Non-Contact Heart Sound Measurement Using Independent Component Analysis

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ABSTRACT A non-contact heart sound measurement method using independent component analysis (ICA) was successfully developed, and the measured heart sound was quantitatively evaluated with the signal-to-noise ratio (SNR). There have been recent developments in the automated diagnosis of cardiovascular diseases based on the measurement of heart sounds. However, measuring heart sounds require physical restraint. Here, we propose a non-invasive and non-constrained method for non-contact measurement of heart sounds using microphones. We successfully demonstrated this method by applying ICA to multi-channel measured sounds with a microphone array. Then, we quantitatively evaluated it by measuring "pseudo heart sounds" at a distance of up to 200 mm from the source using four microphones in an anechoic chamber and a conference room. SNR was improved by increasing the number of microphones. This method could measure pseudo heart sounds even in the presence of artificial noise created by heating, ventilation, and air conditioning systems and human voices. We suggested that measurable distance can be improved by using more microphones. Moreover, we successfully measured actual heart sounds at a distance of 160 mm from the chest wall. This non-contact heart sound measurement method provided valuable information about the heart, such as visual recognition of the first (S1) and the second (S2) heart sounds.

INDEX TERMS Heart sound, non-contact measurement, microphone array, independent component analysis, signal averaging.

I. INTRODUCTION Cardiovascular disease is the most common cause of death worldwide, accounting for approximately 32% of all deaths in 2019 [1]. Heart sounds are short-lived oscillations generated when the heart’s four valves (mitral, tricuspid, aortic, and pulmonary) close and are significant biological signals indicating heart health [2]. Abnormal heart sounds indicate various cardiovascular diseases [2]. Although several studies have shown the automated diagnosis of cardiovascular diseases by analyzing measured heart sounds [3], [4], [5], these measurement methods usually involve physical restraint such as auscultation by a physician. While a few studies have shown wearable devices for heart sound monitoring [6], [7], these devices have disadvantages such as discomfort due to constant wear and the need for intermittent charging. A microphone device such as a smartphone or a smart speaker placed around the user could monitor their heart sounds daily and provide an effective non-contact method to measure heart sounds. It can enable early and automated diagnosis of cardiovascular diseases. Although previous studies have not explored non-contact heart sound measurement techniques, a few have reported non-contact heart rate measurement methods [8], [9], [10], [11]. The heart rate is also a biological signal similar to the heart sound, but it merely includes the number of heartbeats. Therefore, it does not provide information about abnormalities in the heart’s anatomy. A few reports have shown non-contact measurement of seismocardiography (SCG) using a radar [12], [13]. SCG is the chest wall vibration caused by the heartbeat and can indicate abnormalities in the heart. However, these are physically restrained methods because it requires pinpoint
targeting of the chest wall by the radar. This paper discusses a non-invasive and non-constrained method for non-contact measurement of heart sounds using microphones.

There are two main challenges in developing non-contact heart sound measurement methods. The first is the measurement issue. As the heart sound is mostly reflected at the boundary between the chest wall and the air due to their acoustic impedance difference, airborne heart sounds can be buried in ambient noise. Once the noise is superimposed, removing these and extracting the heart sound from the observed sound is difficult. The second involves issues with evaluation. In general, the measurement method is optimized based on quantitative accuracy evaluation. For example, the accuracy of the heart rate measurement can be quantitatively evaluated by comparing it with the electrocardiogram (ECG), which reflects the true heart rate value. However, the heart sound is a biological signal with no true values for two main reasons. First, the heart sound is a mixture of sounds from the four heart valves, and its waveform varies depending on the measurement location on the chest wall because of variations in the mixing ratio of these sounds. Second, the stethoscope has a unique frequency response because of its diaphragm. This characteristic is known to change based on the pressure with which it is placed onto the chest wall. Because of these reasons, stethoscopes cannot uniquely determine heart sounds and hence cannot be used to determine the true value of the airborne heart sounds. Moreover, its measurement accuracy cannot be quantitatively evaluated. Therefore, heart sound measurement methods need to be further developed.

To overcome these challenges, we considered the following approaches. The frequency range of the heart sound is approximately 10 Hz to 600 Hz [3]. The ambient noises, including very low-frequency noises due to wind and building vibrations, household appliances, and voices, have overlapping frequency ranges with heart sounds [14], [15]. Therefore, frequency filters cannot remove these noises. Furthermore, ambient noise characteristics, including the location and intensity of the sources, are also generally unknown because they change periodically. Therefore, based on their characteristics, conventional noise reduction methods cannot be used to extract heart sounds effectively. We utilized independent component analysis (ICA) [16] to address this issue. ICA is a blind source separation technique that can separate multiple superimposed sources into the original sources. ICA requires simultaneous measurement of multi-channel sounds by a microphone array. The number of microphones corresponds to the number of noises removed by ICA. Recent studies have used ICA to enable speech separation for speech recognition [17], [18]. A significant advantage of ICA is that it processes data without a priori information about the sound sources. Therefore, we propose separating the heart sound from ambient noises using ICA for non-contact heart sound measurement (Fig. 1).

To circumvent issues with evaluation, we generated pseudo heart sounds and used them as true values. We then reproduced the airborne heart sound measurement environment to quantitatively evaluate the accuracy of the non-contact heart sound measurement. Previous studies have utilized ICA to remove noises such as lung sounds from heart sounds measured using contact methods like stethoscopes [19], [20], [21], [22], [23], [24]. However, since there are no true values for heart sounds, the accuracy could not be quantitatively evaluated.

Here, we developed a non-contact heart sound measurement method using ICA and evaluated its performance quantitatively. This is a preliminary report on non-contact heart sound measurement using microphones.

II. MATERIALS AND METHODS

A. REPRODUCTION OF AIRBORNE HEART SOUND MEASUREMENT ENVIRONMENT

The pseudo heart sound, used as the true value for evaluation, was generated as follows. First, the waveform of the airborne heart sound was verified. Even when microphones were placed in the air, heart sounds could not be captured because they were buried in noise. Therefore, the quasi-periodicity of the heart sound and the ECG were utilized. The minute potential changes in the ECG can be detected by [25] synchronously averaging it based on its R waves (referred to as R henceforth) to attenuate asynchronous noises. R is the strongest component of the ECG caused by myocardial excitation and is generally used for heart rate detection. We also synchronously averaged heart sounds by simultaneously measuring the R. Heart sounds are quasi-periodic signals where the period between one R and the next forms a cycle. Therefore, this process only amplifies the signal synchronizing with the quasi-period while other signals, including environmental noises, were attenuated. The heart sound and ECG were measured in an anechoic chamber. The heart sound is measured using a microphone (MI-1271 and MI-3170, Ono Sokki Co., Ltd., Yokohama, Japan) kept 30 mm away from the chest wall without clothing. A band pass filter (BPF, 10 Hz to 600 Hz, Butterworth, 10th order) then extracts the frequency range of the heart sound. ECG is measured using a 3-point induction method with an ECG monitor (AD8232 SparkFun Single Lead Heart Rate Monitor, SparkFun Electronics, Niwot, Colorado, USA). The measured ECG is preprocessed, including the power supply.
noise reduction and smoothing, to amplify R. The extracted airborne heart sound, referred to as “pseudo heart sound,” retains all the components of the actual airborne heart sound following the ECG.

Next, we reproduced the environment to measure the heart sounds by outputting the pseudo heart sound at the same pressure as the actual heart sound using a subwoofer, which was a plane source with a diaphragm (200 mm in diameter). The attenuation characteristics of a plane source and a point source were the same at measurement distances greater than 64 mm (≈ 200/π mm). As the heart (specifically, the four valves) is considered closer to a point source than a subwoofer, it is safe to assume that a subwoofer can reproduce the sound pressure of the actual heart sound at a distance of 64 mm or more. The amplitude of the pseudo heart sound was adjusted to equal to the sound pressure of actual heart sounds for a measurement distance of 64 mm or more. However, the sound pressure could not be calculated since the actual heart sound could not be measured. Therefore, a BPF (25 Hz to 45 Hz, Butterworth, 10th order) was applied to the observed actual heart sound to extract the heartbeat component from it, and its amplitude value was considered as the sound pressure. While the BPF could extract the heartbeat component, it could not extract the heart sound because it discarded valuable information about the heart at most frequency ranges.

**B. EVALUATION OF THE ACCURACY OF HEART SOUND EXTRACTION**

By generating the pseudo heart sound and reproducing the non-contact heart sound measurement environment, the signal-to-noise ratio (SNR) can be calculated as

\[
\text{SNR} = 10 \log_{10} \frac{\sum_i (s[i])^2}{\sum_i (s[i] - y[i])^2}.
\]

Here, \(s[i]\) and \(y[i]\) represent the sampled pseudo heart and the sampled observed sounds, respectively. SNR denotes the power of the pseudo heart sound to the noise. In pseudo heart sound extraction, we used the pseudo heart sound output from the subwoofer as \(s[i]\) in (1) to eliminate the effect of subwoofer-specific output frequency characteristics. In actual heart sound extraction, we used the modified pseudo heart sound as \(s[i]\) in (1). The modified pseudo heart sound was generated by sweeping the occurrence interval and amplitude ratio between S1 and S2 to eliminate the effect of respiratory variation of the actual heart sound. The highest SNR of all swept pseudo heart sounds is considered a conclusive SNR. This SNR is called quasi-SNR because the modified pseudo heart sound is not strictly a true value.

Evaluating the success or failure of the pseudo heart sound measurement is important. The SNR and quasi-SNR calculated for the ambient sound without the heart sound are −6.01 ± 1.17 dB and 1.39 ± 0.494 dB, respectively. These values indicate the mean and 95% confidence interval, respectively. SNR below the upper confidence interval limit indicates no heart sound information. Therefore, SNR below −4.84 dB (for pseudo heart sound extraction) and 1.65 dB (for actual heart sound extraction) is considered a failed heart sound extraction. Conversely, an SNR of −4.84 dB and 1.65 dB or higher indicates successful heart sound extraction.

This paper mainly focuses on SNR for analysis as it is a reasonable performance measure for signal extraction and includes all other measures. For example, while other measures such as heart rate, heartbeat interval, and dominant frequency indicate the heart sound extraction efficacy, high accuracy of heart rate detection is not indicative of highly accurate heart sound extraction. This is because a different sound might have a similar cycle rate as the heart sound. The same applies to the others. Conversely, SNR completely corresponds to the accuracy of the waveform and is expected to include all other measures to ensure measurement accuracy. As other quantitative analyses are included in SNR, it enables quantitative evaluation of heart sound measurement. Although qualitative evaluation is also important, it requires medical knowledge, which is out of the scope of this paper. Therefore, we focused on quantitative evaluation with SNR.

**C. SIGNAL PROCESSING FOR HEART SOUND EXTRACTION**

Fig. 2 shows the block diagram of the proposed heart sound extraction method, including the signal processing workflow. This method uses a microphone array to obtain \(m\)-channel sound \(X[i]\). We applied BPF (10 Hz to 600 Hz, Butterworth, 10th order) to \(X[i]\) to extract the frequency range of the heart sound and obtained \(Y[i]\) that could be split into short-time segments such as \(Y[i]_i\) \(i = 1, 2, \ldots\) to reduce the effect of short duration noise. As an extremely short segment reduces its independence, we used the three-second segments empirically. ICA (FastICA [26], sklear, python) was then applied to \(Y[i]\) to separate them into sources, resulting in the \(m\)-channel output, \(Y[i]^*\). SNR was calculated for all channels of \(Y[i]^*\), and the one with the highest SNR was selected for the extracted heart sound, \(y[i]^*\).

After the extraction process, we evaluated its accuracy. The time period of the sound measured from one experiment is 60 seconds, which is split into 20 three-second segments. SNR is calculated for all the segments and expressed as mean...
and standard error. The signals are standardized by z-score normalization for SNR calculation. Specifically, the signal is subtracted by its mean and divided by its standard deviation. These processes adjust the amplitude of all signals to have a mean of 0 and a variance of 1 for every segment.

D. NON-CONTACT HEART SOUND MEASUREMENT

The non-contact measurement of the pseudo heart sound was conducted in a conference room and an anechoic chamber, a room without sound reflections. The environment of the conference room is similar to that of the actual measurement environment. The pseudo heart sound outputted from the subwoofer (SA-CS9, Sony Corporation, Tokyo, Japan) was measured with a microphone array consisting of four microphones (MI-1271 and MI-3170, Ono Sokki Co., Ltd., Yokohama, Japan). The measurement distance varied from 80 mm to 500 mm. After the sound was measured at a sampling frequency of 48 kHz, they were converted from analog to digital and saved with a data logger (DR-7100, Ono Sokki Co., Ltd., Yokohama, Japan) at a quantization resolution of 16 bits.

The experiment was conducted in a quiet environment by turning off the heating, ventilation, and air conditioning (HVAC) systems and other equipment in the conference room and shutting all the doors and windows. The room was quiet according to human hearing, with only the occasional sounds of cars outside. The experiment is also conducted in three different artificial noise conditions, including two types of HVAC operating sounds and one voice sound. The voice was generated using a loudspeaker (Companion 20 multimedia speaker system, Bose Corporation, Framingham, Massachusetts, USA).

The non-contact measurement of the actual heart sound was conducted in an anechoic chamber at a measurement distance ranging between 80 mm to 500 mm from the chest wall without clothing. During the experiment, the subject sat motionless in a chair and breathed slowly.

III. RESULTS AND DISCUSSION

A. REPRODUCTION OF AIRBORNE HEART SOUND MEASUREMENT ENVIRONMENT

Fig. 3 shows the waveforms of one cycle of the pseudo heart sound generated by averaging 1, 4, 16, 64, and 256 cycles, respectively. The duration is 0.6 s. After averaging, 256 cycles, the first (S1) and the second (S2) heart sounds, the components of typical heart sounds can be recognized using the waveform. This figure also shows the gradual enhancement of S1 and S2 as \( n \) (the averaging number) increases. The results show that the airborne heart sound can be measured even when buried in ambient noise and cannot be visually confirmed. This indicates that non-contact heart sound measurement is feasible if it can be extracted. The signal after 256 cycles of averaging is connected to itself as a 0.6 s period and used in the following experiments as the pseudo heart sound.

Fig. 4 shows the experimental attenuation characteristics of the pseudo heart sound and the actual heart sound. These amplitudes were adjusted so that the sound pressure of the pseudo heart sound output from the subwoofer was equal to that of the actual heart sound. The sound pressures for both heart sounds were plotted against the measurement distances from the source (10 mm to 200 mm). This figure shows that, as expected, the attenuation characteristics were different when the distance was below 70 mm but similar when it was above 70 mm.
Based on these results, the measurement distance was set to 80 mm or more for the following experiments.

**B. PSEUDO HEART SOUND MEASUREMENT IN THE ANECHOIC CHAMBER**

Fig. 5 (a) shows the extracted pseudo heart sound waveform using conventional BPF at a measurement distance of 80 mm in an anechoic chamber. The pseudo heart sound is buried in noise, and heart rate variability is not visible. Fig. 5 (b) shows the waveform of the extracted pseudo heart sound. Although some noise still remains, both S1 and S2 of the pseudo heart sound could be visualized, indicating that the pseudo heart sound is successfully measured. Fig. 6 (a) and (b) show spectrograms of the sound shown in Fig. 5 (a) and (b), respectively. While Fig. 6 (b) shows visible S1s and S2s, Fig. 6 (a) lacks some information about the pseudo heart sound. This might be due to the presence of plenty of noise at frequencies ranging from 10 Hz to 100 Hz, which is the same as S1s and S2s shown in Fig. 6 (a). Therefore, conventional BPF could not extract the pseudo heart sound.

Fig. 7 shows the extracted pseudo heart sound measured at a distance of 80, 160, and 320 mm, respectively. Although the sound at 80 mm has visible S1s and S2s, the one at 160 mm has only visible S1s. The one at 320 mm does not have any visible information about the pseudo heart sound. As the distance increases, the pseudo heart sound becomes quieter and gets buried in the ambient noise.

Fig. 8 shows the SNR calculation results for all measurement distances. The plot and error bar represents the mean and standard error, respectively. The horizontal dotted line indicates SNR $-4.84$ dB as the boundary of extraction success or failure. The all SNRs of “conventional BPF” is less than $-4.84$ dB regardless of the measurement distance, indicating that the pseudo heart sound could not be extracted. The SNRs of the “proposed extraction” indicate successful extractions at a distance from 80 mm to 200 mm. For example, the SNR is $14.3 \pm 0.67$ dB at 80 mm, which means that
the sound pressure of the pseudo heart sound is approximately 5.2 times greater than the noise. These results indicate that the proposed extraction method using ICA could separate the pseudo heart sound from some of the ambient noise.

Fig. 9 shows the SNRs with the number of channels, \(m\) (equal to the number of microphones) from 1 to 4. The SNR of \(m = 1\) refers to one of “conventional BPF,” as shown in Fig. 8. The significant difference between \(m = 1\) and \(m = 2\) is greater than the others. Since ICA can remove \(m - 1\) sources of directional noise, this indicates that the most affected ambient noise is considered a single source in this experiment, i.e., most noise interfering with non-contact heart sound measurement is diffusive (not directional). When \(m > 2\), SNR also slightly improved with an increase in \(m\). This means that some directional ambient noises are removed gradually. Specifically, for measuring distances of up to 200 mm, where the SNR is meaningful, the average SNR improvement is 4.67 dB when \(m\) is increased from 2 to 4. This means that increasing the number of channels of the observed sound will further improve the measurable distance of the heart sound.

C. PSEUDO HEART SOUND MEASUREMENT IN THE CONFERENCE ROOM

Fig. 10 shows the SNRs of the extracted pseudo heart sound in the conference room. The five results are plotted. “Anechoic chamber-none” is the result of the anechoic chamber experiment without artificial noise for reference. “Conference room-none” is the one from the conference room without artificial noise. The other three “conference room-type of artificial noise” are the ones in the conference room with three different artificial noises (HVAC 1, HVAC 2, and voice), respectively.

“Conference room-none” shows a comparable SNR (15.5 ± 0.792 dB at 80 mm) to “anechoic chamber-none,” even though a conference room is generally noisier than an anechoic chamber. This indicates that the effect of small directional noises, which are reduced in an anechoic chamber, does not interfere with non-contact heart sound measurements. Therefore, measuring the heart sound contactlessly in an ordinary conference room is feasible.

The SNR of “conference room-HVAC” is under 5 dB even at 80 mm. The four microphones could theoretically remove noises from the three independent sources. Therefore, we expected that “conference room-HVAC” has the same SNR as \(m = 3\), as shown in Fig. 9, if HVAC 1 and 2 were the respective sources. This result, however, shows that the HVACs and voices are not considered a single source as the reverberations from these noises are also regarded as independent sources due to their loudness. In other words, more microphones can improve SNR with loud noises.

D. ACTUAL HEART SOUND MEASUREMENT

The actual heart sound was also extracted using the proposed method. Fig. 11 shows the waveforms of the actual heart sound at distances of 80 mm, 160 mm, and 320 mm from the chest wall, respectively.
sound extracted using the proposed method following measurement in an anechoic chamber at distances of 80, 160, and 320 mm from the chest wall without clothing. The waveform at 80 mm has the characteristic S1s and S2s of actual heart sounds. For the waveform at 160 mm, only S1 could be visually recognized, while that at 320 mm had no information on the actual heart sound. This is consistent with the results for the pseudo heart sound, as shown in Fig. 7, indicating that the produced airborne heart sound measurement environment was appropriate, and the proposed method is effective for not only the pseudo heart sound but also the actual heart sound.

Fig. 12 shows spectrograms of the extracted actual heart sound, as shown in Fig. 11. The spectrogram at 80 mm had visually recognizable S1s and S2s. However, the S2 is unclear compared to the waveform in Fig. 11. S2 generally varies in intensity and timing with respiration, which might have caused the S2 attenuation at 80 mm seen in Fig. 11. However, we need to increase the number of subjects to verify this possibility. The spectrogram at 160 mm had visually recognizable S1 with some confusing noises. The spectrogram at 320 mm has no information on the heart sound. These results are consistent with the ones shown in Fig. 11.

Fig. 13 shows the quasi-SNRs of the actual heart sound. These indicate successful extractions at a distance of 80 mm and 160 mm. For example, the quasi-SNR is 8.46 ± 0.735 dB at 80 mm. These results are consistent with the visual evaluation in Fig. 11 and 12. In addition, the difference between this quasi-SNR at 80 mm and the SNR in Fig. 8 is 5.84 dB. This corresponds to the effect of time variation, including the respiratory variation of the actual heart sound that could not be eliminated by modifying the pseudo heart sound.

IV. CONCLUSION

We successfully developed a non-contact heart sound measurement method using ICA and quantitatively evaluated the measured heart sound with SNR. We applied ICA to multi-channel observed sound with a microphone array to extract minute heart sounds from copious ambient noise. We quantitatively evaluated this extraction method by reproducing the airborne heart sound measurement environment using pseudo heart sounds.

The proposed method could measure the pseudo heart sound at a distance of up to 200 mm from the source by using four microphones, while conventional BPF methods were unable to measure it even at 80 mm. The SNR is 15.5 ± 0.792 dB at 80 mm in the conference room, which was increased by 2.34 dB after adding a microphone. This method could measure the pseudo heart sound even in the presence of artificial noise, such as HVAC sounds and voices. We also suggested that more microphones improve the measurable distance. In addition, this method successfully measured actual heart sounds 160 mm from the chest wall in an anechoic chamber. The quasi-SNR is 8.46 ± 0.735 dB at 80 mm from the chest wall. This non-contact method provided important information about the heart, such as visually recognizable S1 and S2.

To our knowledge, this paper is the first to report a non-invasive and non-constrained method for non-contact heart sound measurement using microphones. This method is advantageous for daily continuous health monitoring by eliminating the need for physical constraints, wearing discomfort, batteries, and dedicated devices compared with the existing methods. Further development of this method, including increasing the number of microphones, will enable daily heart sound monitoring and early automated analysis of cardiovascular diseases.

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