Design Evolution and Feature Enhancement Strategies for Advanced Digital Stethoscopes

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A stethoscope is a fundamental tool for auscultation and diagnosis medical practice and assists in the identification of sounds inside the body to predict cardiovascular and respiratory diseases. The advent of electronic and artificial intelligence (AI)-enhanced digital stethoscopes is prompted by the limitations of traditional auscultation performance, such as the need for a clinician's experience, failure to detect the required sounds in noisy conditions, and the inability to store patient data. This study focuses on the evolution in the design, relative performance characteristics, and areas of future improvement of stethoscopes, including digital devices that incorporate AI. Several studies show the employment of advanced filters to acquire important auscultating frequency bands, a high-gain amplifier to boost low-frequency internal body sounds, a noise cancellation circuit to block out background noise, Bluetooth for data sharing in real-time signal processing, and syncing with other medical devices. Key features that could be introduced in future versions are adaptive frequency filters, AI-based clustering to classify the sound, remote diagnostic functionality, and an improved data storage system. Protection circuits that take the form of lithium-ion batteries, wireless modules, and processing based on a microcontroller are some of the resource components highlighted in terms of portability and efficiency. This research seeks to develop stethoscopes by incorporating innovations while managing limitations, ultimately enhancing tools for healthcare professionals.

Keywords: Artificial Intelligence, Auscultation, Cardiovascular Diseases, Digital Stethoscope, Telemedicine.

Introduction:

Heart and lung diseases remain among the major causes of mortality worldwide [1]. Heart failure and valve illnesses like aortic stenosis affect millions of people, which is a huge strain on the health care system. Even after the recent progress in treatment, the lack of effective monitoring measures still leads to a high death rate and frequent rehospitalization [2]. Nearly one million people died in the US from heart disease and stroke in 2021, with over 75% of cases going undetected, according to the American Heart Association (AHA) figures released in 2024 [3]. According to the World Health organization (WHO), respiratory illnesses like COVID-19 and lower respiratory tract infections are the second leading causes of mortality worldwide, behind cardiovascular diseases (CVDs), which include heart attacks and strokes. In 2022, an estimated 19.8 million deaths per year were linked to CVDs alone [4]. Chronic respiratory diseases such as asthma, which affects close to 300 million individuals worldwide, exhibit characterized by inflammation, airway obstruction, and mucus accumulation, though the underlying cause remains unknown that the underlying cause of asthma remains unknown [5]. The assessment of bowel sounds is particularly crucial in patients recovering after surgery, as it helps to resume the intake early and eliminates the chances of developing a postoperative ileus (POI) [6]. To diagnose a variety of cardiopulmonary and gastrointestinal conditions, auscultation of the heart sounds, lung sounds, and gastrointestinal sounds is crucial [1]. Nevertheless, the challenges of detecting low-frequency sounds, including bowel sounds and heart murmurs that are often inaudible to the human ear, and the lack of consistency in auscultation skill and perception free from bias, limit its applications [2]. Stethoscopes were initially developed to facilitate the auscultation of chest sounds, enabling healthcare professionals to assess cardiovascular and respiratory function, as well as the condition of the trachea and bronchial tree as part of the airway system [7]. While modern diagnostic techniques such as Doppler imaging and ultrasound have gained popularity, auscultation using a traditional stethoscope remains widely practised due to its simplicity and efficiency in detecting health issues [8]. The stethoscope continues to serve a key function in medicine by enabling the detection of internal body sounds, including murmurs, atrial fibrillation, tachycardia, atrioventricular blocks, third and fourth heart sounds, wheezing, rhonchi, pleural rubs, and both fine and coarse crackles, as well as bowel sounds to analyze internal body diseases [8]. Although analogue stethoscopes are cheap and are generally applied in the detection of internal body sounds, they have some significant drawbacks. They are too bulky and heavy for convenient use or long-term monitoring. Moreover, sound analysis is done manually, hence it wholly depends on the skills of the clinician. Such stethoscopes are also not capable of recording or sharing auscultated information among health workers or with the patients. Besides, the human ear tends to miss low-frequency signals, which may lead to missed diagnoses [6]. Electrocardiography (ECG) is highly preferred due to its low cost, non-invasive nature, and diagnostic capability for heart conditions; it often fails to detect structural and valvular abnormalities, which are responsible for heart murmurs. Specifically, it may fail in detecting early heart sounds, S3 and S4 due to their low frequency (50 - 90Hz) with brief observation (120 - 180ms) whereas electronic stethoscopes or phonocardiography (PCG) devices offer a constructive alternative as they allow routine and inexpensive evaluation of cardiovascular condition relative to other equally invasive but expensive measures such as ECG [9]. Digital stethoscopes serve as essential tools for physicians by improving diagnostic accuracy through features such as enhanced sound amplification, noise filtering, and Bluetooth connectivity. In paediatric cardiology, immediate action and favourable long-term results depend on an early and precise diagnosis. Children with congenital or acquired heart diseases require efficient diagnostic approaches; however, conventional methods are often complex, time-consuming, and may not be readily accessible in all clinical environments.

To address these challenges, AI-powered tools such as smart stethoscopes offer fast, non-invasive, and reliable solutions that can greatly enhance paediatric cardiac care [10]. Expanding on this innovation, digital stethoscopes now enable continuous, wireless, and real-time auscultation through soft, wearable systems, offering strong potential as quantitative diagnostic tools across a range of medical conditions [7]. In veterinary practice, identifying diseases at an early stage is difficult because animals cannot communicate the source of their discomfort or describe their symptoms. Smartphone-based digital stethoscopes that combine PCG with single-lead ECG have demonstrated both diagnostic utility and versatility, as shown in studies on healthy sheep, where variables like breed were observed to influence ECG patterns [11].

Evolution of Stethoscopes: From Analogue to Digital Innovations:

The main purpose of stethoscopes is to observe patients' chest sounds, check the circulatory and respiratory systems, and determine if the trachea and bronchial tree can function as an airway. The stethoscope has undergone significant evolution since its inception, transitioning from purely mechanical instruments to sophisticated digital diagnostic tools. A simple mechanical instrument used for auscultation that amplifies chest sounds is the analogue stethoscope, often known as the standard or conventional stethoscope. An analogue stethoscope consists of a binaural earpiece and a chest piece. Sound at higher frequencies was detected on the diaphragm, whereas sound at lower frequencies was detected on the bell. The ears perceive audio as an output after the sound wave passes through the hollow tube to the binaural earpiece [12]. Because it is affordable, does not need a high level of operability in day-to-day activities, is widely available, and is simple for medical professionals to acquire, it appears to be the most likely reason for its appeal among health professionals [13]. The stethoscopes facilitate direct listening with no loss of time in the transmission of sound. However, they have many limitations. Mostly, the low-frequency sounds are difficult to observe, e.g., heart mitral stenosis, and there exists an attenuation in the acoustic fidelity. Furthermore, sound transmission can be reduced or stopped by any problem with the sound route, such as an air leak from the hollow tubing or the binaural earpiece [13]. Electronic stethoscopes were brought in to deal with these weaknesses. These are used to amplify acoustic signals with the use of analogue circuitry and may contain simple filtering algorithms to eliminate uncertainty caused by noise interference. With its electrical intervention, electronic stethoscopes allow for the amplification of chest sounds and offer functions like sound level adjustment, feedback sound, recording, and replay capabilities [14]. Electronic stethoscopes are important for some diagnoses and may discover very low-frequency components that regular stethoscopes are unable to detect. Research on bedside nursing in a clinical setting was also carried out to see whether there was a significant difference in the diagnostic utility of the gadgets. In 65% of patients, the electronic stethoscope was found to have better sound quality [15]. Although it has these benefits, the electronic models lack many essential features, specifically data storage or transmission, and have to be powered by a battery, and they are usually bulky as compared to their analogue counterparts, thereby making usability in some environments more cumbersome. Additionally, the cost and availability of the devices are significant constraints as well [16]. Digital stethoscopes have come onto the scene more recently, also hinting at a radical evolution in auscultation technology. This equipment can code and digitise acoustic data into data records that support capabilities like Bluetooth or Wi-Fi connectivity to transfer and exchange available data in real-time, data analysis, and visualisation. Furthermore, the diagnosis, treatment, and experience of patients and medical personnel are improved when AI or machine learning is incorporated into digital stethoscope programs [17]. Moreover, digital stethoscopes are the only devices that can facilitate data storage and cloud conditioning as well as sophisticated telemedicine features. However, these advances come at a higher cost, depending on the model and feature set—examples include the Eko DUO and the Littmann Core [18]. The shift from conventional to digital stethoscopes reflects a broader transition from subjective, experience-based assessment to objective, data-driven diagnostics. As digital technologies continue to mature, the stethoscope is evolving from a simple acoustic tool into a powerful diagnostic platform integrated with AI and remote communication capabilities. The major developments of stethoscopes from analogue to electronic and then to digital variants are summed up in Figure 1. A more thorough discussion of these developments and a comparison of the various types are offered in the following sections.

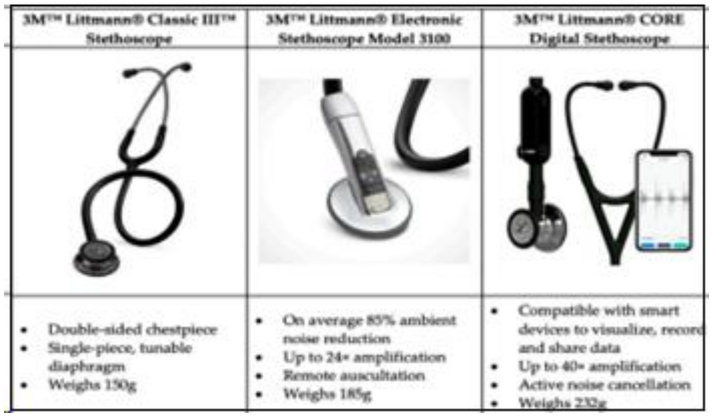

Figure 1. Progression of the stethoscope from Analogue to Electronic and Digital [7] [18]

Smart Display and Smartphone-Integrated Stethoscope Technologies:

Traditional, electronic stethoscopes are not enough to diagnose many diseases because the number of people who are affected is increasing, and the number of medical specialists remains limited. Therefore, it is crucial to develop a diagnostic method that ensures the safety of medical teams and enables healthcare professionals to assess a patient's health condition in real-time, regardless of location, with ease.

Smartphone-Based Auscultation Systems with AI Support:

Smartphones are used to diagnose lung and heart diseases, as they can capture sound through the microphone and sort the data for future analysis by medical professionals. It means that smartphones can find and analyse the disease by auscultation and also store and provide healthcare reports. With AI-enabled chips built into smartphones, the phone itself can act like a smart stethoscope. It can listen to body sounds, process them instantly, and help doctors detect health problems more easily, all without needing extra devices or sending data elsewhere for analysis. It's fast, smart, and portable [19]. An automated mobile health checkup system was presented by a team in Mexico in 2018, consisting of a microphone, a smartphone, and an Android-based application. The primary objective of the system was to identify crackles, abnormal lung sounds, as the traditional stethoscope cannot identify them. In this setup, the microphone captures the respiratory sounds, which are then recorded, stored, reproduced, and analysed by the mobile application with high accuracy [20]. Chinese researchers unveiled Auscal Pi, an affordable, ear-contactless digital stethoscope device based on the Raspberry Pi architecture, in 2021. This device offers a portable and effective auscultation solution by combining key parts such as a speaker, display screen, power source, USB-compatible microphone, and chest piece into a single printed circuit board (PCB). Clinicians can conventionally apply the chest piece to capture thoracic sounds, which may be listened to in real time via an onboard micro speaker or stored for later examination. Auscal Pi showed a statistically significant correlation coefficient between 0.3449 and 0.4797 ($p < 0.001$) with the 3M Littmann electronic stethoscope [20][21]. In 2023, U.S. researchers introduced StethAid (Ausculttech Dx LLC), an AI-assisted auscultation platform tailored for iPhone operating system(iOS) devices. The system is made of a smartphone, a particular application, and a wireless digital stethoscope consisting of five testing modes (bell, diaphragm, pulmonary, cardiac, mid-range, and extended mode [22]. Its frequency range is 20 to 20,000Hz with amplification up to 96 dB [22]. After capturing heart or lung sounds, the data are stored locally and then uploaded to the cloud for AI-based analysis using deep learning models. Among the tested algorithms, Harmonic Networks outperformed ResNet18, achieving better sensitivity (78%), specificity (86%), and overall accuracy (84%). This suggests that cell phones can analyse health data autonomously and deliver instant medical reports using on-device AI chips [23] as shown in Figure 2.

Table 1. A Comparative Table of Smartphone-based Devices [20][23][21]

System	Features	Limitations
Mobile health system	Uses a microphone, smartphone, and Android app. Records, stores, reproduces, and analyzes lung sounds. Identifies accurately crackles and abnormal lung sounds.	High cost. Poor sound quality in ambient noise.
Auscal Pi	Raspberry Pi–based, ear-contactless. Enables real-time listening and storage of lung sounds. Moderate accuracy compared to the 3M Littmann.	Complex design.
StethAid	AI-assisted auscultation platform for iOS. Wireless stethoscope with five modes. Supports cloud and on-device AI analysis. Having 84% overall accuracy.	Limited to iPhone and internet use. High cost.

Diagnostic Accuracy: Smartphone-Based Digital Stethoscope vs. Conventional Stethoscope

A research team in Portugal evaluated how well smartphone microphones perform in lung auscultation compared to traditional stethoscopes [21]. According to H. Lee et al., 134 paediatric and pulmonology patients with conditions like cystic fibrosis, asthma, and other respiratory diseases. Each underwent standard auscultation followed by smartphone recordings at the same chest sites. Cohen's kappa was 0.35, indicating a fair match when it comes to the detection of abnormal lung sounds, e.g., Wheezes and Crackles. These findings suggest smartphones are a promising, practical option for lung auscultation, though further refinement is needed for improved accuracy [19].

Technological Evolution of Sound-Based Diagnostics and Advanced Signal Filtering:

Auscultation methods have naturally advanced over time, as doctors have long relied on listening to body sounds for diagnosis [1]. In the 1950s, researchers began studying sound waves that cannot be heard by the human ear, such as those from blood flow or digestive activity, leading to the development of ultrasound technology [8]. Today, ultrasound is incorporated for examining joints, heart, and brain etc. [24]. Advanced methods, like those from the Focused Ultrasound Foundation, could target precise points in the brain to treat tumours or stimulate specific functions [8]. Early ultrasound systems could convert fetal heart sounds into audible signals, later evolving into M-mode for measuring heart valve function [24]. Modern ultrasound now produces safe, detailed 3D images [8]. Like this, infrasound, a very low-frequency sound wave, may one day be able to identify even the smallest changes in the body at the cellular level [25]. With enough digital data and AI, it may be possible to filter crucial signals from the background noise, just as ultrasound progressed from basic sound conversion to dynamic 3D imaging [19]. These developments highlight how medical diagnostics have moved from simple listening to sophisticated sound analysis, paving the way for modern tools like AI-powered, smartphone-based stethoscopes.

AI Integration in Smartphone-Based Digital Stethoscopes:

A smartphone digital stethoscope device using AI was further explored in [26] in 2019 for heart abnormalities. H. Lee et al. identified 27 significant features that span the time, frequency, and mel-frequency cepstral coefficient domains from the PhysioNet Challenge 2016 dataset, which included over 10,000 heart sound recordings. After evaluating 22 AI models, they found that ensemble classifiers performed best, with 97% accuracy for normal cardiac sounds and 88% accuracy for pathological ones [19]. It's crucial to monitor heart diseases at the early stages, but the major limitations, such as the reliance on computer-based processing, the lack of balance in the training data set, and the limitation to diagnostic accuracy in its entirety, may interfere with clinical trust. Ghanayim et al [27] focused on exploring the application of AI in smartphone-based digital stethoscopes in 2022 by creating VoqX (Sanolla), which intends to be involved in the diagnosis of aortic stenosis (AS). The system has a recorded range of 3-2,000 Hz that captures heart sounds with AI-based analysis of features, ejection time, and signal entropy used to detect moderate and severe aortic stenosis. AI gained a result of 86% and 90% sensitivities, and 100% and 84% specificities in the training/validation and the independent testing, respectively. The sensitivity became 93% in severe aortic stenosis and 55% in mild cases, which indicates the risk of undiagnosed cases. The effects of externalities on performance were also witnessed, which included noisy working environments and the challenges caused by patients, like obesity. The digital stethoscopes based on AI can address numerous disadvantages of the traditional auscultation method because their technology turns analogue sounds of bodies into digital ones and processes them in real-time. This method makes it easier and more conclusive when diagnosing conditions like abnormal breath sounds and heart abnormalities [27][19]. Moreover, the devices can connect to cloud systems where chronic conditions can be monitored remotely, and treatment sustained over a long period. Nevertheless, in order to achieve such potential, there is a need to circumvent the prevailing technical issues and to build trust in the technology and to introduce great legal and regulatory statements in the AI-accelerated smartphone-based digital stethoscope [19].

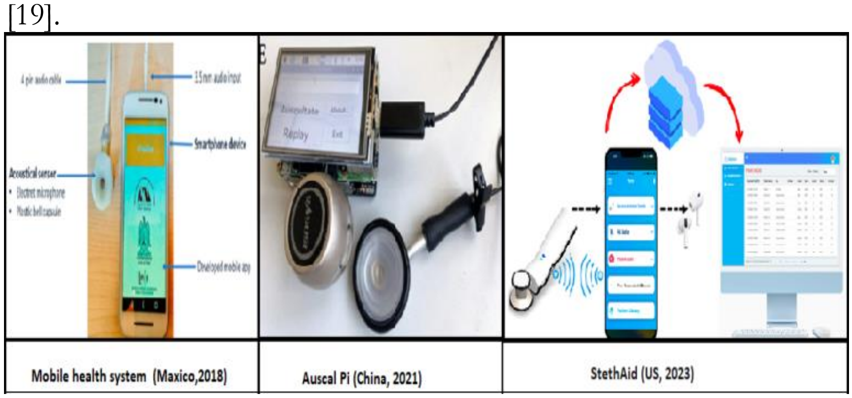

Figure 2. Smartphone-based Devices [20][23][21]

Implementation Barriers: Regulatory, Technical, and Data Management Challenges:

Interrogation of smartphone-based digital stethoscopes laden with AI within the healthcare sector is greatly problematic in terms of regulation and data privacy of sensitive patients, that have grown to be of greater concern [19]. The regulators and policymakers will need to develop a unified system that will deal with all issues of nascent healthcare technologies, touching on patient rights and the protection of medical information. A key priority is protecting personal health information and medical records, as emphasised in the United States Health Insurance Portability and Accountability Act (HIPAA) Privacy Rule [19][27]. AI systems used in healthcare, particularly with continuous sensor-based monitoring, face significant challenges in managing the vast amount of digital data produced. These include difficulties in analysing algorithms for reliability, reproducibility, causality, and potential biases. Despite proposals to improve data storage infrastructure, several barriers remain. Continuous audio recordings from sensors, especially when capturing both audible and inaudible wavelengths, drastically increase data size, in line with the Nyquist–Shannon theorem, which requires high sampling frequencies for accurate signal reconstruction [27]. Data volume is further amplified by duplication from multiple auscultation sites, integration of additional diagnostic modalities, and the need to isolate body sounds from environmental noise. These issues emphasise the urgent need for efficient, high-capacity systems capable of storing, retrieving, and processing real-time medical data without compromising accuracy or performance [19].

Applications in Veterinary Disease Detection:

Detecting diseases early in animals is difficult since they cannot explain their discomfort or symptoms. This makes routine veterinary checkups vital for maintaining their health. Recently, smartphone-based tools, especially in patient monitoring, have gained attention in veterinary research. For example, smartphone ECG systems have shown accuracy comparable to standard ECGs in animals such as cats and dogs [28][29], sheep [11], donkeys [30], cows, and horses [19]. In 2023, Vezzosi et al. [28] carried out a study by evaluating 99 dogs and 9 cats to determine the efficacy and utility of a smartphone-based stethoscope manufactured by Eko Devices, Inc. Some of the abnormalities that the device identified successfully included heart murmur, gallop rhythms, ventricular premature complexes, and ventricular premature blockages, and none of them contained false negative results. The collection of data, however, was not done in approximately 10 per cent of the animals due to their failure to cooperate. Smartphone-enabled digital stethoscopes can be utilised in the industrial animal management industry to effectively limit the spread of infectious diseases. It is possible to identify early abnormalities in individual animals' sounds, allowing for immediate identification of possibly infected animals and the successful management of a herd [31]. However, there are several limitations that need to be addressed when implementing this technology in veterinary medicine. These involve the control of animal behaviour during the recordings, consideration of the anatomical differences of animals across species, and the requirement of animal species-specific datasets to train the AI models. Also, it is imperative that quality and standardisation of data be ensured, which is collected by the animal owners or the farm workers. To make smartphone-based digital stethoscopes a reality in most veterinary practices, it is important to solve these issues.

Future Prospects of Smartphone-Based Digital Stethoscopes:

W. Qiu et al. projected that by 2029, the number of people who will own smartphones will be about 6.4 million [24]. As the use of smartphones becomes more available, this can enable the utilisation thereof in the healthcare sector in making preliminary and routine diagnoses traditionally done based on a stethoscope, CT scanners, and so forth, the level of efficiency and outreach can be enhanced [20]. Digital stethoscopes using an AI-enhanced smartphone, combining with the benefits afforded by auscultation (real-time auscultation, no added hardware), hold potential in pandemic and low-resource environments [21]. Nonetheless, the problems of regulation, accuracy, and data management should be solved [19].

Features Enhancements in Future Versions:

Taye et al. [32] also conducted a study that aimed to create a useful high-tech stethoscope by means of a systematic approach: design and concept selection. To start with, the authors came up with thirty possible functions and design options that were evaluated in numerous ways based on several assessment criteria that included material appropriateness, needs of the users, cost, safety, functionality, usability, and marketability. This thorough checkup allowed discounting the less viable alternatives and choosing the high-priority features. Finally, the paper elaborated on an extended digital stethoscope that would be used to increase the accuracy of diagnoses and overall user experience, featuring an improved filtering and amplification electronic platform and AI. The following are some of the present and upcoming features.

Existing Features in the Advanced Digital Stethoscope:

Among the many characteristics of modern electronic and digital stethoscopes use of a microphone, a type of transducer that transforms an analogue sound signal into a voltage or electrical output [32]. Different microphones have their functions and effects, such as piezoelectric microphones are used to pick the vibrations from the human body, which is a noise-free signal [33]. Many stethoscopes have built-in noise filtration to help pick out important sounds from background noise, along with powerful amplifiers for great sound quality, plus Bluetooth for easy data sharing with smartphones or computers [32]. They're built strong, with high-quality parts that promise a long life and do not let external noises to come in [33]. Several stethoscopes often have displays showing heart rate, volume, date, time, and battery life. Some models have a switch between digital and analogue modes adjust and use flexible acoustic tubes [18]. They can detect low frequencies through the LPF module [33], detect high frequencies through the HPF, and also use extended mode, where the whole frequency band comes in [22], and rely on lithium-ion or AA alkaline batteries for longer use [22]. The advanced versions can record, store, and share sounds [34] and can adjust the volume, also having a button to switch between diaphragm and bell modes, and work alongside blood pressure devices by integration with sphygmomanometers, while the advanced versions have the ability of wireless charging [22]. All these features set a solid foundation for what's next in stethoscope technology.

Proposed Innovations for Next-Generation Stethoscopes:

Future stethoscopes are expected to expand the traditional use of stethoscopes to include more advanced sensing, connectivity, and decision support features. Possible improvements involve introducing remote-dielectric sensing to measure the lung fluid concentration and the bio-impedance sensors to measure the tissue physiology and pathology in the chronically ill patients. To achieve that, automated arrhythmia detection systems connected to blood pressure alarm, wearable or implantable wireless fibre-optic oximeter catheter to continuously monitor oxygen levels, and non-invasive external pacemakers to provide emergency cardiac pacing could be added to cardiovascular diagnostic capabilities. Diagnostic flexibility along the same lines can be supplemented with handheld confined devices of echocardiography at work correlation and prototypes of cardiopulmonary exercise testing systems enabling close oversight of metabolic workloads based on heart rate, oxygen saturation, and physical activity intensity. The integration of AI with suggested models to identify the state of the patient, apply adaptive filters to separate respiratory or cardiac sounds, and draw phonograms in real-time on Wi-Fi-connected mobile phones. Telemedicine would also be possible through such AI-based systems due to the possibility of sharing auscultation information immediately with other medical personnel and making a shared diagnosis. Real-time feedback device features Cardiopulmonary resuscitation (CPR) can support life-saving interventions, and mechanical ventilators that automatically control humidity level, and extracorporeal pneumatic cardiac compressors are supported in critical care settings. More advanced models can also include options of varying the frequency ranges, so that clinicians can enhance particular bands of the sound within the range to receive diagnostics. All of these developments may gradually turn stethoscopes into multifunctional, connected, and smart diagnostic systems that will be able to facilitate early detection, constant monitoring, and remote medical care [14].

Core Resource Requirements for High-Performance Models:

The digital stethoscopes with advanced AI that can achieve high efficiency and reliability should have essential elements. It has a Lithium-ion battery, noise-cancelling earphones, an analogue or digital filter, and a backup power supply. Wireless communication networks facilitate a smooth flow of connections between them, and they have a charging system and a safety battery protection circuit. The linear voltage regulator, noise cancellation microphone, and high-gain amplifiers and analysis using an AI are sensitive enough to maintain their stability in performance [14].

Conclusion:

Understanding the benefits and limitations of traditional, electronic, and digital stethoscopes is an essential consideration for diagnosing chronic cardiopulmonary, gastrointestinal disease, and, more importantly, for the global health crises where human mobility is restricted. There are many methods available to perform a comparison of the different types of stethoscopes, allowing for improved credibility and result validation. Digital stethoscopes are taking new dimensions to improve the diagnosis of internal body diseases by the implementation of AI and machine learning algorithms in smartphones and improved technological characteristics. Moreover, other features like noise reduction, data storage, and portability need enhancement. As research and innovation continue, healthcare technology improves continuously over time, overcoming the limitations of the previous stethoscope options by integrating new medical engineering solutions. The rationale of these advancements is to improve diagnostic accuracy, enable remote healthcare, and support data-driven medical decision-making. The future models can be even more reliable and convenient to use, thus able to assist healthcare professionals in providing patients across the world with much better care.

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