Development and validation of a low-cost electronic stethoscope: DIY digital stethoscope

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INTRODUCTION

COVID-19 pandemic has presented us with unique challenges. One of them is evaluating patients with lung pathologies. Wearing personal protective equipment (PPE) (especially coveralls), because of covering of ears, precludes use of one of the time-tested tools of patient assessment—the stethoscope. Because of this, rapid assessment of patients at multiple points of time is affected. To overcome this, use of bedside ultrasonography has been advocated[1] ; however, ultrasonography is costly and requires additional training. Also, the availability of ultrasonography is not universal. Besides, there is no easy alternative for detection of wheeze and evaluation of symmetry of breath sounds, both of which have therapeutic implications.

One of the ways around is to use electronic stethoscopes, but they are too costly for mass deployment, with a price averaging around US$500 from the established brands.[2 3] We have developed a low-cost system to convert user's existing stethoscope to a digital one without damaging it: do-it-yourself (DIY) digital stethoscope. The system consists of a microphone attached to the stethoscope, custom-built Android-based app available on Google Play Store[4] and headphones. We present here the development and validation of this frugal innovation.

MATERIAL AND METHODS

A digital stethoscope requires a sensor to collect the sounds, a processor and a playback system. We tried various permutations and combination of multiple sensors (electret vs micro-electro-mechanical system vs piezoelectric) in different configurations (directly applied to skin vs within the chestpiece vs within the tubing of the stethoscope vs at the ear tip). For our model, we decided to use an electret microphone (eg, collar mic) at the earpiece of the stethoscope.

Summary box

What are the new findings?

- An easy way to convert your stethoscope to a digital stethoscope without harming it.

How might it impact on healthcare in the future?

- Facilitate auscultation while wearing personal protective equipment.
- Telemedicine—auscultate from distant location.
- Medical education—allows simultaneous auscultation by multiple people and for better learning experience.

The objective of processing was to amplify the signal and reduce the noise. During preliminary testing, we captured audio directly into an open-source, free license software called Audacity (Audacity, USA), V.2.4.2, running on a computer. Thereafter, we compared multiple audio-processing algorithms for each above said objectives, in different combinations, determined the optimum settings and adapted them to the DIY stethoscope app for automated use on a mobile phone.[4] The app uses the following processes on the signal: Android noise suppressor, audacity noise reduction, low pass filter, compressor and amplification with noise floor.

Device assembly protocol

1. Select an earpiece which has a large opening and adequate elasticity to accommodate the microphone.[5]

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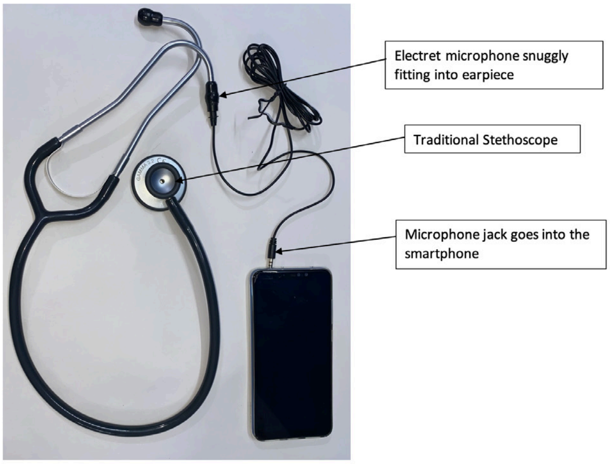

Figure 1 Device assembly showing the stethoscope, microphone and the mobile phone.

2. Remove the foam covering from the microphone.
3. Fit the microphone into the earpiece; ensure a snug fit.
4. Plug the jack from the microphone into the smartphone (figure 1).
5. Pair your headphones to the smartphone.
6. Open the DIY stethoscope app.
7. Hold the chestpiece gently to the area you want to auscultate.

Testing

For our study, we compared the performance of DIY digital stethoscope with a conventional one on the following parameters:

- Loudness of sound.
- Sound clarity.
- Loudness of noise.
- Interference caused by noise.
- Satisfaction.
- Comfort.

Observers were asked to give a rating of 1–10 on each of the above parameters for both types of stethoscope. In addition, the observers were asked to report on any abnormal sounds heard on auscultation by the two techniques.

We conducted this study in internal medicine and paediatrics wards of a tertiary care hospital of Northern India in the month of November 2020. To reduce bias, two stethoscopes of the same maker were used: Littmann Classic III (3M, USA). Microphone was attached to one of them and was converted to a DIY stethoscope. A sample size of 100 auscultation events was decided on for this validation study. Observers were identified from within the residents posted in these wards. Due to the nature of the study, blinding was not possible. The observer had to perform auscultation of lung and cardiac fields for each patient using both the stethoscopes, followed by filling of the assessment forms. Random number table was used to determine which stethoscope was to be used first for each of the patients. Patients were identified using convenient sampling. After explaining the procedure to the patient/parent/guardian and taking informed consent, auscultation was done. All patients more than 1 month of age were approached and those who were prone or uncooperative or crying children were excluded.

Statistical analysis

Two assessment forms were filled for each patient. All the data were entered into MS Excel (Microsoft Corp, Redmond, Washington, USA) and analysed using Stata software (StataCorp, College Station, Texas, USA). Descriptive statistics such as median value as well as IQR for each parameter were calculated for each device, and compared between the two devices using Wilcoxon signed-rank analysis. Agreement between the various assessment parameters for the two devices for identifying a pathology was correlated using Cohen's kappa.

RESULT

Sixteen (12 men) residents from the above wards participated as observers in this study. Their median (IQR) age was 27 (25–27) years, and the median (IQR) years of residency training was 2 (2–4) years.

One hundred and seven patients were approached, seven were excluded (four were crying children and three did not give consent). One hundred patients were auscultated, their median (IQR) age was 22 (7–33) years. Details of patient characteristics are given in table 1.

The median (IQR) score for loudness was significantly higher in DIY stethoscope as compared with conventional stethoscope: 8 (7–9) vs 8 (7–8). Scores for sound clarity, comfort and overall satisfaction were similar between the two devices. However, DIY stethoscope had significantly louder ambient noise as well as greater interference in auscultation because of the noise as compared with conventional stethoscope (table 2).

Abnormal findings were identified in 31 patients using the DIY stethoscope and 31 patients in conventional stethoscope, with good agreement between the two devices (kappa=1).

During testing, a lag in playback of about 0.7 s was also identified in the DIY stethoscope.

DISCUSSION

We developed and validated a frugal electronic stethoscope. In this study, we found DIY stethoscope provided sounds with good clarity and good overall satisfaction, with median score of 8 for both the parameters, which is similar to a conventional stethoscope. While the DIY stethoscope had higher noise levels, it did not impact the ability to identify auscultation findings and both the devices had good agreement on it (kappa=1).

For the DIY stethoscope, we chose to use an electret microphone (a collar mic) for our device because of low cost, wide availability and easy interface with the smartphone. The sensor can be placed directly on

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Table 1 Characteristics of observed patients

Total number of patients	100
Age*	22 (7–33) years
0–5 years	20
5–10 years	16
10–18 years	10
>18 years	54
Sex	65 males, 35 females
Mechanically ventilated	7
Randomisation	49: conventional stethoscope first

*Median (IQR); other values are 'n'.

the skin but pairing it with the chestpiece of a stethoscope takes advantage of its bigger collecting surface. The design and quality of chestpiece and tubing of the stethoscope has an impact on the audio output, with efficiency improving with smaller length and diameter of tubing.[6] The microphone could be placed anywhere, from the chestpiece to within the tubing or at the earpiece. The advantage of placing the microphone at the earpiece is that it does not require sacrificing the stethoscope, and it can be restored back to its original state. So, one can take advantage of better acoustics of expensive stethoscopes, without worrying about the cost. The microphone should fit snugly into the earpiece, not allowing any leakage of sound around it. Placing the sensor at earpiece allows interference from the ambient sound, presumably entering through the 'open' earpiece. Blocking it or placing sound-absorbing material resulted in interference with the signal captured at the sensor probably as a result of signal from the 'open' earpiece being reflected back towards the stethoscope and interfering with the signal. Therefore, we chose to keep the earpiece open and use noise-reduction algorithms to reduce the noise.

Removal of ambient noise and other artefacts such as motion artefact is a challenging task, with some commercially available products using active noise cancellation[7]: adaptive line enhancement or least mean squared or other machine learning protocols, with varying degrees of success.[7 8] We chose not to use them, as simultaneous playback of the captured sound was required and these are computationally taxing algorithms and may not work very well with wide range of processing capacities in different mobile smartphones.

The audio output could be through an externally connected speaker, inbuilt speaker of the mobile, earphones, headphones, etc. Since the signal consists of sounds mainly in low-frequency range, devices capable of sound reproduction in this range, that is, high bass, offer better output. Headphones offer ease of wearing, comfort and ability to transmit sound while wearing PPE. Playback of sound through speaker, during auscultation, may cause an audio loop with the same sound being fed forward to sensor and being amplified repeatedly, however they may be excellent choice for training.

We took a modular approach for our device, taking advantage of the fact that most healthcare workers already possess good quality components required for an electronic stethoscope (eg, high-end stethoscope, a smartphone and headphones). They may need to buy, only the microphone, which is inexpensive. This device offers a low-cost solution to one of the challenges faced in managing patients with COVID-19. It can be rapidly deployed and can have an impact on patient care, not only in inpatient settings (figure 2) but also in outpatient settings where doctors can auscultate the patient from a safe distance. This device can also be used for telemedicine where healthcare workers at remote settings can help doctor auscultate the patient and make a more informed decision. The solution allows multiple users to auscultate simultaneously by playback through a speaker, which can be used in medical education. The device can also help healthcare professionals with hearing deficits.

Among the configurations possible, microphone at earpiece does not harm the stethoscope However, one can also salvage any old/broken stethoscope with intact chestpiece to be used in other configurations (figure 3). Keeping the microphone within the tubing would also reduce the noise levels as compared with keeping it in earpiece.

There are no standardised techniques to test the output of a stethoscope. Of late, electronic stethoscopes have been tested, by applying them over

Table 2 Summary of results comparing DIY stethoscope with conventional stethoscope

	DIY stethoscope	Conventional stethoscope	P value
Loudness of sound	8 (7–9)	8 (7–8)	0.0002
Sound clarity	8 (7–8)	8 (7–8)	0.152
Loudness of noise	3 (2–4)	2 (1–2)	<0.0001
Interference by noise	2 (1–3.5)	1 (1–2)	<0.0001
Comfort	8 (7–9)	8 (7–8)	0.1317
Overall satisfaction	8 (7–8)	8 (7–9)	0.1495
Abnormal sounds identified, n (%)	31/100 (31)	31/100 (31)	Kappa=1

Values are median (IQR) unless indicated p value calculated using signed-rank analysis.
DIY, do-it-yourself.

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Figure 2 Do-it-yourself stethoscope used in COVID-19 facilities.

an instrument which generates sound of various frequencies and at varying intensities and the output is assessed using the spectral analysis.[9 10] Another method to compare stethoscopes is rating by the observer of different devices on a Likert scale on various parameters such as intensity of sound, noise, comfort, etc.[11–13] We opted for this approach, as although being subjective, this approach captures the real-world scenario and allows testing in various settings such as in ventilated patients or noisy environment of wards as compared with quiet testing in a laboratory.

Compared with other electronic stethoscopes, this device provides similar functionalities such as sound amplification, noise reduction, and the ability to share auscultated sounds but is cheaper, does not need to be charged and there are no limitations to the length or number of recordings that can be made.

As DIY stethoscope has higher ambient noise levels, it might be difficult to use it in a noisy environment such as an ambulance. Using it in quieter environment and noise reduction at source, such as muting any unnecessary alarm, will improve the auscultation quality. The quality of auscultation also depends on components used for the assembly. Good quality stethoscopes provide better input to the microphone, playback devices with good bass allow for more accurate reproduction of auscultated sounds. There is also a lag in playback, so situations requiring coordination between auscultation and another process such as manual blood pressure measurement may require more careful measurement or alternative method. Although not complicated, some physicians might require time to get used to the interface and to the sounds generated. Future versions of this device should strive to reduce the lag and improve on noise reduction. As blinding was not possible, some bias may have been introduced because of this. We tried to reduce this by enrolling multiple observers. We also did not compare the DIY stethoscope with other electronic stethoscopes. Future studies may compare it with other electronic stethoscopes.

Figure 3 Microphone attached at chestpiece.

CONCLUSION

Here, we present a technique to convert a stethoscope to an electronic one, aimed at improving patient care while wearing PPE. The device could also be used for training of students in medical and nursing colleges. The sound clarity and identification of pathological sounds is similar to that of a conventional stethoscope, but noise levels are higher in DIY stethoscope.

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Contributors AgJ was involved in conceptualisation, development and testing of the device, and wrote the paper. RL was involved in conceptualisation, development and testing of the device, and contributed to writing the manuscript. RS was involved in conceptualisation, development and testing of the device, and contributed to writing the manuscript. PS was involved in testing of the device and contributed to writing of the manuscript. ArJ and TG developed the app and contributed to writing the manuscript.

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Competing interests None declared.

Patient consent for publication Obtained.

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