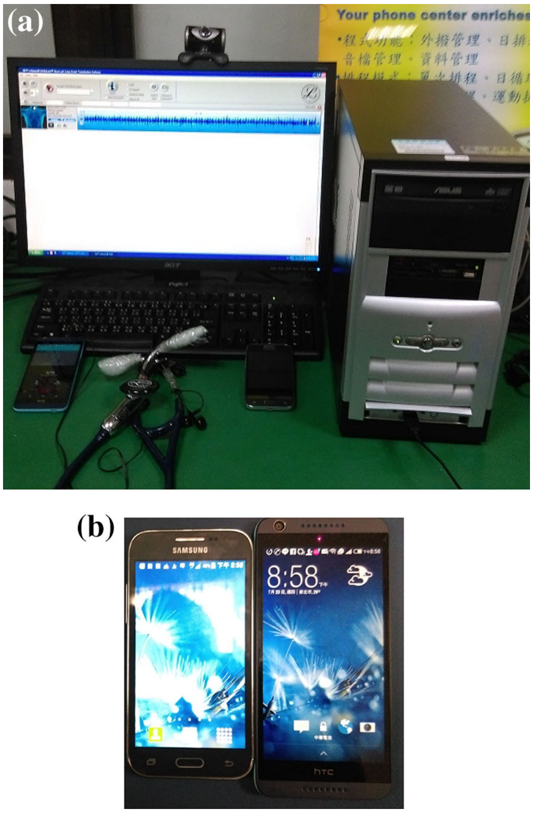

Fig. 2 The system setup of the RMA: **a** system setup, and **b** the smart phones

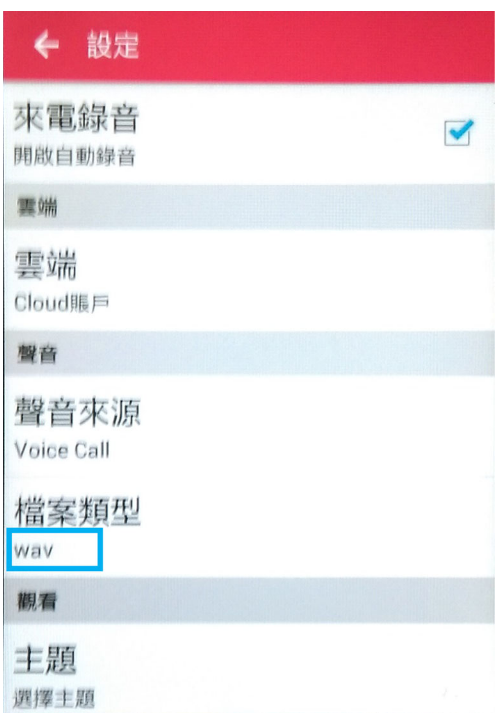

Fig. 3 The APP : “Automatic Call Recorder”

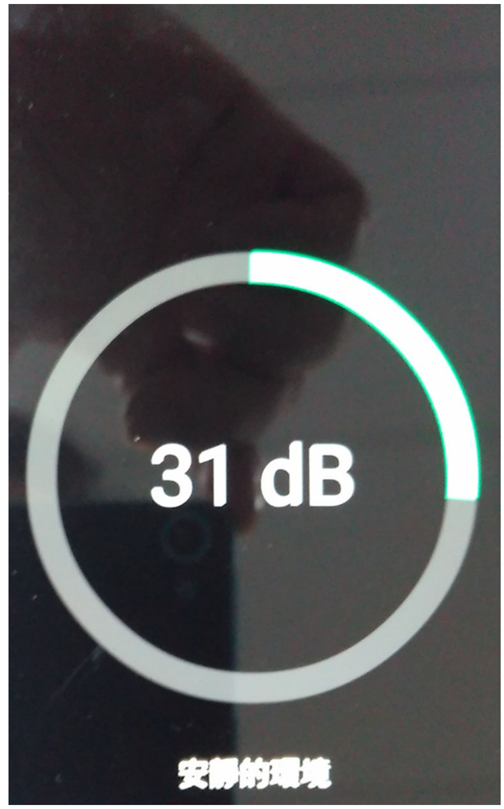

Fig. 4 The APP: “Noise Detector”

are convenient tools for speech recognition [7,8]. Such tools can be employed to analyse respiratory acoustic signals. An element at time τ in a spectrogram is defined as follows [7]:

$$|X_\tau\ (j\ \omega)|^2 = \left| \int_{-\infty}^{\infty} x\ (t)\ Ø_{\tau,\omega}\ (t)\ \mathrm{d}t \right|^2, \tag{1}$$

where $x\ (t)$ is the signal in the time domain, $Ø_{\tau,\omega}\ (t)$ is the complex basis function, and $|X_\tau\ (j\omega)|^2$ is the power distribution in the frequency domain at the time τ. This form of the Fourier transform, also called the short-time Fourier transform, has numerous applications in speech, sonar, and radar processing. The spectrogram of a sequence is the magnitude of the time-dependant Fourier transform versus time.

The comparison of the recorded sounds from the transmitter $(x(t))$ and receiver $(y(t))$ of the mobiles and the original recorded sounds $(w(t))$ were transferred through Bluetooth communication technology from the electronic stethoscope into the personal computer.

3 Results

Figure 5 illustrates a comparison of signal $y(t)$ with signal $w(t)$ (i.e. the signal of the receiver (Samsung Core Prime) v.s. the signal to the personal computer through the Bluetooth

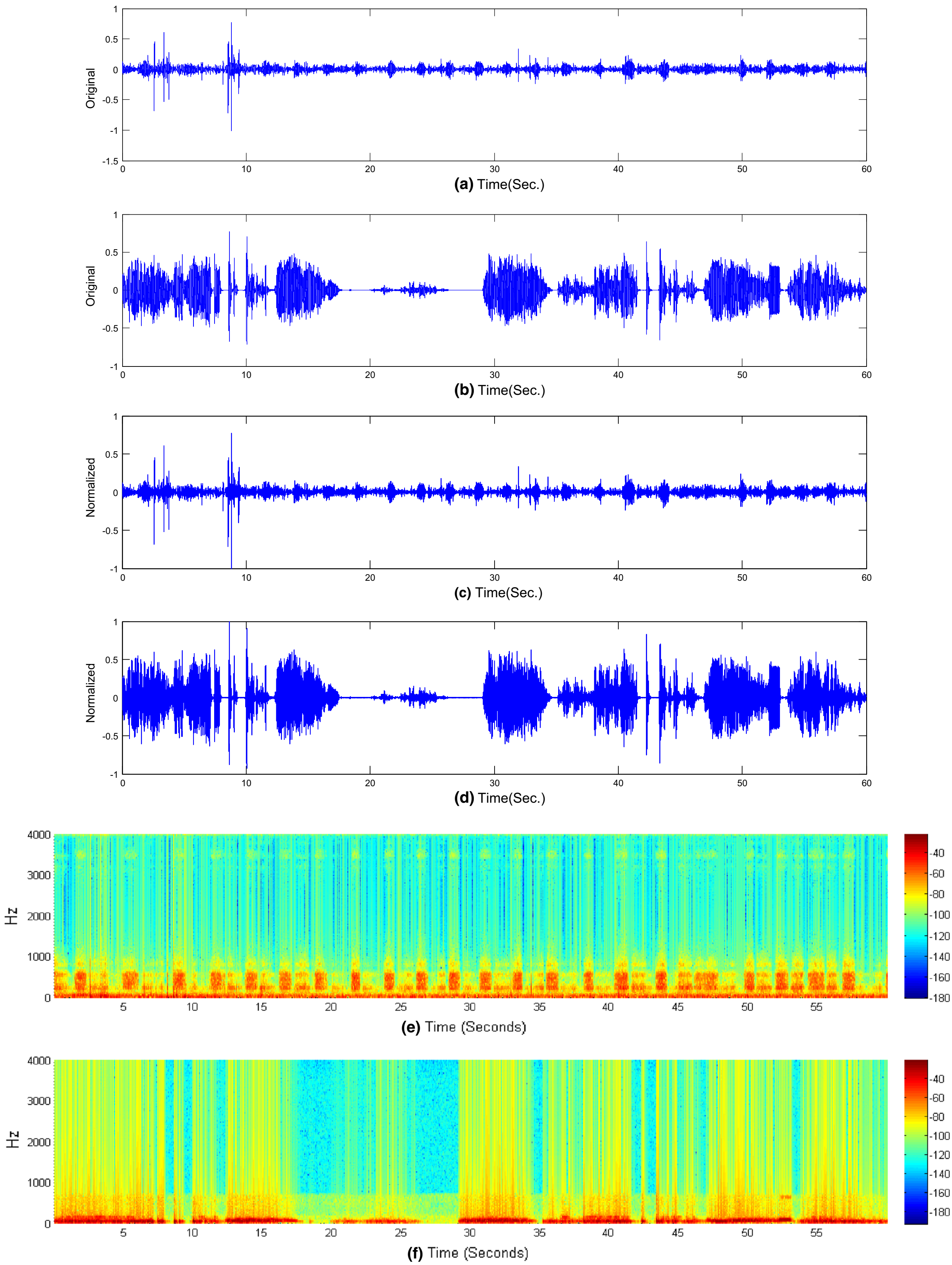

Fig. 5 $y(t)$ versus $w(t)$, i.e. the signal of receiver (Samsung$^{\text{TM}}$ Core Prime) v.s. the signal into the personal computer through the Bluetooth radiator: **a**, **c**, and **e** were the original, normalised, and spectrogram in dB of the signal $w(t)$, respectively. In addition, **b**, **d**, and **f** were those of $y(t)$

radiator): Fig. 5a, c, and e shows the original, normalised, and spectrogram values (in dB), respectively, of signal $w(t)$. In addition, Fig. 5b, d, and f shows the original, normalised, and spectrogram values (in dB), respectively, of signal $y(t)$. Signal $w(t)$ was recorded using the diaphragm filter mode of the 3M Littmann stethoscope. A 60-s duration was selected during the recording. The correlation coefficients of (a) versus (b), (c) versus (d), and (e) versus (f) were 0.0088, 0.0088, and 0.5003, respectively ($p < 0.01$, where p is denoted as a reliable interval). However, signal $w(t)$ was a real signal generated from the touched site of a patient's neck skin and not the sound listened to by the medical doctor; this is because the conventional auscultation is always conducted with the function of the mechanical amplification by the tubes.

Figure 6 illustrates a comparison of signal $y(t)$ with signal $x(t)$ (i.e. the signal of the receiver (Samsung Core Prime) versus the signal into the earphone of the transmitter (HTC Desire 620)): Fig. 6a, c, and e shows the original, normalised, and spectrogram in linear scale of signal $x(t)$, respectively. The correlation coefficients of (a) versus (b), (c) versus (d), and (e) versus (f) were 0.5419, 0.5419, and 0.8461, respectively ($p < 0.01$). The correlation coefficient was greater than 0.85 ($p < 0.01$) when $x(t)$ and $y(t)$ were transmitted into the spectrogram in dB. The high-positive correlation supported the feasibility of the RMA.

The statistical analysis of $x(t)$ and $y(t)$ verified the quality of the mobile-to-mobile communication in lung sound auscultation. A comparison between $w(t)$ and $y(t)$ revealed a high dispersion of the lung sound communication. The high-correlation coefficients of signals $x(t)$ and $y(t)$ indicated that the dispersion was caused by the small-scale microphone. Therefore, the mobile communication was proven to be satisfactory for distant auscultation.

The experienced medical doctor who is the director of the Section of Respiration, Department of Integrated Diagnostics and Therapeutics, National Taiwan University Hospital, has ausculated by the RMA and evaluated the quality of sounds. He said, "The quality of lung sound is good enough, because the medical doctor concerned the component of lung sound whose frequencies are higher than 60 Hz. However, the quality of heart sound is not as good as lung sound's. The lower frequency response needs to be enhanced". National Taiwan University Hospital which gethers the talentest medical doctors in Taiwan is one of the best hospitals in Taiwan, and some of the research fields such as internal medicine, liver cancer therapy, and medical images are famous in the world. Therefore, we believe that the RMA is reliable for the lung sound auscultation.

4 Discussion

The environmental noise levels ranged from 25 to 40 dB. Achieving this noise level condition by using the RMA is easy. The transmitter and receiver mobiles were placed in the same room; therefore, this setup can be considered an ideal case of mobile communication. A comparison of the sounds before and after the ring in a spectrogram revealed that the environmental noise was relatively low in higher frequency components and high in the lower frequency components, explaining the low correlation coefficients of signals $w(t)$ and $y(t)$. As mentioned, the high-positive correlation of signals $x(t)$ and $y(t)$ supports the feasibility of the RMA.

An excellent stethoscope assists medical doctors in detecting heart or airway problems in patients. However, abnormal sounds do not always occur from the patients. When patients visit a hospital, their major complaints are typically assessed from the time at which the patient seeks medical care; however, the onset of major problems does not typically occur at the time the patients seek medical care. The system designed in this study supports the possibility of making real-time diagnoses by enhancing the auscultation precision.

The electronic stethoscope amplified the detected sound by using electronic amplifiers to produce high-fidelity sound. Although the sound was detected using speakers, the sound quality was guaranteed, which is the key contribution of this RMA system because heart and lung sounds can facilitate the diagnosis of cardiac murmurs, mitral regurgitation, wheezing, and other cardiovascular and respiratory disorders. In the communication process, the electronic stethoscope exhibited a 4-KHz sampling rate, whereas the mobile exhibited an 8-KHz sampling rate. In our previous study [9], a theoretical proof was derived using the Fourier transform and statistical analysis; it was conducted using a computer simulation to achieve a box plot of the root-mean-square errors obtained in 100 trials for each variable. The sampling rates were 44.1, 22.05, 11.025, 5.5125, and 2.76125 KHz. The statistical results were presented in a box-and-whisker plot. The input signals were sine waves with amplitude of 1, and the frequencies were 200 Hz, 400 Hz, 600 Hz, 800 Hz, 1 KHz, 1.2 KHz, 1.4 KHz, and 1.6 KHz. The signal-to-noise ratios were 30 dB for the subjects with normal breathing and 35 dB for those presenting with wheezing. Thus, we propose 11.025 KHz as the fixed sampling rate for reducing the noise in the wheezing sounds, and as the time-variant adjusted sampling rate for optimal noise cancellation. In addition, an 8-KHz sampling rate of the mobile and Voice over Internet Protocol was evaluated to efficiently record the wheezing sounds. The sampling rate determined in this study supports the results of our previous studies [8,9]. Moreover, noise occurs because the physiological signals are typically band-limited; therefore, the optimal sampling frequency can be used to simplify the system design.

The structure of human ears is an instinctive filter; therefore, comments from the medical doctor's auscultation are the real golden rule of the sound qualities from the RMA. Therefore, the correlation coefficient was higher than 0.85

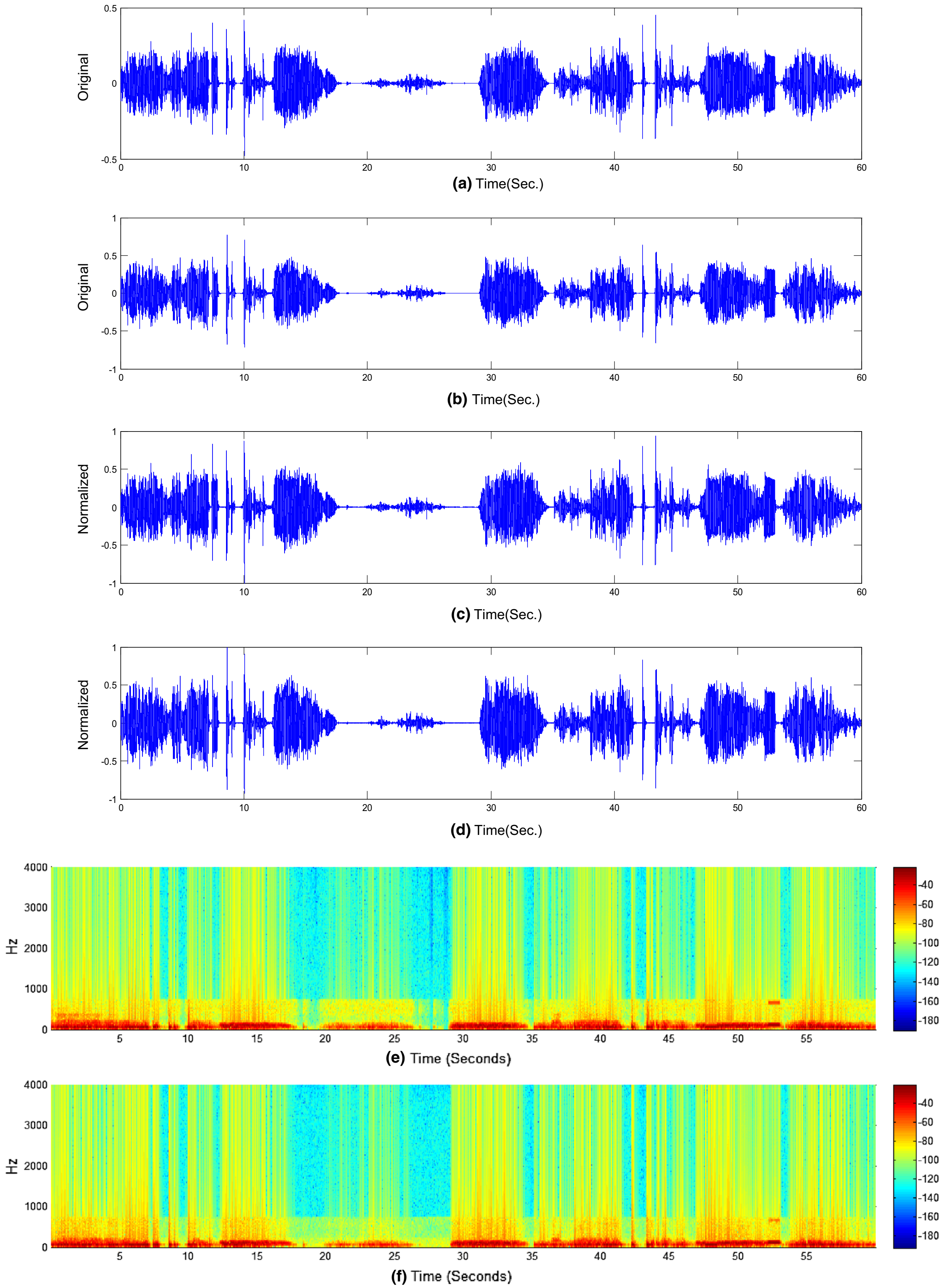

Fig. 6 $y(t)$ versus $x(t)$, i.e. the signal of receiver (Samsung^{TM} Core Prime) versus the signal into the earphone of transmitter (hTC^{TM} Desire 620): **a**, **c**, and **e** were the original, normalised, and spectrogram in dB of the signal $x(t)$, respectively. In addition, **b**, **d**, and **f** were those of $y(t)$

($p < 0.01$) when $x(t)$ and $y(t)$ transferred into the spectrogram in dB. The high-positive correlation supports the feasibility of the RMA. This study proposed a scientific measurement method, however, not the real sound quality evaluation of the auscultation. Therefore, we are going through the clinical trials and asking for comments of the medical doctors.

5 Conclusion

This study presents a relatively simple trial of a method for transmitting audio signals derived through auscultation. This distant electronic stethoscope is an excellent tool for use in health care. According to the tests conducted in this study, we believe that the proposed system is reliable and that it can be improved by managing a database for the diagnosis-aided systems in hospitals. Therefore, we suggest that medical doctors verify the sound quality produced by this system and establish a server to manage the audio files. The auscultation technology has been developed for approximately 200 years. The communication technology makes the auscultation sounds transmittable at any time and anywhere. The proposed real-time mobile-to-mobile stethoscope functions for distant health care, and in the modern electronic era, it provides medical staff with a new method to take care of patients.

Based on the auscultation of the experienced medical doctor, we believe that the RMA is reliable for the lung sound auscultation. Several previous studies have proposed the application of Internet networking to achieve distant auscultation as we did in our research. However, because conventional telecommunication is popular and user-friendly for medical doctors, the proposed system can be easily used by medical doctors, particularly experienced doctors. We strongly suggest implementing the proposed system for the benefits of medical doctors and patients.

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