Single-Channel Adaptive Noise Canceller for Heart Sound Enhancement during Auscultation

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SUMMARY In this paper, a single-channel adaptive noise canceller (SCANC) is proposed to enhance heart sounds during auscultation. Heart sounds provide important information about the condition of the heart, but other sounds interfere with heart sounds during auscultation. The adaptive noise canceller (ANC) is widely used to reduce noises from biomedical signals, but it is not suitable for enhancing auscultatory sounds acquired by a stethoscope. While the ANC needs two inputs, a stethoscope provides only one input. Other approaches, such as ECG gating and wavelet de-noising, are rather complex and difficult to implement as real-time systems. The proposed SCANC uses a single-channel input based on Heart Sound Inherency Indicator and reference generator. The architecture is simple, so it can be easily implemented in real-time systems. It was experimentally confirmed that the proposed SCANC is efficient for heart sound enhancement and is robust against the heart rate variations.

key words: heart sound, adaptive noise canceller, signal enhancement, auscultation, noise reduction

1. Introduction

Cardiac auscultation is used to diagnose anatomical problems and physiological disorders of the heart. Heart sounds acquired by a stethoscope provide important information about heart conditions. However, they are affected by breath sounds and the patient’s motion. For these reasons, auscultation is heavily dependent on the diagnostician’s skill and patients must temporarily stop breathing during auscultation. Sometimes, such as with children or during emergencies, it is difficult to improve heart sounds via noise attenuation because it is difficult to acquire clear heart sounds under these conditions.

Auscultatory sound consists of various internal body signals and varies by location. Many studies have been conducted to enhance the desired auscultatory sounds. Cortes et al. [1] and Bai et al. [2] used a two-channel adaptive filter to enhance heart sounds, and obtained good results, but the methods devised were unsuitable with a stethoscope, because a stethoscope provides one signal source but they needed two input sources. Other studies obtained good results using a single-channel filter. Anindya S. Paul et al. [3] used a modified minimum mean squared error estimator with ECG gating. This study was conducted using a single-channel but it also needed another channel for ECG signal. Tinati et al. [4] used an adaptive line enhancer (ALE) to enhance heart sounds obtained in the apex area. It was based on the periodicity and frequency of heart sounds. However, these characteristics vary with physiological variations and cardiac diseases, and the performance of the ALE decreased rapidly when physiological condition changed. One of the most recent methods was based on heart sound de-noising in wavelet domain. C. Tianhua et al. [5] used the wavelet de-noising method for heart sound enhancement. It showed good performance results, but results were dependent on the composition level.

In this paper, a single-channel adaptive noise canceller (SCANC) is proposed to enhance heart sounds during auscultation. The proposed SCANC employs a single input channel by replacing the reference signal with an alternative signal derived from the primary signal. The alternative signal was generated by the proposed reference generation method using a Heart Sound Inherency Indicator and a reference generator. To verify the performance of the proposed SCANC, two types of experiments were conducted. One experiment was to compare SCANC with ALE, quantitatively, and the other experiment was to confirm operation using an electric stethoscope. The experimental results confirmed that the proposed SCANC effectively enhanced heart sounds during auscultation and produced better results than the other methods without any restriction.

2. The proposed Single-Channel Adaptive Noise Canceller (SCANC)

Figure 1 shows a structure of the adaptive noise canceller (ANC). Let $s$ and $n_0$ be the original signal and noise, respectively. If $s$ is uncorrelated with $n_0$ and the reference signal $n'$, which is correlated with $n_0$, were possible to be acquired, ANC could optimally remove $n_0$ from the primary signal.
input signal by updating the coefficient of the adaptive filter to fit \( n' \) to be similar to \( n_0 \). Finally, \( n_0 \) can conceivably be removed from the output by the ANC.

As shown in Fig. 1 the ANC needs two different signals, but a stethoscope can acquire only one signal. Thus, to measure more signals simultaneously, more stethoscopes are needed.

A SCANC was designed based on the assumption that noises were uncorrelated with heart sounds but correlated with the noise in the primary input. Figure 2 shows a structure of the proposed SCANC.

The proposed SCANC can be divided into two parts: reference signal generation and noise cancellation. In the reference signal generation part, the reference signal is generated from a Heart Sound Inherency Indicator and a Reference generator. The Heart Sound Inherency Indicator is designed based on the properties of heart sounds, such as periodicity, larger amplitude than noises, and regular duration. It produces an indication signal which predicts a heart sound or noise.

Figure 3 shows the process of Heart Sound Inherency Indicator. Let \( p(k) \) be \( k \)-th sample of discrete-time primary input signal and \( M_p(k) \) be maximum variation of \( p(k) \), where \( k \) is every integer value for \( k > 0 \). \( M_p(k) \) is acquired from differential \( D_p(i) \) of \( p(i) \) in the fixed section \( L \), where, \( i \) is integer value for \( k - L \leq i \leq k \). An auscultatory sound is generally stable before heart sound generating thus \( M_p(k) \) only changes slightly. However, when heart sounds are generated, \( M_p(k) \) rapidly rises. The expectation \( E(k) \) for \( j \) windows of \( M_p(k) \) is less affected by changes in amplitude than \( M_p(k) \) because it is based on the mean value of \( M_p(k) \). Therefore, although the amplitude of \( M_p(k) \) rapidly increases when heart sounds are generated within auscultatory sound, it is possible to detect them using \( E(k) \). When \( M_p(k) > E(k) \), the primary signal can be regarded as heart sound, and thus, the Heart Sound Inherency Indicator is set to 0 to extract heart sounds from the primary signal.

Figure 4 shows one example of heart sound enhancement procedure using the proposed method. The window length \( L \) was 0.2 seconds according to characteristics of heart sound, and the number of windows \( j \) was 10 which was determined experimentally. Figure 4(a) shows the input signal and Fig. 4(b) shows the Heart Sound Inherency Indicator signal acquired from the proposed method. A reference generator extracts heart sounds from primary signals primary signal based on results of the Heart Sound Inherency Indicator, when the value of the Heart Sound Inherency Indicator is 1, a reference generator passes the input signal.
as a reference signal and when the value of the Heart Sound Inherency Indicator is 0, it stops passing the input signal and sets 0 as a reference signal. Figure 4 (c) shows the reference signal $R$ generated by the proposed method. As shown in Fig. 4 (c), heart sounds are almost excluded from the reference signal using the proposed method. The noise cancellation part performs the same role of the ANC. The primary input $P$ is $S + N$, where $S$ is heart sounds and $N$ is the original noises. The output of the ANC is described as $e = P - Y$. Taking expectations of both sides of equations, and realizing that $S$ is uncorrelated with $N$ and with $Y$, yields:

$$E[e^2] = E[S^2] + E[(R - Y)^2]$$  \(1\)

The signal power $E[S^2]$ will be unaffected as the filter is adjusted to minimize $E[e^2]$. Therefore, $E[(R - Y)^2]$ is also minimized. The filter output is then the best least squares estimate of the original noise \(6\).

Figure 4 (d) shows the result obtained using the proposed method. To simulate the proposed SCANC, the number of adaptive filter coefficients was set to 256 and the gain constant was set to 0.01. From the result, it was confirmed that most of heart sounds were enhanced and noises were reduced by the SCANC.

### 3. Experiment

First, an experiment was performed to confirm the performance of HSII and reference generator. The goal of HSII and reference generator is to make the reference signal $R$ uncorrelated with heart sound. Table 1 shows correlation coefficients for overall signal between heart sound and signals of system, primary input $P$ and reference signal $R$.

As shown in Table 1, the correlation coefficient of heart sound and reference signal generated by HSII and reference generator is remarkably decreased compared to that of heart sound and primary input, at all heart rates. Therefore, it is confirmed that the HSII and reference generator effectively removes heart sound and generates a reference signal for SCANC.

Then, two experiments were performed to verify the performance of the proposed SCANC. One was an experiment performed using an educational database, to compare an ALE with the proposed SCANC, quantitatively. The other experiment was performed using real data acquired from an electric stethoscope to confirm the performance of an ALE and the proposed SCANC.

First, to compare an ALE with the proposed SCANC, quantitatively, an auscultatory sounds database known heart rates was used. Figure 5(a) shows heart sounds at a heart rate of 54 beats per minute. Figure 5(b) shows a result of ALE and Fig. 5 (c) shows the result of the proposed SCANC and the quantitative results are shown in Table 2.

Table 2 shows signal to noise ratio (SNR) of experimental results at two different heart rates. Both methods effectively reduced noise at 54 bpm. However, results were quite different at 93 bpm. The performance decline of the ALE was caused by a fixed delay time, which could pose problems when the patient’s heart rate changes abruptly. Figure 6 shows the effect of a heart rate change. Figure 6 (a) shows heart sounds when the heart rate changed from 54 beats per minute to 93 beats per minute. Figure 6 (b) shows the ALE result, when delay time was fixed, and Fig. 6(c) shows the result of the proposed SCANC. Table 3 shows quantitative result. According to experimental results, the proposed SCANC efficiently removed noises, regardless of heart rate changes and provided better performance than ALE.

Next, to confirm signal enhancement performance, signals from the electric stethoscope were used. The auscultation sounds were stored using BIOPAC 36. The measurement point was at the left parasternal second intercostals space. The bit rate was 16 bits and the sampling frequency was 10 kHz. Figure 7 (a) shows the auscultation signal was

| Table 1 | Correlation coefficients between heart sound and signals of system. |
|---------|-----------------------------|
|          | 54 bpm | 93 bpm | 54 to 93 bpm |
| Coefficient between heart sound and primary input $P$ | 0.80 | 0.87 | 0.84 |
| Coefficient between heart sound and reference signal $R$ | 0.00 | 0.01 | 0.01 |

| Table 2 | Signal to noise ratio (SNR) of the two methods. |
|---------|-----------------------------|
|          | Primary input | ALE | SCANC |
| 54 bpm | 2.8 | 6.4 | 8.4 |
| 93 bpm | 4.8 | -0.1 | 10.4 |

| Table 3 | Signal to noise ratio (SNR) when heart rate changed. |
|---------|-----------------------------|
|          | Primary input | ALE | SCANC |
| SNR | 2.3 | 0.9 | 9.9 |
acquired using an electric stethoscope of adult man in his thirties. Figure 7(b) shows the result of ALE, it shows some loss of heart sounds. On the other hand, as shown in Fig. 7(c), the proposed SCANC enhanced heart sounds and reduced most of noise. From experimental results, it was confirmed that the proposed SCANC effectively removed noise regardless of heart beats and produced better results than the ALE, quantitatively and qualitatively. Furthermore, it is easy to implement in a real-time system because the proposed process is composed of simple calculations such as, summations, relative operations, and a multiplication.

4. Conclusion

Auscultatory sounds, acquired using a stethoscope, include noise generated by respiration and patients’ motion. This study proposed an SCANC that can enhance heart sounds during auscultation. To simplify ANC based on multi-channel input, a reference signal was generated from the primary input signal by the proposed reference generation method. Experimental results confirmed that the proposed SCANC efficiently removed noises and enhanced heart sounds. In addition, its architecture is so simple it can be easily implemented and used in real-time systems. Accordingly, clear heart sounds could be provided during auscultation. Therefore, we expect that the proposed SCANC will be widely utilized in various portable devices for elderly people and patients who need to observe heart conditions continuously as well as to monitor emergency cardiac situations.

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References

[1] S. Cortés, R. Jané, A. Torres, J.A. Fiz, and J. Morera, “Detection and adaptive cancellation of heart sound interference in tracheal sounds,” 28th Annual Intern. Conf. of the IEEE/EMBS, pp.2860–2863, 2006.
[2] Y.W. Bai and C.L. Lu, “The embedded digital stethoscope uses the adaptive noise cancellation filter and the type I Chebyshev IIR band-pass filter to reduce the noise of the heart sound,” Proc. 7th Intern. Workshop on Enterprise networking and Computing in Healthcare Industry, pp.278–281, 2005.
[3] A.S. Paul, E.A. Wan, and A.T. Nelson, “Noise reduction for heart sounds using a modified minimum-mean squared error estimator with ECG gating,” Proc. 28th IEEE EMBS Annu. Int. Conf., New York City, NY, Aug.-Sept., pp.3385–3390, 2006.
[4] M.A. Tinati, A. Bouzerdoum, and J. Mazumdar, “Modified adaptive line enhancement filter and its application to heart sound noise cancellation,” Proc. International Symposium on Sign, Proc. and its Applications, vol.2, pp.815–818, 1996.
[5] C. Tianhua, X. Suxia, G. Peiyuen, T. Haitao, and Y. Zheng, “The design of digital collecting system of heart sound signals based on DSP,” Biomedical Engineering and Computer Science (ICBECS), 2010 International Conference, pp.1–4, 2010.
[6] B. Widrow and S.D. Steams, Adaptive Signal Processing, Prentice Hall, 1985.