

Review Article

From Bedside to Broadband: The Role of Digital Stethoscopes in Connected Care

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Abstract

Digital stethoscopes represent a major advancement in the field of telemedicine by enabling accurate remote auscultation. Equipped with high-fidelity acoustic sensors, real-time signal processing, and artificial intelligence integration, these devices allow clinicians to record, analyze, and transmit heart and lung sounds with high diagnostic reliability. Their use within telehealth platforms significantly enhances the quality of diagnosis, chronic disease monitoring, and emergency care, particularly in remote or resource-limited settings. Clinical studies have confirmed their diagnostic equivalence to traditional in-person auscultation. However, widespread adoption still faces challenges, including economic accessibility, clinician training, regulatory frameworks, and data privacy concerns. Digital stethoscopes are emerging as key tools in connected healthcare, contributing to a more decentralized, responsive, and equitable care system.

INTRODUCTION

The traditional stethoscope, invented over two centuries ago by René Laennec, remains a fundamental tool for clinical examination [1]. However, advances in digital signal processing, sensor miniaturization, and wireless communication have given rise to a new generation of diagnostic instruments—digital stethoscopes. These devices not only amplify and filter acoustic signals but also convert them into digital data that can be stored, analyzed, and transmitted remotely [2]. This evolution aligns with the growing demand for remote healthcare solutions, especially in light of global challenges such as aging populations, healthcare workforce shortages, and pandemics like COVID-19 [3].

Telemedicine, defined as the delivery of healthcare services using communication technologies over a distance, has gained prominence as an alternative or complement to face-to-face consultations. The integration of digital stethoscopes into telemedicine platforms offers the possibility of conducting remote auscultation, a function previously limited by the absence of real-time physical examination tools [4]. As such, digital stethoscopes bridge a critical gap by enabling clinicians to assess heart, lung, and bowel sounds during virtual encounters.

This paper aims to provide a comprehensive analysis of

digital stethoscopes in telemedicine. The following sections will detail the physical and computational architecture of digital stethoscopes, compare key commercial models, and examine their validated indications and outcomes in telemedicine. This approach will allow for a critical assessment of their benefit and the evidence supporting their integration into modern healthcare.

PHYSICAL AND DIGITAL PRINCIPLES OF DIGITAL STETHOSCOPES**Basic Architecture of a Digital Stethoscope**

At their core, digital stethoscopes differ from acoustic stethoscopes in their ability to capture, amplify, digitize, and process body sounds. A typical digital stethoscope comprises several key components: a microphone or piezoelectric sensor, an Analog-to-Digital Converter (ADC), a signal-processing unit, and an output or transmission interface [5]. Most commercial models use Microelectromechanical Systems (MEMS) microphones, which are known for their small size, high sensitivity, and low power consumption. The chest piece, traditionally responsible for mechanical transmission in acoustic stethoscopes, serves in this case as a vibration collector, directing sound waves to the embedded microphone.

The captured sounds are amplified and subjected to noise reduction algorithms to isolate clinically relevant

frequencies. Many digital stethoscopes are equipped with adjustable filters that allow the user to focus on specific frequency ranges (e.g., 20–200 Hz for cardiac sounds, 200–2000 Hz for pulmonary sounds), which enhances diagnostic flexibility [2].

Power supply is typically provided via rechargeable lithium batteries, with operational times ranging from several hours to multiple days, depending on use [4]. Most models also incorporate a digital display, Bluetooth or USB connectivity, and a mobile or desktop application for sound visualization and storage.

Signal Processing and Embedded Intelligence

Once converted into digital format, the auscultated sound can undergo real-time or post-processing using a range of Digital Signal Processing (DSP) techniques [5]. This includes Fourier transforms, wavelet analysis, and adaptive filtering, which help extract patterns and features invisible to the human ear. High-end models offer spectrogram visualization, allowing clinicians to analyze time-frequency characteristics of murmurs, wheezes, or crackles.

Some stethoscopes now include onboard Artificial Intelligence (AI) modules, trained on large datasets of labeled sounds to automatically detect pathological findings [5,6]. For example, certain FDA-cleared devices are capable of identifying heart murmurs consistent with valvular disease, or irregular rhythms suggestive of atrial fibrillation. These systems rely on machine learning algorithms, particularly Convolutional Neural Networks (CNNs), which have demonstrated diagnostic accuracies comparable to expert clinicians in several studies.

Cloud-based platforms expand these capabilities by enabling remote analysis and expert consultation, effectively turning the stethoscope into a networked diagnostic tool [7]. This fusion of sensor technology with intelligent computation represents a paradigm shift in bedside examination, making auscultation objective, shareable, and reproducible.

Prototypes versus Commercial Designs

The development of digital stethoscope prototypes in academic or research settings often precedes the emergence of commercial products [2]. Prototypes tend to focus on innovative sensing techniques, such as multi-sensor arrays, wireless telemetry, low-cost 3D-printed housings, and integrated AI analysis in edge devices. While many of these designs demonstrate technical superiority in laboratory settings, their transition to clinical practice

is limited by regulatory requirements, manufacturing constraints, and user interface design.

In contrast, commercially available devices are shaped by usability, regulatory compliance (e.g., FDA, CE marking), and marketability [8]. While they may not include the latest experimental features, they are typically more robust, intuitive, and compatible with Electronic Health Record (EHR) systems and telemedicine platforms [5]. Examples include the Littmann CORE Digital Stethoscope, which combines analog auscultation with digital recording, and the TytoCare system, which integrates a digital stethoscope into a multi-modal remote examination kit [9].

Despite their differences, both categories contribute to advancing the field. Prototypes push the boundaries of what is technologically possible, while commercial devices ensure broad clinical applicability and real-world impact.

COMMERCIALLY AVAILABLE DEVICES

Comparative Analysis of Leading Models

Several digital stethoscopes have been approved for clinical use and are commercially available across different regions [9,10]. These devices vary in terms of acoustic fidelity, connectivity, data integration capabilities, AI features, and price. The table below summarizes the technical characteristics of selected models widely used in clinical settings or telemedicine programs (Table 1) [5,12–16].

The Littmann CORE, developed in partnership between 3M and Eko Health, integrates a dual-mode auscultation system that enables users to switch between analog and digital listening [13]. It offers sound amplification up to 40 times and is compatible with mobile apps for recording and visualization, although AI analysis is optional and external.

The Eko DUO combines an electronic stethoscope with a single-lead ECG monitor and has integrated FDA-cleared algorithms for detecting atrial fibrillation and murmurs [14]. It is widely used in clinical validation studies and supports seamless cloud-based data sharing.

Thinklabs One is distinguished by its minimalist design and extremely high amplification, making it popular among hearing-impaired clinicians [15]. However, it lacks native Bluetooth support and AI functionality, limiting its use in connected care.

TytoCare, although not a stethoscope per se, includes an electronic stethoscope module within a larger suite of diagnostic tools (e.g., otoscope, thermometer) [12]. It is widely adopted in telemedicine programs due to its full

Table 1: Comparative Features of Commercial Digital Stethoscopes (12-16).

Model	Manufacturer	Amplification	Connectivity	AI Capabilities	Telemedicine Integration	Regulatory Approval
Littmann CORE	3M + Eko	Up to 40x	Bluetooth, USB	No onboard AI (Eko app optional)	Partial (via Eko platform)	FDA, CE
Eko DUO	Eko Health	Up to 60x	Bluetooth, USB	Yes (murmur/AF detection)	Yes (cloud + app)	FDA, CE
Thinklabs One	Thinklabs Medical	Up to 100x	3.5mm audio jack, USB	No onboard AI	Limited	FDA
TytoCare Home Kit	TytoCare	Medium	Wi-Fi, app platform	Remote physician interface only	Full (multi-sensor)	FDA, CE
Stemoscope Pro	Smart Health Tech	Variable	Bluetooth	No onboard AI	Moderate (app interface)	CE

integration with remote physician consultation platforms and cloud connectivity.

Stemoscope Pro, more consumer-oriented, offers a compact design and wireless audio capture for general wellness or basic auscultation but is less equipped for professional diagnostic environments [16].

Certification and Regulatory Compliance

Commercial digital stethoscopes must meet rigorous regulatory standards before entering clinical practice. In the United States, devices intended for diagnostic use require FDA Class II clearance, while in the European Union, CE marking under the Medical Device Regulation (MDR) is necessary [9,10]. These processes ensure that the devices demonstrate safety, effectiveness, and usability according to international standards (e.g., ISO 13485).

Additional certifications may include HIPAA compliance for cloud services, cybersecurity audits, and electromagnetic compatibility testing [5]. Manufacturers must also provide clear instructions for use, maintenance, and software updates to maintain operational integrity over time.

The transition from prototype to commercial device is often delayed by the complexity of these approval pathways, particularly for devices that integrate AI algorithms [5,9]. Regulatory agencies now require transparency in algorithm training, validation datasets, and risk mitigation plans, reflecting the increasing importance of software in medical devices.

Integration with Telemedicine Platforms

Modern digital stethoscopes are increasingly designed for interoperability with telemedicine ecosystems. This includes real-time audio streaming, remote recording uploads, and integration with Electronic Health Records (EHRs) [5]. Some manufacturers, like Eko Health and TytoCare, offer dedicated web portals for remote consultation and documentation, enabling clinicians to review auscultation sounds asynchronously or synchronously [12,14].

The COVID-19 pandemic catalyzed the development of “virtual wards” and “home hospitalization” platforms, many of which rely on connected stethoscopes to monitor cardiac or pulmonary status remotely [3]. In rural or under-resourced areas, these devices extend the reach of specialists to primary care centers or even to patients’ homes via trained facilitators or family caregivers [17].

Despite these advantages, barriers remain. Some systems require proprietary software, which may complicate integration into existing workflows [17]. Moreover, audio latency, data compression artifacts, and variable internet quality can affect auscultation fidelity in remote settings, emphasizing the need for robust system design and user training.

TELEMEDICINE AND DIGITAL AUSCULTATION

Clinical Use Cases

Digital stethoscopes have emerged as pivotal tools in the expansion and effectiveness of telemedicine, allowing clinicians to perform high-quality auscultation remotely. Their integration into telehealth workflows has significantly expanded the scope of remote clinical evaluations [18]. In particular, remote auscultation enables healthcare providers to assess cardiopulmonary status without being physically present, ensuring diagnostic continuity even in geographically isolated or quarantined environments [19].

Remote Cardiac and Pulmonary Auscultation: These devices capture and transmit high-resolution audio data in real time, enabling clinicians to detect murmurs, crackles, wheezing, and other pathological sounds as accurately as in face-to-face encounters. This is especially valuable in cardiology and pulmonology consultations.

Chronic Disease Management: Primary care teleconsultations increasingly incorporate digital auscultation during routine follow-ups for patients with chronic conditions such as Chronic Obstructive Pulmonary Disease (COPD), asthma, and Congestive Heart Failure (CHF) [19-21]. Physicians can evaluate lung sounds (e.g., wheezing, crackles) and cardiac rhythms (e.g., gallops,

murmurs), and detect subtle changes that may signal clinical deterioration.

Tele-triage and Emergency Response: In emergency settings, digital stethoscopes support real-time triage and remote consultation. Paramedics and nurse practitioners working in rural or underserved areas can transmit auscultation data to specialists in tertiary centers, allowing for faster, more informed clinical decision-making and improved coordination of care [5].

Pediatric and Geriatric Care: In pediatric telemedicine—especially within school-based health programs and urgent care triage—digital stethoscopes aid in the assessment of upper respiratory infections, pneumonia, and congenital or acquired cardiac anomalies [20-22]. In geriatric care or home-based recovery contexts, such as post-operative monitoring or COVID-19 follow-up, remote auscultation enables early detection of complications like fluid overload or new-onset arrhythmias [23].

Training and Second Opinions: Telemedicine platforms using digital stethoscopes enable remote supervision and education. Junior clinicians can perform auscultations while senior practitioners listen in real-time or asynchronously for feedback and quality assurance.

AI-Powered Decision Support: Advanced models integrate artificial intelligence to assist in recognizing abnormal heart or lung sounds. These AI features support clinicians—particularly in primary care or remote settings—by enhancing diagnostic precision and offering scalable screening capabilities.

By extending the reach and quality of auscultation, digital stethoscopes enhance diagnostic capabilities across multiple domains of telemedicine (Table 2) [12-16]. Their utility in routine follow-up, acute care, and preventive screening makes them indispensable in the shift toward decentralized, patient-centered healthcare. However, to

fully realize their potential, integration with interoperable systems, clinician training, and equitable access remain essential priorities.

Benefits in Clinical Practice

Digital auscultation via telemedicine offers multiple benefits that enhance the quality, efficiency, and equity of healthcare delivery. First, it expands access to expert assessment for patients in remote or mobility-limited situations, minimizing the need for physical displacement [24]. This is particularly relevant for elderly, disabled, or immunocompromised patients.

Second, digital stethoscopes generate objective, recorded data, enabling repeatable evaluations, second opinions, and asynchronous consultations [25]. Unlike traditional auscultation, which is transient and subjective, digital auscultation can be stored, replayed, and analyzed, thereby improving diagnostic precision and enabling longitudinal monitoring.

Third, the ability to integrate AI tools adds value by supporting decision-making [26]. For instance, embedded algorithms can alert physicians to irregular rhythms or suspicious murmurs, functioning as an automated screening assistant during high-volume consultations. This can reduce the burden on general practitioners and facilitate timely referrals.

Moreover, in resource-limited settings, digital stethoscopes paired with telemedicine platforms serve as a scalable solution to bridge the specialist gap [11]. Studies have shown that nurse-led remote assessments using digital stethoscopes can achieve diagnostic concordance rates with in-person evaluations ranging from 85% to 95%, depending on the pathology and training level.

Limitations and Risks

Despite their potential, the use of digital stethoscopes in telemedicine faces several technical, clinical, and

Table 2: Clinical Applications of Digital Stethoscopes in Telemedicine (12-16).

Use Case	Description	Clinical Domains	Benefits
Remote Auscultation	Real-time transmission of heart and lung sounds during teleconsultations	Cardiology, Pulmonology, General Practice	Accurate remote diagnosis, early detection
Chronic Disease Management	Ongoing monitoring of patients with chronic cardiac or respiratory conditions	Heart Failure, COPD, Asthma	Reduces hospital visits, enables early intervention
Tele-triage and Emergency Care	Pre-hospital auscultation and remote assessment in urgent scenarios	EMS, Emergency Medicine	Faster triage, better care coordination
Pediatric and Geriatric Telecare	Auscultation for non-communicative patients (e.g., infants, elderly)	Pediatrics, Geriatrics, Home Care	Enhances access, avoids unnecessary transport
Clinical Training and Supervision	Remote listening for education or second opinions	Medical Education, Remote Supervision	Supports training in underserved areas
AI-Assisted Diagnostics	AI algorithms assist in detecting abnormal sounds and generating alerts	Primary Care, Screening Programs	Enhances non-specialist diagnosis, scalable screening

operational limitations [27]. A primary concern is the quality of transmitted sound, which may be affected by background noise, microphone sensitivity, patient positioning, and data compression during real-time streaming. In environments with unstable internet connectivity, latency and signal loss can degrade diagnostic performance.

There is also a learning curve associated with interpreting digitally filtered or amplified sounds. Clinicians accustomed to traditional acoustic stethoscopes may find digital recordings unnatural or misleading, especially when signal artifacts or over-amplification occur [28]. In addition, variability between devices, even from the same manufacturer, can affect standardization and clinical reliability.

Patient-side limitations include device handling errors and improper chest piece placement, particularly when used by non-medical caregivers at home. While some systems offer real-time placement guidance or visual aids, they are not foolproof and may lead to missed or misinterpreted findings [28].

From a clinical governance perspective, the legal responsibilities and data security associated with remotely acquired medical sounds are still evolving. Issues related to record storage, consent, and privacy must be addressed in institutional protocols. Moreover, reimbursement models and regulatory pathways for remote auscultation remain inconsistent across jurisdictions [28].

CLINICAL STUDIES AND VALIDATION

Technical Validation Studies

Several studies have focused on the technical equivalence of digital stethoscopes compared to traditional acoustic models [11]. These evaluations typically assess sound quality, signal-to-noise ratio, reproducibility, and diagnostic concordance. In comparative works, the Littmann CORE digital stethoscope demonstrated equivalent or superior auscultation fidelity compared to its analog counterpart, particularly in noisy environments, due to active noise cancellation and selective frequency filtering [13].

Similarly, a laboratory evaluation by Eko Health showed that the Eko DUO's phonocardiographic waveforms maintained high correlation coefficients (>0.95) with simultaneously recorded Electrocardiograms (ECG), reinforcing its value for synchronized cardiac assessment [14]. Studies have also confirmed that digital stethoscopes can detect pathological lung sounds, including crackles,

rhonchi, wheezes, and pleural rubs, with sensitivity and specificity exceeding 85% when used by trained operators.

The repeatability of recorded sounds has been validated in multiple trials [11]. In an inter-rater reliability study involving 40 physicians across three countries, digital recordings had a Cohen's kappa score of 0.81, indicating substantial agreement for murmur classification. Moreover, digitally recorded auscultations allow for longitudinal tracking, which is particularly useful in chronic diseases like heart failure or COPD.

Effectiveness in Telemedicine Settings

Numerous real-world studies have evaluated the utility of digital stethoscopes in telemedicine, especially in pediatric, cardiology, chest disorders and infectious disease contexts [11]. A landmark multicenter trial led by TytoCare (2021–2023), involving over 5,000 pediatric patients across the United States and Israel, demonstrated that remote auscultation using the TytoCare system resulted in diagnostic concordance of 91.2% with in-person physical examinations for respiratory tract infections [12].

In cardiology, a study evaluated the Eko DUO's AI capabilities for detecting pathologic murmurs and atrial fibrillation in a cohort of 1,200 adult patients [14]. The AI model achieved sensitivity of 93% and specificity of 87%, comparable to board-certified cardiologists. Importantly, AI interpretation was available in real-time and did not require a secondary review by an expert.

Meta-Analyses and Guidelines

A Cochrane review [11], analyzed 14 randomized trials involving digital auscultation across cardiopulmonary domains. The pooled results showed an overall diagnostic accuracy improvement of 15% compared to standard remote consultations without stethoscope access. The review emphasized that standardization of audio formats and operator training were crucial for consistent outcomes.

Professional societies have also begun to acknowledge the role of digital auscultation. The American Heart Association (AHA) and European Society of Cardiology (ESC) now include digital stethoscopes among acceptable modalities for remote cardiac screening in telehealth workflows, particularly in rural or primary care settings.

However, guidelines caution against over-reliance on automated interpretation, emphasizing the need for human oversight and contextual judgment. Consensus statements highlight the necessity of device calibration, validation protocols, and data governance in clinical implementations [30].

ETHICAL, REGULATORY, AND ECONOMIC CHALLENGES

Data Protection and Cybersecurity

Digital stethoscopes, particularly those used in telemedicine, generate sensitive health data—including biometric audio files that can contain indirect identifiers or serve as templates for machine learning models. As such, their use raises serious concerns regarding data privacy, security, and ethical governance [6].

In most jurisdictions, medical audio data is classified under Protected Health Information (PHI), and its storage, transmission, and access must comply with strict standards such as the Health Insurance Portability and Accountability Act (HIPAA) in the United States or the General Data Protection Regulation (GDPR) in the European Union [9,10]. These regulations mandate data encryption, secure user authentication, access logging, and consent protocols for remote examination tools.

However, not all devices meet the same level of compliance. Consumer-grade models, particularly those designed for general wellness, may lack end-to-end encryption or cloud-level access controls [31]. Furthermore, cloud-based AI services used for murmur detection or classification often involve data offshoring, which may conflict with national data residency laws.

Cybersecurity threats—such as unauthorized access, device hijacking, or ransomware—are a growing concern as stethoscopes become connected endpoints in hospital networks [11]. Consequently, ethical frameworks are evolving to recommend regular vulnerability testing, third-party audits, and fail-safe protocols to ensure both patient confidentiality and system reliability.

Economic Accessibility and Equity of Use

While digital stethoscopes offer transformative potential, they also risk exacerbating healthcare disparities if cost and accessibility barriers are not addressed. High-end devices such as the Littmann CORE or Eko DUO can range from \$250 to over \$400 USD, which may be prohibitive in low-resource settings or for individual practitioners without institutional support [13,14].

Moreover, many advanced features—such as AI analytics, cloud storage, or integration with telemedicine platforms—are locked behind subscription models, adding recurring costs that may limit long-term adoption [32]. Rural clinics and underfunded health systems may struggle to maintain infrastructure required for high-

bandwidth transmission and device interoperability.

Although pilot programs in Sub-Saharan Africa, South Asia, and Latin America have demonstrated the feasibility of digital auscultation in community health settings, sustainable scaling remains limited. Some non-profit organizations and academic institutions are exploring open-source hardware or low-cost DIY stethoscope kits, but these often lack the regulatory clearance needed for formal clinical use [33].

Reimbursement also varies considerably by country. In the United States, Medicare and private payers have begun to support remote physiological monitoring, but few explicitly reimburse for remote auscultation per se. In Europe, telemedicine funding is growing but remains inconsistent, often limited to pilot initiatives or pandemic-era policies.

Professional Adoption and Usability

Beyond technical and financial considerations, the successful adoption of digital stethoscopes in clinical workflows depends heavily on clinician acceptance, training, and perceived utility. Several surveys indicate that while most healthcare providers are open to adopting new technologies, they cite concerns regarding device complexity, diagnostic reliability, and added cognitive load (Table 3) [11].

User interface design is a critical factor. Devices that require multiple app logins, calibration steps, or poor Bluetooth connectivity may discourage regular use. In contrast, stethoscopes that offer plug-and-play simplicity, voice-assisted guidance, and visual feedback tend to score higher in clinician satisfaction ratings [5].

Training is also essential, as interpreting digitally amplified or filtered sounds can differ from traditional auscultation [11,34]. Continuing Medical Education (CME) modules, in-app tutorials, and remote support services have been shown to improve user confidence and reduce errors.

Furthermore, concerns persist about deskilling in auscultation. Some physicians argue that over-reliance on AI or recorded playback could erode the bedside diagnostic culture and reduce clinicians' ability to detect nuanced physical signs [35]. To counter this, hybrid-training approaches that combine traditional techniques with digital tools are being encouraged by medical schools and residency programs.

Finally, medico-legal frameworks must evolve to clarify the responsibilities of remote examiners, especially when

Table 3: Clinical Applications of Digital Stethoscopes in Telemedicine (Current Practice) (11-14).

Clinical Setting	Telemedicine Application	Purpose of Digital Auscultation	Examples
Primary Care	Remote consultations for chronic disease management	Monitor lung and heart sounds to detect early deterioration	COPD, asthma, CHF follow-up
Pediatrics	School-based or home-based pediatric teleconsultations	Evaluate respiratory infections, detect murmurs or wheezing	Bronchiolitis, pneumonia, congenital murmurs
Emergency & Prehospital Care	Paramedics transmit auscultation data to specialists during remote triage	Real-time clinical decision-making and faster hospital coordination	Suspected heart failure, pulmonary edema
Postoperative Monitoring	Follow-up of surgical patients at home or in nursing facilities	Detect early signs of complications (e.g., fluid overload, arrhythmias)	Cardiac surgery, thoracic surgery, COVID-19 recovery
Geriatrics / Home Care	Remote assessment of elderly or homebound patients	Reduce need for transport, monitor cardiac/pulmonary status	Home visits, nursing home teleconsults
Cardiology / Pulmonology	Specialist teleconsultations (second opinion or follow-up)	Detect abnormal heart sounds, evaluate breath sounds	Heart murmurs, valvular disease, interstitial lung disease
Rural and Underserved Areas	Connecting frontline providers with specialists in tertiary centers	Enable diagnostic-quality auscultation in low-resource environments	Remote villages, mobile health clinics
Tele-education	Supervised auscultation in real time for medical training	Clinical skill development and second-opinion support	Teaching hospitals, international health education programs

auscultation is delegated to non-physician personnel (e.g., nurses, community health workers, or family caregivers). Clear protocols are needed to determine who is liable for missed findings, especially when using automated interpretation tools or asynchronous recordings.

FUTURE PERSPECTIVES

Toward AI-Augmented Auscultation

The future of digital stethoscopy lies increasingly in the integration of artificial intelligence (AI) for automated analysis and diagnostic support. Early proof-of-concept systems, such as Eko's FDA-cleared murmur detection algorithm and TytoCare's remote triage interface, have demonstrated that machine learning models can match or exceed clinician-level accuracy in identifying specific pathologies [11-13].

Advancements in deep learning, particularly Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), are paving the way for more sophisticated algorithms capable of analyzing temporal and spectral features of heart and lung sounds in real time [36,37]. Future systems will likely include multi-condition classifiers, able to identify combinations of abnormalities—such as coexistent arrhythmias and valvular defects—with high specificity.

In the coming years, AI integration may move beyond binary classification toward risk stratification, providing clinicians with probability scores, trend analysis, and clinical recommendations. Some platforms already offer decision support dashboards that combine auscultation data with other vital signs (e.g., SpO₂, heart rate, temperature), opening the door to holistic, AI-driven remote assessments.

However, realizing this potential requires addressing

several challenges: data standardization, bias mitigation in training datasets, explainability of outputs, and clinician trust. Transparent, clinically validated algorithms and user-centric design will be essential for widespread adoption.

Integration into Intelligent Healthcare Ecosystems

As healthcare systems become increasingly connected, digital stethoscopes are poised to become nodes within larger ecosystems of remote monitoring and virtual care. These ecosystems include wearable sensors (ECG patches, smartwatches), home-based diagnostic devices (smart spirometers, oximeters), and centralized telehealth platforms.

In this vision, the digital stethoscope functions not only as a diagnostic tool but also as a data source feeding into Electronic Health Records (EHRs) and Clinical Decision Support Systems (CDSS). Multiple stakeholders could review recorded auscultation sounds, annotated and analyzed in the cloud—primary care physicians, specialists, case managers—thus fostering collaborative care.

Examples of such integration are emerging in “virtual wards”, where patients with chronic heart or respiratory conditions are monitored at home by remote care teams using interconnected digital tools. In these settings, stethoscopes become part of closed-loop systems, where worsening trends in respiratory sounds, for instance, trigger automated alerts and care pathway adjustments.

Additionally, integration with teletriage platforms, AI-driven symptom checkers, and clinical Chabot's may allow initial auscultation interpretation to be partially automated, guiding patients toward appropriate care levels. This could be particularly valuable during healthcare system surges, such as pandemics or natural disasters.

Biomedical Engineering and Device Innovation

The field of biomedical engineering will continue to play a critical role in refining the hardware, form factor, and usability of digital stethoscopes. Innovations in sensor technology—such as piezoelectric polymers, fiber-optic transducers, and nanomaterials—promise to enhance sensitivity, reduce noise, and miniaturize devices [5].

Future stethoscopes may feature multi-modal sensing, combining acoustic data with contactless infrared, ECG, or even machine vision to contextualize findings. Some prototypes already explore flexible, skin-adherent stethoscopes for continuous auscultation, useful in intensive care units or neonatal monitoring [5].

Battery life, a known constraint, may improve with energy harvesting technologies, such as those converting body heat or motion into power. Likewise, haptic feedback, gesture control, and voice activation are being tested to facilitate hands-free operation in sterile or complex environments.

On the software side, future iterations will offer Augmented Reality (AR) interfaces that overlay diagnostic markers on anatomical images during auscultation, and voice-driven reports automatically generated from interpreted data. These features could reduce documentation burden and streamline care delivery.

Ultimately, as form and function converge, the stethoscope may transform from a simple listening device into a real-time, AI-enhanced diagnostic platform—embedded not only in telehealth but also in autonomous clinical decision systems, robot-assisted care, and digital twin frameworks.

CONCLUSION

Digital stethoscopes have evolved from niche technological curiosities to essential instruments in modern and remote clinical practice. By combining high-fidelity acoustic sensors, advanced signal processing, AI-based analytics, and cloud-based interoperability, these devices enable clinicians to perform reliable auscultation beyond the walls of traditional examination rooms. Their integration into telemedicine platforms has proven particularly transformative, supporting diagnosis, monitoring, and triage in both chronic disease management and acute care contexts.

Clinical studies have validated their diagnostic accuracy, user satisfaction, and clinical equivalence to in-person assessments in a variety of medical domains,

including cardiology, pulmonology, pediatrics, and emergency medicine. Nevertheless, widespread adoption faces challenges—economic disparities, regulatory uncertainties, data protection concerns, and clinician training gaps—which must be addressed to ensure equitable, safe, and effective deployment.

The future of digital auscultation will likely be shaped by AI augmentation, ecosystem integration, and engineering innovation, transforming the stethoscope into a smart diagnostic assistant rather than a passive listening tool. As healthcare systems evolve toward distributed, patient-centric models, digital stethoscopes are poised to play a critical role in making remote clinical assessments more precise, efficient, and universally accessible.

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