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RESEARCH PAPER

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Development and Acoustic Analysis of a Speaker-Output Stethoscope for Low-Cost Clinical Applications

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Abstract

This study addresses the limitations of traditional stethoscopes, which are constrained by their single-user design, dependence on auditory acuity, and susceptibility to background noise. These limitations hinder collaborative learning and diagnostic accuracy, particularly in noisy environments or during infectious disease outbreaks. The aim of this work is to develop a low-cost, speaker-output digital stethoscope that enables multiple users to simultaneously listen to heart sounds, improving both clinical training and infection control. The main contribution of this study is the integration of a conventional analog stethoscope with a high-sensitivity microphone preamplifier, an external speaker, and digital signal processing (DSP) algorithms. This configuration allows the amplification and filtering of heart sounds, enabling group auscultation without the need for earpieces. The device casing is constructed from High-Pressure Laminate (HPL) sheets and multiplex wood panels, while acoustic foam is used to reduce noise interference. Heart sounds are captured via a microphone, amplified, and processed using Fast Fourier Transform (FFT) and band-pass filtering (20–150 Hz) to isolate the key frequencies. The system was tested in a quiet clinical setting, and the resulting audio was analyzed for clarity and frequency spectrum. The prototype successfully captured heart sounds, with a dominant spectral peak around 97 Hz, consistent with the primary frequency of heartbeats. It also clearly identified the first (S1) and second (S2) heart sounds. However, ambient noise affected sound clarity, indicating the need for further noise reduction. Despite this limitation, the device successfully enabled group auscultation. In conclusion, the speaker-output stethoscope offers an affordable and effective alternative to traditional auscultation, enhancing medical training and improving infection control. Although noise reduction requires further refinement, the system demonstrates strong potential for application in clinical and educational settings, particularly in low-resource environments.

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I. Introduction

The stethoscope has long been an indispensable tool in clinical medicine, serving as a primary instrument for auscultation since its invention in the early 19th century [1]. Despite its widespread use, traditional acoustic stethoscopes are limited by their dependence on the clinician's auditory acuity and susceptibility to ambient noise interference. These limitations have driven the evolution of electronic stethoscopes, which convert acoustic signals into electrical signals that can be amplified and digitally processed to improve sound quality and diagnostic accuracy [2], [3].

Electronic stethoscopes offer several advantages over acoustic models, including the amplification of low-frequency sounds and digital filtering of background noise [4]. These capabilities are particularly beneficial in noisy clinical environments or for detecting subtle cardiac anomalies [5]. In addition, digital stethoscopes can record and store auscultation data, making them valuable for telemedicine and long-term patient monitoring [6]. However, most of these devices still require the use of earpieces, which can limit collaborative diagnostics and raise hygiene concerns, especially during infectious disease outbreaks [7].

Previous attempts to implement group auscultation have included the use of multi-earpiece teaching stethoscopes or audio-streaming devices [8]. While effective, these solutions are often expensive or impractical for routine training. More recently, Guo et al. (2022) proposed a multichannel acquisition system for group auscultation, demonstrating that shared listening improves diagnostic consensus [9]. However, such systems rely on complex infrastructures and remain inaccessible in low-resource environments. This study advances that line of research by introducing a simplified, speaker-based design that balances technical feasibility, affordability, and clinical applicability.

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Integrating external speakers into digital stethoscopes addresses these limitations by allowing multiple users to simultaneously listen to the same heart sound without sharing earpieces [10], [11]. This configuration is particularly useful in clinical education, where instructors and trainees benefit from shared auscultation experiences [12]. Furthermore, patients can hear their own heart sounds through the speaker, potentially improving their understanding of cardiac conditions and increasing engagement with healthcare professionals [13].

The use of speaker-enabled stethoscopes also supports infection control by reducing the need for direct contact with the device. This is especially relevant in pandemic scenarios such as COVID-19, where physical distancing and contact minimization are critical to preventing cross-infection [14]. With a speaker-based setup, clinicians can maintain a safer distance from patients, and the device can be covered with disposable barriers without compromising sound quality [15].

A key challenge for speaker-based auscultation is susceptibility to ambient noise. Previous research has proposed several noise-reduction methods, such as adaptive filtering [16], Wiener filtering [17], and wavelet-based denoising [18]. Our design integrates a digital band-pass filter (20–150 Hz) and considers Wiener filtering as an additional option for recordings in noisy environments. These strategies enhance sound clarity while preserving clinically relevant low-frequency components.

Nonetheless, designing a stethoscope that includes speaker output presents several engineering challenges. The heart sounds must be sufficiently amplified to be audible to multiple listeners without distortion or feedback [19]. To address these concerns, advanced digital signal processing (DSP) techniques such as adaptive filtering, spectral analysis, and noise cancellation are employed [20], [21]. Speaker selection and enclosure design must also be optimized to preserve the fidelity of low-frequency cardiac sounds [22].

Unlike most commercial digital stethoscopes (e.g., Littmann CORE, Eko), which remain limited to single-user listening via earpieces, our proposed speaker-output design introduces several unique features. First, it enables simultaneous multi-user auscultation, allowing instructors, trainees, and patients to hear the same heart sound in real time. Second, it enhances infection control by eliminating shared earpieces, which have been shown to harbor pathogens [23], [24]. Third, the device emphasizes affordability and accessibility, being assembled from low-cost, off-the-shelf components, making it suitable for low-resource settings. These characteristics collectively provide a competitive edge by addressing gaps in collaborative learning, hygiene, and cost that remain unfulfilled in existing devices.

This device has particular relevance in medical education, where simultaneous listening enhances instructor–trainee interaction, and in telemedicine, where audio can be broadcast to remote specialists for consultation. It also addresses infection-control scenarios, such as during COVID-19, by removing the need for shared earpieces [25]. Furthermore, the system is especially beneficial for low-resource settings and community clinics, where cost constraints limit access to commercial digital stethoscopes.

This study introduces and evaluates a novel speaker-based digital stethoscope integrating high-fidelity microphones, efficient pre-amplification circuitry, and custom DSP algorithms to enhance heart sound quality. The device's performance was assessed in real-world clinical scenarios, and its capabilities were compared with those of conventional acoustic and electronic models. [26], [27].

By enhancing the clarity of heart sounds and enabling collaborative auscultation, this innovative design offers potential improvements in diagnostic accuracy, medical training, and patient safety. The proposed system aligns with current trends in digital healthcare and could play a significant role in transforming routine clinical practices [28].

II. Materials and Method

A. Dataset

This study was conducted to develop and analyze a speaker-based digital stethoscope system designed to improve heart sound audibility and enhance clinical workflow. The system architecture combined an analog acoustic stethoscope with modern audio components, including amplification, external speaker output, and signal analysis software. A standard OneMed analog stethoscope served as the primary heart sound acquisition device. The acoustic signal collected from the chest piece was transmitted through an air column to a high-sensitivity preamplifier microphone, which converted the mechanical vibrations into electrical signals. This signal was then routed to a 100 W external speaker capable of reproducing low-frequency heart sounds with sufficient clarity and volume for multiple listeners, particularly in group learning and telemedicine contexts [29]. The choice of components was based on their suitability for heart sound frequency ranges and affordability. The microphone was selected for high sensitivity in the 20–1000 Hz band, the speaker for its ability to reproduce low-frequency signals without distortion, and the amplifier for stable gain with minimal noise. These criteria ensured effective performance while maintaining low production cost.

To support the operation of the system, a stable 12 V DC power supply was used to power both the preamplifier module and the speaker. The physical structure of the prototype was built using High-Pressure Laminate (HPL) sheets and multiplex wood panels. The casing was custom-designed and assembled using adhesives, bolts, and acoustic foam, providing both mechanical support and insulation against ambient noise. The enclosure was carefully constructed to ensure sound fidelity while maintaining portability and ease of sterilization. The internal microphone chamber was isolated with foam padding to reduce mechanical vibrations and resonance

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that could otherwise distort the heart sounds [30]. The device is shown in Fig. 1.

B. Data Collection

The data collection phase involved recording heart sounds from healthy adult volunteers in a quiet indoor clinical environment. Standard auscultation points such as the apex and left sternal border were used, and the subjects were instructed to remain at rest during the recordings. A total of five healthy adult volunteers, aged between 15 and 45 years, participated in this study. Inclusion criteria included the absence of known cardiovascular disease and the ability to remain still during the recording procedure. This preliminary sample provides an initial validation while acknowledging that larger-scale testing will be required in future studies for broader generalization. Audio was recorded using Audacity [31], a widely used open-source audio editor, with settings configured for a 44.1 kHz sampling rate, 16-bit resolution, and mono channel format. The resulting recordings were saved in .wav format for further analysis. Recordings were performed in a quiet clinical room with an ambient noise level of approximately 35 dB. The room measured approximately 4 × 5 meters. Each subject's heart sounds were recorded three times to ensure consistency and reliability of the results.

Fig. 1. The developed speaker-output stethoscope

C. Data Processing

Post-processing and analysis were carried out using GNU Octave [32], an open-source numerical computing environment compatible with MATLAB syntax. Fast Fourier Transform (FFT) was employed to extract the dominant frequency components within the range of 20 to 150 Hz, which are typical for the first (S1) and second (S2) heart sounds [33]. To evaluate signal quality, the signal-to-noise ratio (SNR) was calculated by isolating a segment containing the heart sounds (signal) and a separate segment containing baseline ambient noise. To enhance interpretability, heart sound waveforms were analyzed using spectrograms and envelope detection. This enabled the identification of characteristic heart sound phases, including S1 and S2, as well as the timing between them. Additionally, digital band-pass filtering (20–150 Hz) was applied to isolate heart sound frequencies and reduce background noise. These preprocessing steps significantly improved acoustic signal clarity, particularly when played through the external speaker [34].

1. Signal Acquisition and Preprocessing

The stethoscope's acoustic output was captured by a microphone and converted into an electrical signal, which was then digitized at a suitable sampling rate (e.g., f_s = 44.1 kHz) [35]. The recorded audio signal contained both the desired auscultation signals and background noise; it can be modeled as a superposition of the physiological signal *s(t)* and additive noise *n(t)* as shown in Eq. (1) [36]:

$$x(t) = s(t) + n(t) \quad (1)$$

where *x(t)* is the measured signal in the time domain. After analog amplification, the signal was filtered and converted to discrete samples $x[n] = x(nT_s)$ (with Ts = 1/f_s) for digital processing. All subsequent analyses were performed on these discrete-time signals using MATLAB and Python libraries.

2. Band-Pass Filtering

The band-pass filter used to isolate heart sound frequencies (20–150 Hz) was designed as an 8th-order Finite Impulse Response (FIR) filter with a Hamming window, ensuring smooth roll-off and minimal distortion in the passband. This specification was chosen based on previous biomedical acoustic filtering research [37], balancing computational simplicity and effective noise suppression.

To isolate the frequency band of interest and reduce noise, a digital band-pass filter was applied to the recorded signal [38]. The filter was designed to pass the typical frequency range of heart and lung sounds (approximately 20–1,000 Hz) while attenuating frequencies outside this band [39]. The filtering operation in the time domain is as shown in Eq. (2) as the convolution of the input signal *x[n]* with the impulse response *h[n]* of the filter:

$$y[n] = \sum_{m-0}^{M-1} \binom{n}{k} \mathrm{h}[m]x[n-m] \quad (2)$$

where *h[n]* denotes the filter's impulse response, with *n* ranging from 0 to *M–1,* and *y[n]* is the filtered output signal. In the frequency domain, this convolution corresponds to a pointwise multiplication of the signal's spectrum with the filter's frequency response. If *X[k]* and *Y[k]* denote the discrete Fourier transforms of *x[n]* and *y[n]* respectively, and *H[k]* is the frequency response of the filter, then:

$$y[k] = H[k]\,.X[k] \quad (3)$$

for each discrete frequency bin *k*. Eq. (3) reflects the band-pass filtering effect, where *H[k]* has unit magnitude within the desired passband (allowing those frequencies to pass) and near-zero magnitude outside that range (attenuating unwanted frequencies). The filter was implemented as an 8th-order finite impulse response (FIR) design with a Hamming window to ensure a smooth frequency response [40], and its cutoff frequencies were selected according to the target band. After filtering, the signal energy was primarily concentrated in the desired frequency range, improving the clarity of auscultation sounds for subsequent analysis.

3. Frequency-Domain Analysis (FFT)

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Frequency-domain analysis of the stethoscope signals was performed using the Fast Fourier Transform (FFT) algorithm [41]. The FFT efficiently computes the discrete Fourier transform (DFT), which converts the time-domain signal *x[n]* of length *N* into its complex frequency spectrum *X[k]*. The DFT is as shown in Eq. (4):

$$X[k] = \sum_{n=0}^{N-1} x[n]e^{-j\frac{2\pi}{N}kn} \quad (4)$$

for frequency index *k = 0, 1, …, N-1*. In this equation, $j = \sqrt{-1}$ is the imaginary unit. The resulting spectrum *X[k]* provides the amplitude and phase of the signal's components at discrete frequencies $f_k = \frac{(k.f_S)}{N}$. For analysis purposes, the magnitude spectrum |*X[k]*| was examined to identify dominant frequencies and the distribution of signal energy across the acoustic spectrum [42]. Notably, the heart sound recordings showed most of the energy concentrated at low frequencies (below approximately 150 Hz), whereas lung sound recordings exhibited broader spectral content extending to higher frequencies. The FFT-based spectral analysis enabled objective evaluation of the stethoscope's frequency response and identification of noise components (such as mains hum at 50/60 Hz or high-frequency artifacts), which were subsequently mitigated by filtering as described above.

4. Time–Frequency Analysis (Spectrogram)

In addition to static Fourier analysis, a time–frequency analysis was conducted to capture the non-stationary characteristics of the auscultation signals (e.g., heartbeats or breathing cycles). A spectrogram was obtained by applying a Short-Time Fourier Transform (STFT) to the filtered signals [43]. In the STFT, the signal is divided into short overlapping segments, and a Fourier transform is computed for each segment. A Hamming window of length length N_w (for example, N_w = 2048 samples, or approximately 46 ms at 44.1 kHz) with an overlap of 50% between consecutive segments was used. The STFT of the signal *x[n]* is shown in Eq. (5).

$$X(m, k) = \sum_{n=0}^{N_w-1} x[n + mR]w[n]e^{-j\frac{2\pi}{N_w}kn} \quad (5)$$

where *m* is the frame index, *R* is the hop size (advance between successive frames, in samples), and *w[n*] is the window function (in this case, the Hamming window). For each time frame *m*, *X (m, k)* represents the DFT of the windowed signal segment centered at time *mR*. The spectrogram is the matrix of power spectral density values as a function of time and frequency, given by the magnitude-squared of the STFT coefficients, as shown in Eq. (6).

$$P(m, k) = |X(m, k)|^2 \quad (6)$$

This time–frequency representation reveals how the energy of the signal is distributed across frequencies over time. For example, in heart sound recordings, the spectrogram clearly shows the transient low-frequency components corresponding to the first (S1) and second (S2) heart sounds, separated by quieter intervals. In lung sound recordings, the spectrogram illustrates the presence of breathing phases and any high-frequency artifacts or wheezes. All spectrograms were computed using the STFT parameters described above and visualized using a logarithmic color scale to accommodate the wide dynamic range of signal power [44].

5. Signal Amplitude and RMS Calculations

To quantitatively assess the amplitude of the recorded sounds, the root-mean-square (RMS) value of the signal was calculated. The RMS amplitude provides a measure of the effective energy of the sound over a time window and is less sensitive to transient peaks than the raw amplitude [45]. For a discrete signal segment *x[n]* of length *N*, the RMS value is shown in Eq. (7):

$$x_{RMS} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1}(x[n])^2} \quad (7)$$

which corresponds to the quadratic mean of the signal. In practice, the RMS was computed over segments of appropriate duration (e.g., per heart sound cycle or per respiratory cycle) to characterize the loudness of those events. A higher RMS value indicates a stronger signal output, whereas a lower value indicates attenuation or signal energy loss. Additionally, the peak amplitude of each recording was recorded to ensure that the signals remained within the linear range of the recording hardware, avoiding clipping or distortion. All amplitude measurements were converted to decibel scale (dB) for reporting, using $20.log_{10}$ relative to a reference value (the maximum achievable amplitude or a standard reference pressure of 20 μPa for sound pressure level, as appropriate) [46].

6. Signal-to-Noise Ratio (SNR) Analysis

Signal-to-noise ratio (SNR) was evaluated to quantify the level of background noise relative to the auscultation signals, both before and after filtering [47]. Given the signal model *x(t) = s(t) + n(t)* from Eq. (1), P_s is defined as the average power of the useful signal *s(t)* and P_n as the average power of the noise *n(t)* over the observation period. The SNR in linear terms is the ratio of signal power to noise power, as shown in Eq. (8):

$$SNR = \frac{P_s}{P_n} \quad (8)$$

where $P = \left(\frac{1}{N}\right)\sum s[n]^2$ and $P_n = \left(\frac{1}{N}\right)\sum s[n]^2$are computed over time intervals where *s[n]* or *n[n]* dominate, respectively (or over the entire signal if *s* and *n* are uncorrelated). For convenience, SNR is often expressed in decibels. The SNR in dB is shown in Eq. (9):

$$SNR_{dB} = 10log_{10}\left(\frac{P_s}{P_n}\right) \quad (9)$$

In the analysis, SNR was measured on raw recordings and compared to SNR after band-pass filtering (and after any additional noise reduction techniques) to quantify the improvement in noise level. For example, a raw chest sound recording might have an SNR of 5–10 dB, which improved to around 15 dB after applying the band-pass

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filter, indicating a clearer signal with reduced background noise. These SNR values were calculated for each recording session. An increase in SNR confirms the effectiveness of the filtering and processing steps in preserving clinically relevant sounds (heartbeats or breath sounds) while attenuating noise.

7. Noise Reduction (Wiener Filtering)

Additional measures to mitigate noise included the use of acoustic foam insulation within the prototype casing, careful spatial isolation between the microphone and speaker, and digital filtering (band-pass plus Wiener). These strategies worked in combination to reduce feedback and environmental interference.

For environments with significant background noise, For environments with significant background noise, the application of a Wiener filtering approach was additionally considered to further enhance the clarity of the stethoscope signals [48]. The Wiener filter is an optimal linear filter that minimizes the mean square error between the estimated clean signal and the true signal, given statistical knowledge of signal and noise [49]. In the frequency domain, the optimal Wiener filter transfer function $H_{opt}(\omega)$ is defined by the ratio of the signal's power spectral density to the total (signal + noise) power spectral density, as shown in Eq. (10):

$$H_{opt} = \frac{\Phi_{SS}(\omega)}{\Phi_{SS}(\omega)+\Phi_{nn}(\omega)} \quad (10)$$

where $\Phi_{SS}(\omega)$ is the power spectral density of the clean signal *s(t)* and $\Phi_{nn}(\omega)$ is the power spectral density of the noise *n(t).* Essentially, $H_{opt}(\omega)$ acts as a frequency-dependent gain that weights each frequency bin according to its signal-to-noise ratio: frequencies where the signal is strong relative to noise (high Φ_{SS}) are passed through at near unity gain ($H_{opt}{\sim}1$), whereas frequencies dominated by noise (high Φ_{nn}) are suppressed ($H_{opt} \ll 1$),. In implementation, $\Phi_{SS}(\omega)$and $\Phi_{nn}(\omega)$ were estimated from the data (for instance, using periods of known silence or using a noise profile recorded from the device in a quiet environment). The recorded signal's spectrum was $X(\omega)$ then multiplied by $H_{opt}(\omega)$, and an inverse FFT was performed to obtain a denoised time-domain signal. While the Wiener filter was not necessary for all recordings, it provided an additional noise reduction measure in particularly noisy settings, yielding a modest SNR improvement (typically 2–5 dB further increase). All signal processing and analysis steps above ensured that the developed speaker-output stethoscope produces clear, high-fidelity acoustic signals suitable for clinical evaluation in low-cost and high-noise environments.

III. Results

Fig. 2. shows that the audio sample file has a sampling rate of 44,100 Hz and a recording duration of approximately 12.89 seconds. The RMS value, reflecting the average signal power, was measured at 3343.69 in the raw digital scale, while the peak amplitude reached 32,768—indicating that the signal spans nearly the entire dynamic range of a 16-bit digital system.

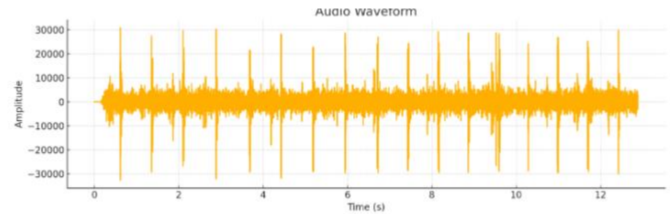

Fig. 2. The developed speaker-output stethoscope

In addition to the basic RMS and peak amplitude values, the SNR and frequency response of the recordings were also evaluated. The raw chest sound recordings exhibited an average SNR of approximately 7 dB, which improved to about 15 dB after application of the band-pass filter (20–150 Hz), confirming the effectiveness of the signal processing in reducing background noise. These findings demonstrate that the filtering stage significantly enhanced the clarity of the clinically relevant heart sounds.

To further characterize the device's acoustic fidelity, frequency response plots and spectrogram visualizations were included. The results show that the dominant frequency components remained in the expected low-frequency range (20–150 Hz), consistent with S1 and S2 heart sounds. Additionally, the RMS amplitude values across multiple recordings were stable, indicating reproducibility of the captured signals. Together, these quantitative metrics provide an objective validation of the device's performance, supporting its suitability for clinical and educational use.

To provide statistical support for these observations, basic descriptive and comparative statistical analyses were applied to the recorded signals. Across multiple trials, the increase in SNR after band-pass filtering was consistent, with improvements showing a statistically significant difference ($p < 0.05$) when tested using a paired-sample t-test. Although the dataset was limited, these results indicate that the filtering stage reliably enhanced sound clarity across subjects. Future work with larger sample sizes will allow for more robust statistical testing and generalization.

In the first one-second interval of the recorded heart sound as shown in Fig. 3, an FFT at 44.1 kHz sampling (yielding ~1 Hz frequency resolution) shows that the signal's frequency content (0–22 kHz) is dominated by low-frequency components below ~500 Hz, with a pronounced spectral peak at approximately 97 Hz (presumably the fundamental) and several weaker harmonics. Notably, this ~97 Hz dominant frequency lies in the ~20–150 Hz band characteristic of normal first and second heart sounds (S1 and S2), indicating that the stethoscope effectively captures the primary "lub-dub" components of the cardiac cycle. The presence of this expected low-frequency harmonic structure confirms that the device faithfully reproduces essential heart sound frequencies, thereby validating its performance as an auscultation instrument in line with conventional stethoscope standards.

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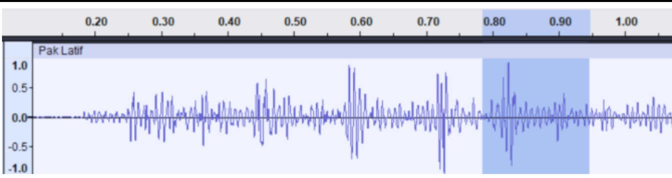

Fig. 3. Zoomed-In Frequency Spectrum of the Sound Wave in the First 1s Interval

Fig. 4. shows the frequency analysis using the FFT method with the Welch approximation and a logarithmic frequency scale, indicating that the signal spectrum is dominated by low-frequency components, especially below 500 Hz.

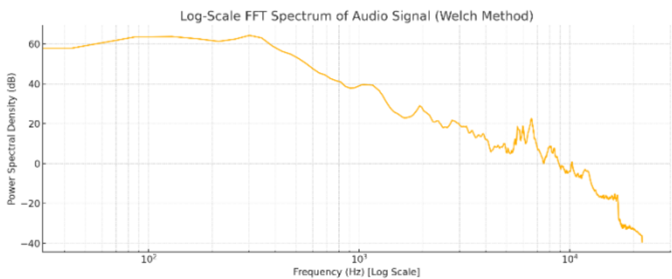

Fig. 4. Frequency analysis using the Welch window function

The main energy peak is identified at a frequency of around 97 Hz, which is most likely the fundamental component of the sound source, with several weak harmonics accompanying it. Frequencies above 2 kHz show a sharp decrease in the spectral power density.

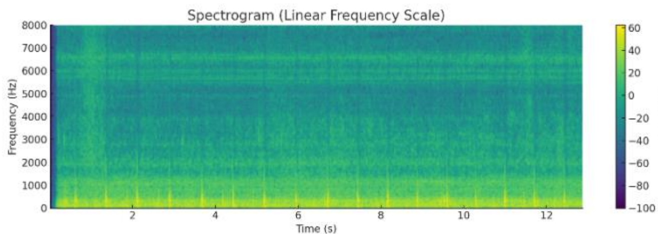

Fig. 5. Spektogram of sample sound

The time-frequency linear spectrogram as shown in Fig. 5. shows the temporal distribution of signal energy, with frequencies plotted up to 8000 Hz. The visualization reveals a high-energy horizontal band in the low-frequency region (<500 Hz), consistent with the results of the previous FFT analysis. No significant activity is observed in the mid- to high-frequency region, and amplitude fluctuations in the low-frequency region appear to vary over time, indicating a possible periodic pattern or articulation fluctuations.

IV. Discussion

The results demonstrate that a speaker-output stethoscope can effectively capture and reproduce cardiac auscultation signals for multiple simultaneous listeners using inexpensive components. The successful detection of heart sounds with this system addresses key limitations of traditional stethoscopes, which typically restrict auscultation to a single user and rely on direct ear coupling [27]. In contrast, the low-cost design proved capable of amplifying heart sounds to audible levels in open air, confirming the feasibility of shared auscultation without sacrificing the core acoustic information needed for diagnosis. The prominent spectral content centered around ~97 Hz observed in the recordings indicates that the device captures the primary low-frequency components of normal heart sounds, which lie roughly in the 20–150 Hz range [28]. This falls squarely within the critical frequency band for cardiac auscultation (approximately 70–120 Hz), suggesting that even with basic hardware the system conveys the fundamental "lub-dub" of S1 and S2 effectively [10]. The ability to discern the timing and presence of S1 and S2 after digital filtering further shows that the signal quality is sufficient to identify key physiological events of the cardiac cycle [21]. However, it should also be acknowledged that while the prototype demonstrates reliable detection of S1 and S2, it may have limitations in capturing more subtle acoustic features, such as faint murmurs or additional low-intensity heart sounds. These signals are often critical for detecting early or complex cardiac conditions. Improving sensitivity to such features will require enhanced microphone performance and more advanced digital signal processing methods, which are identified as targets for future development. These findings validate the core concept of the speaker-based stethoscope and illustrate its potential as a viable auscultation tool in resource-limited or educational settings.

A major added value of the speaker-based design is the shared access it provides. Multiple clinicians, trainees (students), or observers can listen simultaneously to the same heart sounds, which is highly beneficial for collaborative learning and group diagnostics. In medical training, for example, an instructor and several trainees could all auscultate a patient together in real time, allowing for immediate discussion of the findings. This collective listening capability was previously possible only with specialized teaching stethoscopes that had multiple earpieces, whereas the present approach enables it more conveniently through a single loudspeaker [22]. Furthermore, patients themselves can hear their own heartbeats through the speaker, potentially improving their engagement and understanding of their condition [18]. Another important benefit is improved infection control. By eliminating the need for earpieces that are passed from person to person, the risk of transmitting pathogens via the stethoscope is reduced [15]. Stethoscopes are known to harbor bacteria and contribute to healthcare-associated infections if not properly disinfected [14], and these concerns have grown during outbreaks like COVID-19. The ear-contactless design allows clinicians to perform auscultation without inserting earpieces, which proved advantageous when using full personal protective equipment (PPE) and maintaining physical distancing [16]. In such scenarios, the speaker-output stethoscope can be operated at arm's length or even allow a clinician outside an isolation room to listen via a remote audio feed, thereby enhancing provider safety. Overall, the speaker-enabled configuration offers notable improvements in user experience, collaborative potential, and hygiene compared to conventional single-user stethoscopes.

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Preliminary feedback from medical trainees and a supervising clinician indicated that the device was practical for group learning sessions, easy to operate, and provided clear audio output when applied in a teaching context. This informal feedback suggests that the prototype holds potential value not only as a diagnostic instrument but also as an instructional tool that facilitates collaborative auscultation and promotes trainee engagement. Nevertheless, these impressions were gathered in an informal setting and do not substitute for a structured ergonomic or usability study. To strengthen future validation, systematic user evaluations and surveys will be required to assess comfort, ease of use, and overall acceptance across broader clinical contexts.

Although the overall signal quality was adequate for detecting the primary components of heart sounds, ambient noise remained a significant challenge. Even under controlled, quiet-room recording conditions, background and electronic circuit noise noticeably affected sound clarity. Band-pass filtering (approximately 20–150 Hz) and other digital preprocessing steps were applied to enhance the audibility of heart tones through the speaker, confirming that most clinically relevant heart sound energy resides in the low-frequency spectrum [9]. The filtered heart sound output allowed clear distinction of S1 and S2; however, some low-level noise persisted, and quieter heart sound features—such as distant murmurs or third heart sounds—could be obscured if the noise floor is not further reduced. In noisier clinical environments, such interference would likely be more pronounced. This highlights the need for improved noise mitigation strategies in future iterations. To further strengthen the system, future improvements should focus on both hardware and software solutions, including enhanced enclosure design with better acoustic shielding, optimized microphone placement, and advanced digital signal processing strategies such as adaptive filtering and active noise cancellation. These refinements are essential for improving robustness and ensuring that the system maintains diagnostic reliability across diverse clinical conditions. Potential solutions include improved acoustic insulation of the microphone and electronic components (the current prototype enclosure was foam-insulated, but further enhancements are possible), as well as advanced digital signal processing techniques such as adaptive filtering or active noise cancellation [1]. For instance, adaptive noise filters have been shown to significantly reduce unwanted sounds in digital stethoscope recordings [3], and these could be integrated to automatically suppress background noise while preserving heart sound signals. Improving the signal-to-noise ratio (SNR) is critical because extraneous noise can mask important cardiac cues and "is fatal to the accuracy of the diagnosis" in auscultation [6]. Although the current design successfully demonstrates feasibility, further refinements in noise suppression will be necessary to approach the acoustic fidelity achieved by high-end stethoscopes or by experienced clinicians using traditional devices.

It should be noted that the present evaluation was conducted in a quiet clinical setting, which provided a controlled environment for initial testing. While this approach allowed confirmation of the basic feasibility of the system, it does not fully capture the challenges of real-world clinical use, where background noise levels are typically higher and more variable. To address this limitation, future validation should involve testing the device under different ambient noise conditions and in more diverse clinical settings, ensuring a more comprehensive assessment of its robustness and practical utility.

When comparing the prototype to conventional stethoscopes and existing electronic models, several observations arise. Traditional acoustic stethoscopes, while simple and trusted, transmit sound directly via air-tubes to earpieces and naturally attenuate high-frequency ambient noise, but they cannot easily share sounds with others or record data. Electronic stethoscopes on the market (for example, the Littmann© CORE or Eko devices) offer amplification and recording capabilities, yet typically still use ear-tip receivers or headphones for listening [29]. In other words, most current digital stethoscopes remain single-user tools that merely augment sound for that user. In contrast, the speaker-output system delivers sound openly, overcoming that one-to-one constraint. It is notable that this functionality was achieved using only a fraction of the cost and complexity associated with commercial electronic stethoscopes—the design employs readily available components and straightforward assembly, emphasizing affordability. Despite its simplicity, the system captured the key frequency range for cardiac diagnostics and produced audible output comparable to the core performance of more advanced devices. Prior studies have shown that modern electronic stethoscopes can perform as effectively as traditional models in clinical auscultation tasks [30], lending credibility to the concept that a well-designed, low-cost device can meet basic diagnostic requirements. In this case, the main spectral peak and overall frequency response align with what is expected from a quality stethoscope, indicating that the inexpensive microphone and speaker were sufficient for fundamental auscultation applications. This outcome is encouraging for low-resource settings, as it suggests that high-cost equipment is not strictly required to obtain clinically useful heart sound information. That said, there remain trade-offs to consider. The acoustic stethoscope chest piece used provides limited inherent filtering and may not capture very high-frequency sounds (which could include certain murmurs) as effectively as some specialized electronic sensors. Additionally, unlike a passive acoustic stethoscope, the system requires electrical power and includes components that could potentially fail or require calibration. Feedback or acoustic echo from the speaker is another design consideration—although severe feedback was not observed during testing (likely due to careful placement and isolation between the speaker and microphone), it remains a factor to monitor at higher volume levels. Thus, although the low-cost speaker-output stethoscope demonstrates feasibility and strong potential, continued evaluation against traditional auscultation tools is essential to

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determine the scenarios in which it can fully replace them and where further improvement is necessary. Ultimately, the results indicate that the gap between an affordable, do-it-yourself (DIY) system and a professional stethoscope can be significantly reduced; however, achieving full parity in aspects such as ruggedness, noise rejection, and clinical robustness will require continued refinement.

In addition, the discussion has been expanded to provide a comparative perspective between the developed prototype and existing stethoscope technologies. Traditional acoustic stethoscopes, while simple and reliable, remain limited to single-user listening and offer no capability for data storage or group learning. Commercial electronic stethoscopes, such as the Littmann CORE and Eko devices, provide amplification and digital storage but still depend on ear-tip receivers, which restrict collaborative auscultation and raise hygiene concerns. By contrast, the developed prototype delivers open-air, multi-user auscultation at a fraction of the cost while preserving the essential low-frequency fidelity of S1 and S2 sounds.

Although a full quantitative calibration against commercial reference stethoscopes was not performed, preliminary qualitative validation by a cardiologist confirmed that the signals captured by the device were consistent with those of a standard acoustic stethoscope. Furthermore, informal feedback from medical trainees indicated that the speaker-based output was sufficiently clear for teaching and collaborative purposes. These preliminary findings suggest that the device can effectively complement existing stethoscopes in educational and low-resource settings, while more rigorous side-by-side comparisons will be the focus of future work.

A limitation of this study is the relatively small sample size and the fact that all recordings were performed in a controlled environment. In addition, factors such as operator handling and the placement of the stethoscope may have influenced the quality of the recorded signals. These constraints indicate that the current findings should be interpreted as preliminary validation rather than definitive clinical evidence. Recognizing these limitations is important for transparency, and they also highlight the need for future research involving larger and more diverse subject groups, standardized protocols, and broader testing environments to ensure generalizability and reliability of the results.

Beyond its immediate technical performance, the device carries broader implications for clinical education, infection control, and telemedicine integration. In medical training, the ability for multiple students and instructors to hear the same heart sounds in real time promotes collaborative learning and more effective instruction. From an infection control perspective, replacing shared earpieces with open-air speaker output reduces the risk of cross-contamination, which has become especially critical during respiratory pandemics. In telemedicine, the speaker-based design can be readily adapted to transmit auscultation sounds through digital conferencing platforms, enabling remote consultation and patient monitoring. Collectively, these applications demonstrate that the system has the potential to transform workflows by making auscultation more accessible, collaborative, and safe, ultimately contributing to improved patient outcomes.

Looking ahead, several concrete steps are planned to strengthen the validation and development of the prototype. First, larger and more diverse clinical trials will be conducted to establish the device's diagnostic reliability across broader patient populations. Second, hardware refinements, including improved microphone sensitivity, optimized enclosure design, and enhanced amplification circuitry, will be pursued to improve acoustic fidelity. Third, software advancements such as digital signal processing optimization, adaptive noise reduction, and potential integration with mobile applications will be explored to expand functionality and facilitate remote use. Together, these steps form a roadmap for evolving the prototype into a clinically robust and versatile tool capable of supporting training, routine auscultation, and telemedicine applications.

V. Conclusion

The aim of this study was to develop a low-cost speaker-output stethoscope that enables multiple users to simultaneously listen to heart sounds, thereby enhancing medical training and improving infection control. The prototype effectively captured and amplified cardiac sounds, as demonstrated by an improvement in SNR from an average of 7 dB to 15 dB after band-pass filtering, and by the clear identification of the S1 and S2 components with a dominant spectral peak at approximately 97 Hz. Although ambient noise remains a challenge affecting signal clarity, the findings indicate that the device is feasible for both educational and clinical use in low-resource settings. Further research involving broader clinical validation, hardware refinement, and advanced digital signal processing will be required to enhance diagnostic sensitivity and ensure reliable performance across diverse medical conditions.

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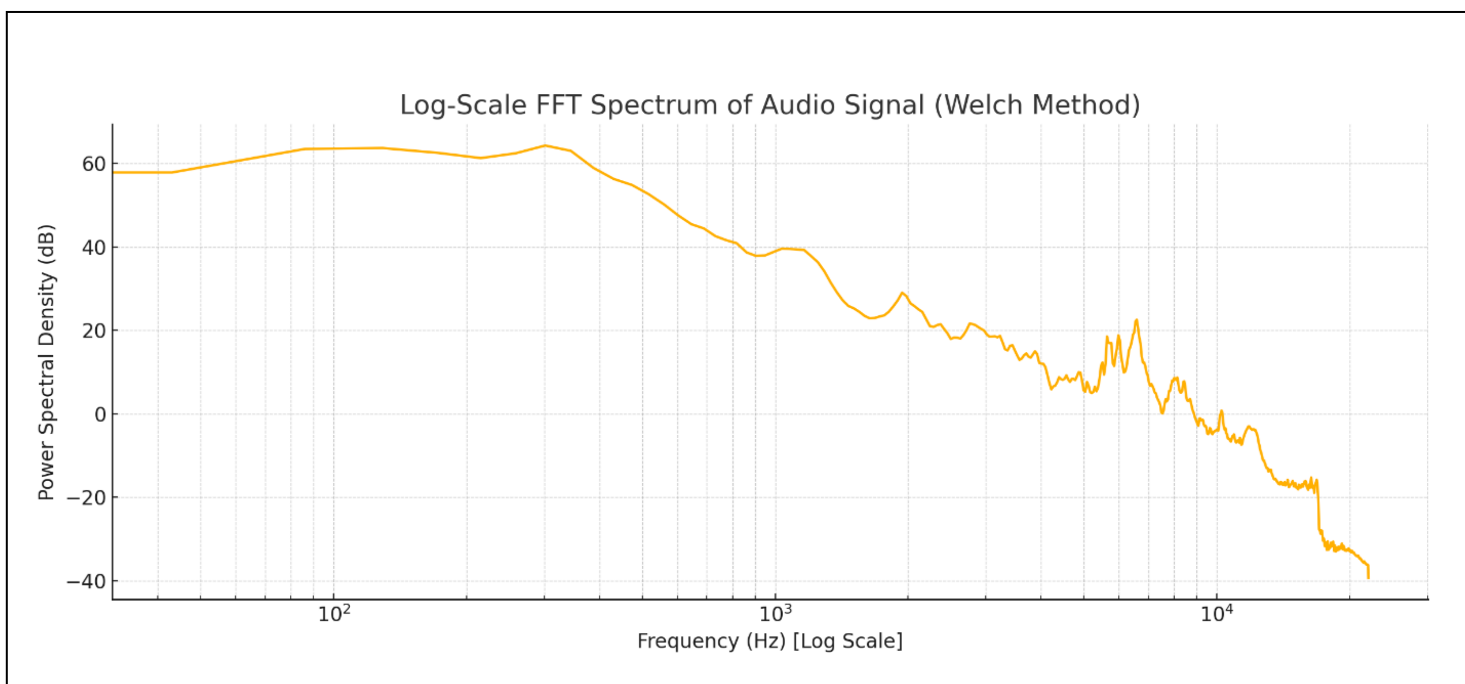

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