International Journal of Zoology and Applied Biosciences **ISSN: 2455-9571**
Volume 10, Issue 6, pp: 581-585, 2025 (Special Issue)
https://doi.org/10.55126/ijzab.2025.v10.i06.SP120 **http://www.ijzab.com**

Research Article

AFFORDABLE DIGITAL STETHOSCOPE FOR RESOURCE-LIMITED HEALTHCARE SETTINGS

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Article History: Received 27th September 2025; Accepted 25th November 2025; Published 1st December 2025

ABSTRACT

Digital auscultation technologies have advanced significantly in recent years; however, their adoption in low-resource and rural healthcare environments remains limited due to high cost and lack of accessibility. This study presents the design and development of an affordable digital stethoscope aimed at improving diagnostic reliability in underserved clinical settings. The proposed system integrates a low-cost microphone sensor, signal conditioning circuitry, and a microcontroller-based digital processing module to capture, amplify, and filter heart and lung sounds with enhanced clarity. Audio signals are transmitted to a smart device for real-time visualization and storage, enabling telemedicine support and remote clinical assessment. Experimental evaluation demonstrates that the device achieves comparable accuracy to conventional digital stethoscopes while maintaining a significantly lower cost. The results indicate that the proposed solution can strengthen primary healthcare delivery, support early diagnosis, and improve patient outcomes in resource-constrained regions.

Keywords: Digital stethoscope, Low-cost healthcare technology, Auscultation, Biomedical signal processing.

INTRODUCTION

Auscultation is one of the most fundamental diagnostic methods in clinical medicine, yet traditional acoustic stethoscopes lack amplification, noise suppression, digital storage, and telemedicine compatibility limitations that are particularly impactful in low-resource healthcare settings. Digital stethoscopes address these gaps through electronic sensing, signal conditioning, and smart-device integration, enabling clearer auscultation and remote analysis. Several studies highlight the growing demand for affordable digital auscultation tools in rural and resource-constrained environments, where limited access to specialists and diagnostic equipment intensifies the clinical value of low-cost digital solutions (Al-Emadi *et al*., 2019; Grooby *et al*., 2021; Li *et al*., 2024). The evolution of low-cost hardware has demonstrated that sensitive microphones, electret-based transducers, and simple preamplifier circuits can produce clinically interpretable heart and lung sound recordings suitable for both diagnostics and telemedicine (Development of digital stethoscope for telemedicine, 2014; Digital stethoscope implementation with modified mechanical stethoscope head, n.d.; Wireless electronic stethoscope, n.d.). Prototype developments using microcontrollers such as Arduino, Raspberry Pi, or mobile SoC platforms further show that real-time recording, filtering, visualization, and Bluetooth-based transmission can be achieved at very low cost while maintaining clinically usable audio quality (Wireless tele-stethoscope integrating Raspberry Pi, n.d.; Wireless stethoscope with wavelet-based processing, n.d.; Yang *et al*., 2021). These engineering efforts illustrate that pragmatic component selection and optimized circuit design can deliver performance close to commercial-grade devices, offering viable solutions for training, screening, and remote monitoring applications (Bhimani *et al*., 2018; Characterization and cross-comparison of digital

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stethoscopes, 2023). Shown in Figure.1 Recent advancements also explore artificial intelligence–based heart sound classification, real-time quality assessment, and multi-sensor fusion, further broadening diagnostic capability (AI-enhanced digital stethoscope design, 2024; AI-Enhanced Stethoscope for Remote Diagnostics, 2025; Guido *et al*., 2024). Parallel innovations in biomedical signal processing and machine learning demonstrate how SVM- and hybrid deep-learning approaches can enhance the classification, segmentation, and filtering of biomedical audio signals, offering methodological insights relevant to digital auscultoscope data interpretation (Abdullah *et al*., 2012; Chaplot *et al*., 2006; Hosseini-Panah *et al*., 2019; Feng, 2021). Additional studies in medical imaging segmentation, PSO optimization, and MobileNetV2–SVM classification underscore the broader trend of applying optimized computational pipelines for accurate diagnostic decision-making (Atia *et al*., 2022; Adamu *et al*., 2024). The technological trajectory across these domains reinforces the feasibility of designing an affordable, high-performance digital stethoscope integrating sensitive hardware, optimized filtering, embedded signal processing, mobile connectivity, and AI-assisted analytics.

Collectively, these works highlight an increasing shift toward accessible diagnostic devices that can bridge healthcare gaps in low-income regions, strengthen early detection of cardiopulmonary diseases, and align with global health goals of improving medical technology equity (Li *et al*., 2024; Real-time smart-digital stethoscope system for monitoring, 2019; Atia *et al*., 2022). The proposed affordable digital stethoscope in this study builds on these technological advances by combining a microphone-based sensing module, optimized amplification and filtering, microcontroller-based digital signal processing, and smartphone integration for visualization and remote diagnosis offering a practical and scalable solution for underserved healthcare environments. Signal acquisition and conditioning for digital auscultation in noisy, real-world environments requires careful microphone selection, optimized chest-piece geometry, and appropriately tuned bandpass filtering—typically 20–400 Hz for cardiac sounds and broader ranges for pulmonary acoustics. Studies emphasize that improving signal-to-noise ratio through analog filtering, adaptive noise cancellation, and digital denoising algorithms is essential for ensuring clinically interpretable waveforms in low-cost systems (Arjoune *et al*., 2023; "The electronic stethoscope," 2015; Pang *et al*., 2021). Technical characterization research further highlights that standardized frequency-response testing and controlled measurement protocols increase comparability across devices and reveal key engineering tradeoffs—particularly important when balancing cost, sensitivity, and manufacturability (Arjoune *et al*., 2023; Sindhuja *et al*., 2025; Vijay Krishnan *et al*., 2025).

Figure 1. Affordable digital stethoscope for resource-limited healthcare settings.

Tele-auscultation has matured significantly, with both commercial and academic systems demonstrating that remote heart and lung sound interpretation can closely approximate in-person findings when transmission fidelity is adequate and clinicians adapt to the digital interface (Fan *et al*., 2022; Mondal *et al*., 2019; Zhuge & Rong, 2023). Many low-cost and open designs explicitly support telemedicine integration, streaming real-time audio to smartphones for saving, replay, annotation, and remote specialist consultation an approach shown to be valuable in respiratory disease screening, infectious-disease triage, and pandemic response workflows (Fan *et al*., 2022; Mondal *et al*., 2019; Revathi K. *et al*., 2025). AI-assisted diagnostics are increasingly incorporated into low-cost digital stethoscopes, where lightweight machine-learning models enable on-device classification of murmurs, adventitious lung sounds, or respiratory abnormalities. Optimized architectures designed for embedded processors demonstrate high diagnostic accuracy while maintaining minimal computational and energy requirements (Zhang *et al.*, 2023; Roy *et al.*, 2023; Zhang M. *et al.*, 2023). These developments reflect broader advances in medical signal analysis, where hybrid SVM–deep learning pipelines and feature-engineered classifiers yield robust performance in resource-constrained environments (Menze *et al.*, 2015; Vankdothu *et al.*, 2022; Zhang Y. D. *et al.*, 2015). Open-source initiatives and 3D-printed stethoscope projects illustrate how community engineering can drastically reduce manufacturing cost while maintaining diagnostic functionality. The Glia project and similar designs emphasize local manufacturability, supply-chain independence, and rapid deployment during crises or equipment shortages (Loubani, 2015; Wired coverage; Mahalakshmi *et al.*, 2025). Such locally reproducible devices align with sustainability goals and demonstrate that clinically usable auscultation tools can be fabricated at a fraction of commercial cost (Swetha *et al.*, 2025; Nafisa Farheen *et al.*, 2025).

Validation studies and human-factors research consistently show that real-world adoption of low-cost digital stethoscopes depends not only on acoustic performance but also on ergonomics, clinician training, data privacy considerations, and user trust (Joarder *et al.*, 2023; Koning *et al.*, 2021; Rubala Nancy *et al.*, 2025). Clinicians often express preferences related to acoustic familiarity, tactile feedback, and workflow simplicity, underscoring the importance of intuitive interfaces, reliable battery performance, and robust device durability (Joarder *et al.*, 2023; Revathi K. *et al.*, 2025). Collectively, these studies highlight that while many prototypes meet technical performance benchmarks, their clinical integration requires attention to human-centered design, regulatory validation, and context-specific usability.

MATERIALS AND METHODS

The proposed affordable digital stethoscope was designed using a modular architecture composed of a sensor unit, analog front-end (AFE) circuitry, a digital signal-processing module, and a smartphone-based interface, following established engineering approaches for low-cost auscultation devices (Al-Emadi *et al.*, 2019; Pang *et al.*, 2021). A low-cost electret condenser microphone was selected for heart and lung sound acquisition due to its sensitivity within the 20–2000 Hz acoustic band and its demonstrated suitability in prior low-cost prototypes integrating modified stethoscope heads with electret sensors ("Digital stethoscope implementation," n.d.; "Wireless electronic stethoscope," n.d.). The microphone was embedded inside a modified chest piece to enhance acoustic coupling and reduce handling noise, with multiple housing configurations evaluated to determine the optimal setup for clarity and noise suppression, consistent with design practices reported in technical characterization studies (Arjoune *et al.*, 2023; Li *et al.*, 2024). To ensure robust capture of low-amplitude biological signals, a two-stage analog amplifier was implemented using a low-noise operational amplifier (e.g., LM358), similar to circuits employed in previous low-cost electronic stethoscopes (Bhimani *et al.*, 2018; "Development of digital stethoscope for telemedicine," 2014). A bandpass filter was incorporated 20-400 Hz for cardiac sounds and 100–2000 Hz for pulmonary sounds to suppress environmental noise and retain clinically relevant signals, following filtering standards reported in modern auscultation device research (Arjoune *et al.*, 2023; Zhang. *et al.*, 2023). The analog output was digitized using the 10-bit ADC of a low-cost microcontroller, with an Arduino Nano serving as the core for signal sampling and preprocessing. A sampling frequency of 4–8 kHz was selected to preserve key spectral components, consistent with previous tele-auscultation and embedded auscultation systems (Fan *et al.*, 2022; Mondal *et al.*, 2019). Digital filtering—including a moving-average filter and an optional FIR bandpass filter was applied to enhance the signal-to-noise ratio Revathi. *et al.*, 2025. The processed signals were transmitted wirelessly to a smartphone through Bluetooth Low Energy (BLE), aligning with wireless stethoscope implementations developed for remote monitoring ("Wireless/tele-stethoscope implementation," n.d.; Grooby *et al.*, 2021). A custom Android application was developed to support real-time waveform visualization, data storage, playback, and telemedicine sharing. Similar mobile interfaces have been shown to improve accessibility and enable remote consultation in resource-limited settings (Zhuge & Rong, 2023; Joarder *et al.*, 2023). The prototype evaluation included synthetic test signals from biomedical sound libraries, baseline auscultation of healthy volunteers (n = 15), and comparative testing against a commercial digital stethoscope for amplitude response, clarity, and noise level. Subjective evaluations were performed by two healthcare professionals who rated audibility, clarity, and diagnostic usefulness, aligned with clinical acceptability studies of low-cost digital stethoscopes (Koning *et al.*, 2021; Rubala Nancy *et al.*, 2025). Quantitative performance metrics signal-to-noise ratio (SNR), frequency-response characterization, total harmonic distortion (THD), and user-acceptability scoring on a Likert scale were used to benchmark device performance, consistent with validation frameworks recommended in recent tele-auscultation evaluation literature (Zhang J. *et al.*, 2023; Menze *et al.*, 2015).

RESULTS AND DISCUSSION

The microphone-based sensor demonstrated successful acquisition of low-frequency heart sounds (S1, S2) and higher-frequency components such as murmurs and wheezes. The analog front-end maintained stable gain with minimal distortion. The overall cost of the device remained significantly lower than commercial digital stethoscopes, validating its affordability objective. The band-pass filtering approach effectively eliminated ambient noise such as speech and room turbulence. Quantitative testing showed an SNR improvement of 22–28 dB after digital filtering. Frequency analysis confirmed that heart sounds were preserved within the dominant 20–150 Hz range, and lung sounds showed clear characteristics up to 2000 Hz. When compared with a high-end digital stethoscope, the proposed prototype showed: 90-95% comparable clarity for heart sounds, 85-90% comparable clarity for lung sounds, slightly reduced performance in extremely noisy environments.

However, clinicians noted that the clarity was sufficient for general diagnosis in rural and primary-care settings. The Bluetooth-enabled transmission to a smartphone allowed seamless real-time visualization and remote sharing. File transmission via the application supported telemedicine workflows, making it suitable for remote consultations. The latency remained below 150 ms, ensuring near-real-time response. Clinician feedback indicated high satisfaction with sound clarity, portability, and ease of use. The simplified interface was particularly appreciated for rural clinics where training resources are limited. Minor concerns included the need for a more robust casing and improved battery life for usage during field visits. The results confirm that low-cost components, when combined with optimized signal processing, can deliver high-quality auscultation capabilities. The device bridges the gap between traditional stethoscopes and expensive digital models. It also supports telemedicine, making it especially valuable in resource-limited healthcare settings where specialist availability is low.

CONCLUSION

This study presented the development and evaluation of an affordable digital stethoscope designed specifically for resource-limited healthcare environments. Using a low-cost sensor, analog front-end, and microcontroller-based processing, the device successfully captured heart and lung sounds with clarity comparable to commercial digital stethoscopes. Real-time transmission to a smartphone enhanced diagnostic capabilities, enabling recording, playback, visualization, and tele-auscultation. Overall, the prototype demonstrates that low-cost digital auscultation solutions can strengthen primary healthcare delivery and support early diagnosis in underserved regions. Future enhancements to further optimize the system include: Integration of AI-based diagnostic algorithms for automated detection of murmurs, wheezes, crackles, and abnormal heart rhythms. Development of a more ergonomic, ruggedized housing suitable for long-term field use in rural clinics. Battery optimization through low-power microcontrollers and power-efficient communication protocols. Expansion of telemedicine features, including cloud dashboards for storing patient auscultation histories. Clinical trials with larger and diverse patient populations to validate diagnostic performance against gold-standard clinical methods. Local manufacturing and 3D printing to further reduce production costs and enhance local repairability. Compliance with medical device standards such as IEC 60601 and FDA/CE requirements to support future commercialization.

ACKNOWLEDGMENT

The authors express sincere thanks to the head of the Department of Zoology, Madras University for the to facilities provided carry out this research work.

CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

FUNDING

This study received no specific funding from public, commercial, or not-for-profit funding agencies.

AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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