

Agreement of artificial intelligence equipped stethoscopes with known echocardiogram results in screening emergency department patients for audible murmurs

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Abstract

Background and objectives

Cardiac auscultation can be limited in the emergency department (ED) because of many factors. We tested the ED performance of a digital stethoscope attachment coupled with AI interpretation of the sounds.

Methods

Eko Core is a listening attachment added to a stethoscope's tubing which amplifies, filters, and uploads heart sounds to a database where SENSORA artificial intelligence reports on presence or absence of a heart murmur that is at least mild. We tested the device's AI output as well as that of blinded human annotators from Centaur Labs in ED patients with recent echocardiograms. Sensitivity, specificity, positive (PPV) and negative predictive value (NPV) with 95% Confidence intervals were calculated for AI interpretation of the sounds and compared with the human interpretation, both in conjunction with the known echocardiogram results. False positives and negatives were analyzed.

Results

AI sensitivity for echo-proven disease was 75%, specificity 62%, PPV 73%, and NPV 65%. Much of the valvular heart disease was inaudible to blinded human reviewers of recordings who had sensitivity 69%, specificity 83%, PPV 89%, NPV 57%. Finally in recordings in which human annotators could attest that echocardiogram shown disease was audible, AI sensitivity was 98%, specificity 71%, PPV 73%, and NPV 98%.

Conclusion

We found the AI interpretation of sounds to be more sensitive than that of human ears, very good for detection of disease audible to reviewing cardiologists. There remained structural heart disease that was not audible of relatively mild clinical significance.

Introduction

When diagnosing valvular heart disease, cardiac auscultation with a traditional stethoscope has historically been the primary screening tool, typically followed by an echocardiogram for confirmation and grading. (Mrsic et al., 2018). However, there is a level of subjectivity with auscultation as it can vary from one physician to the next based on their ability to discriminate the sounds and other confounding factors such as body habitus, disease severity, and noise level in a clinic (Hafke-Dys et al., 2019).

Left untreated, valvular heart disease has significant morbidity and mortality. For example, Lancellotti et al., 2018 found 8% mortality over 2 years in patients with severe aortic stenosis. However, the prognosis for valvular heart disease has improved considerably due to the advancement of medical technology and

surgical options, such as TAVR. Smith et al. 2011 conducted a study assigning 699 patients with severe aortic stenosis to either a TAVR or surgical replacement. The results found that there were similar outcomes between the two groups, but patients receiving the TAVR had improvements in their symptoms thirty days following the procedure. Thus accurate diagnosis can pay off with improved clinical outcomes better than ever before.

Use of artificial intelligence (AI) in medicine can improve detection of conditions that can be missed by human factors. Electronic stethoscopes have been shown to be more accurate for hearing heart and lung sounds (Tourtier et al., 2011). When using electronic stethoscopes for auscultation in air medical transport, they were found to reduce external sound and amplify the sounds that were being identified (Tourtier et al., 2011). Artificial intelligence has started to be paired with digital stethoscopes. A study done by Ghanayim et al 2022 found that AI was successful in detecting aortic stenosis using an electronic stethoscope for patients referred for an echocardiogram with moderate or severe aortic stenosis. Prince 2023 demonstrated that an AI, developed by Eko, had a sensitivity of 97.9% and specificity of 90.2% for grade two murmur detection in adults.

Our hypothesis is that use of a digital stethoscope equipped with AI technology can effectively identify the presence of a clinically significant murmur when used in the emergency department environment.

Materials and Methods

Study Setting and Design

From November 2023 through March 2024 a convenience sample of patients who had cardiac symptoms such as chest pain were recruited by study personnel when available in our community emergency department with an EM residency and an annual volume of just under 50,000. This study obtained institutional IRB approval from our hospital's IRB.

Electronic Stethoscope and AI Description

Stethoscopes used in this project were the 3M Littmann CORE Digital Stethoscope. The Eko CORE is a listening device attachment that can be added to the tubing of a stethoscope with a dual purpose. It amplifies and filters the sounds a clinician hears through the earpieces and records the audio of the auscultation, uploading it via Bluetooth to the HIPAA compliant Eko SENSORA platform in real time. The SENSORA platform is a cardiac disease detection technology which uses AI to detect clinically significant heart murmurs (Prince, 2023).

Human Annotation of Recorded Heart Sounds

Each heart sound was annotated using the Centaur Labs platform. Each recording was presented to multiple annotators, each of whom specified the content of the recording (i.e. presence of audible

murmur). Each recording was assigned as the majority annotation of the Centaur Labs annotators. All annotators underwent training and quality assessment for accuracy relative to a panel of expert cardiologists.

Power Calculation

Historically the Eko Core paired with SENSORA was able to detect interpretable heart sounds from all four listening posts 65.2% of the time (Prince, 2023). We estimated we would need 30 patients to show non-inferiority (within 1%) for one listening post and 87 patients to show non-inferiority (within 1%) for all four listening posts. Sensitivity and specificity were calculated for SENSORA as compared to the historical echocardiograms.

Data Collection

Our study population was composed of emergency department patients over the age of 50 who had an echocardiogram in the previous two years with results viewable in the electronic health records. We excluded patients in contact isolation, non-English speakers, prisoners, and patients present when study personnel were not available. Patients meeting criteria were approached by study personnel to request permission to obtain recordings and compare the results to the historical echocardiogram. Study personnel obtaining permission and recordings from patients were comprised of third year medical students as well as a research technician with EMS experience. Heart sounds were recorded from each of the four cardiac listening posts and uploaded using a study generated code to the SENSORA database. Age, sex, race, BMI, chief complaint, heart rate, respiratory rate, SENSORA results for each listening post, and echocardiogram results for each valve were recorded in a spreadsheet stored on secure hospital servers.

Outcomes

Our primary outcome was to determine whether the AI-paired device could get adequate recordings for interpretation in a potentially noisy emergency department. Our secondary outcome was to determine whether the results of these recordings would agree with the patients' historical echocardiogram results. While we did compare the device's interpretation to the echocardiograms, the definition of ground truth was that the patient had at least mild valvular disease on echocardiogram in whose recording was also deemed audible and analyzable by annotators when they listened to the recording.

Primary Data Analysis

Sensitivities, specificities, positive, and negative predictive values are reported along with 95% confidence intervals.

Results

Demographics

We gathered data on 102 patients in the study, however, three patients had to be excluded. Two were enrolled accidentally: one did not have an echocardiogram, and another had an echocardiogram more than two years preceding their index visit. A third patient had to be excluded when an incorrect medical record number was recorded making it impossible to retrieve echocardiogram data, resulting in 99 patients. These 99 participants consisted of 53 women and 46 men. The median age of the participants was 73.5 (interquartile range of 62 to 80). Nineteen patients were black or African American, one patient identified as Pacific Islander, and 78 patients were white. The median BMI for the included participants was 28.96 kg/m² with an interquartile range of 24.96 kg/m² to 33.33 kg/m².

Recording Quality

Of the 99 patients in whom recordings were attempted, recordings were able to be uploaded from each for the aortic, pulmonic, and tricuspid areas. In one patient a recording was not able to be obtained from the mitral area. These recordings were sufficient for SENSORA to analyze nearly all the time (Table 1). In contrast when human Centaur Labs annotators listened there was useable data for human analysis in at least one listening post for 72 patients (73%).

Table 1
Recording quality

Position	N	SENSORA AI rated good signal	Human rated good signal
All	395	391 (99.0%)	163 (41.3%)
Aortic	99	99 (100%)	39 (39%)
Pulmonic	99	97 (98%)	47 (48%)
Tricuspid	99	98 (99%)	52 (53%)
Mitral	98	97 (98%)	25 (26%)

SENSORA Performance Compared to Echocardiogram

Fifty-seven of the 99 patients (58%) had historical echocardiograms demonstrating at least mild valvular heart disease of at least one valve. These echocardiograms were performed a median of 2 months prior to the index visit, (4.7 months mean) with interquartile range (Q3-Q1 = 8 months). SENSORA agreement with the echocardiograms is presented in Table 2.

Table 2
SENSORA agreement with echocardiograms

SENSORA (+)	Echocardiogram (+)	Echocardiogram (-)	total
	43	16	59
SENSORA (-)	14	26	40
total	57	42	99

The resulting sensitivity and specificity was 75% (95%CI 62% to 86%) and 62% (95%CI 46% to 76%) respectively with a positive predictive value of 73% (95%CI 64% to 80%) and negative predictive value 65% (95%CI 53% to 76%).

Of the 14 false negatives only one had a murmur identified by the human annotators. Nine patients were identified as having mild valvular heart disease, four with mild-moderate, and one (a patient with moderate tricuspid regurgitations) deemed inaudible by human review had moderate disease on echocardiogram. Mean BMI of the 14 false negatives was 27 (SD 7.3) whereas for the 82 other patients it was 30 (SD 8.0), $p = 0.13$ (95%CI of the mean difference - 1.0 to 7.8)

Human Reviewers Compared to the Echocardiogram

The recordings were analyzed by human Centaur Lab annotators. Seventy-two patients had recordings which were graded by humans as having evaluable sounds. Forty-eight of these 72 patients (67%) had at least mild valvular heart disease on their echocardiograms. Human annotators were able to hear a murmur in 33 of the 48 patients (69%) and did not hear murmurs in 20 of 24 patients (83%) in whom echocardiogram also did not find at least mild valvular heart disease. Human sensitivity and specificity were 69% (95%CI 54% to 81%) and 83% (95%CI 63% to 95%). Human positive predictive value was 89% (95%CI 77 to 95%) and negative predictive value 57% (95%CI 46% to 68%).

SENSORA Compared to Auscultable Echocardiograms

Forty-four of the 99 patients (45%) had echocardiograms demonstrating at least mild valvular heart disease which was able to be heard by the human annotators. SENSORA identified 43 of these 44 patients (98%). SENSORA agreed there was no audible valvular heart disease in 39 of 55 patients (71%). It did also identify a murmur in 16 of the 55 patients (29%) of patients in whom a murmur was not felt to be present by annotators. In this scenario sensitivity was 98% (95%CI 88 to 99%), specificity was 71% (95%CI 57% to 82%) with a resulting positive predictive value of 73% (95%CI 64% to 80%) and negative predictive value of 98% (95%CI of 85% to 99%). Of the 16 false positives, 9 did have trace valvular heart disease on the echocardiogram. Notably, when limited to cases in which mild or worse valvular disease on echocardiogram was also audible to cardiologist reviewers, the AI achieved a sensitivity of 98% (95%CI 88% to 99%).

Performance in the Presence of Increased Endogenous Chest Sounds

Three patients in our series were on BiPAP or had a tracheostomy which would increase the sounds heard inside the chest, which would have the possibility of confusing the software which “cleans” the recordings of exogenous background noise. Performance is reported in Table 3.

Table 3
Performance in patients with increased endogenous chest sounds

Patient history	SENSORA AI output	Centaur human annotation	Echocardiogram result	Device performance
75yo M, BMI 33, chief complaint: respiratory failure	Continuous murmur at RUSB, LLSB, apex	Structural murmur	Moderate AS, mild TR, trace MR. EF 45–50%	True positive
38yo F, BMI 22, chief complaint: SOB, trach	No structural murmur	No structural murmur	Trace MR. EF 65–70%	True negative
52yo F, BMI 45, chief complaint: chronic pain	Diastolic murmur at LLSB, apex	No findings <i>(recording quality was inadequate to determine murmur presence)</i>	Normal echocardiogram. EF 60–65%	False positive

Discussion

Overall, the results of the study show that the AI assisted device performed well in the setting of the emergency department at detecting the presence of audible VHD. When compared to the echocardiogram findings of known disease, SENSORA had a 75.4% sensitivity and a 61.9% specificity. The positive predictive value was reported as 73% and the negative predictive value as 65%. These numbers exceeded the human review of the recordings. This is consistent with the observation that a lot of valvular heart disease is not detectable with auscultation; we would expect false negatives compared to an echocardiography gold standard. In a review of 23 articles comparing auscultation to a mixture of echocardiography, pulsed Doppler, aorto- or ventriculography or point-of-care ultrasound, Davidsen (2023) found sensitivity and specificity of auscultation to range from about 30 to 100%. At the low end was Gardezi (2018) finding that traditional auscultation in the primary clinic setting had a sensitivity of 32% for mild disease and only 44% for significant VHD. Only one of these articles was performed in an ED setting; Reichlin (2004) found a sensitivity of 80% and specificity of 69% for physicians in the ED

compared to echocardiogram. Their physicians did however have full access to the patient's past medical records including prior echocardiogram data. This study was carried out at a Swiss hospital staffing its ED with internal medicine residents and attendings with internal medicine board certification. The highest sensitivity and specificity reported by Davidsen was from Draper 2019 where cardiologists seeing patients referred to an English murmur clinic achieved 91% sensitivity and 100% specificity for auscultating murmurs.

Because of the difficulties with accurate auscultation, a number of studies have examined AI Assisted Auscultation (AIAA). Thompson 2019 tested an algorithm that had 93% sensitivity and 81% specificity when applied to a recording database obtained in a large academic pediatric cardiology center. A study done by Ghanayim et al. (2022) found that AI-paired stethoscopes also had a high rate of detection for murmurs. This study focused on aortic stenosis and reported a sensitivity of 86% and a specificity of 100% for patients that were found to have severe AS. Furthermore, a study done by Susic et al. 2022 used two different types of electronic stethoscopes to compare their efficacy to the cardiologist interpretation in patients who already had pre-existing heart failure. Using these two devices, researchers found that there was a 72% classification accuracy as compared to the cardiologist interpretation which had a detection rate of 50%. Chorba et al studied the product used in this study (Eko SENSORA) in multiple academic cardiology offices finding sensitivity of 76% and specificity of 91%, with a sensitivity of 90% if grade 1 intensity murmurs were excluded.

Our goal was to show that this device previously tested in academic cardiology offices, likely in ideal conditions, would also work well in a frequently noisy and chaotic emergency department. The AI demonstrated strong performance for audible disease, achieving 98% sensitivity in patients with mild or worse valvular disease on echocardiogram that was also identified by cardiologist reviewers. This underscores the potential for AI-augmented auscultation to enhance detection of clinically meaningful murmurs in noisy environments like the emergency department. Only one of our false negatives was indicated as having a murmur by a blinded human reviewer of the recording. Only one of the false negatives had disease rated by the echocardiogram as moderate. We did not find BMI to be a contributing factor to false negatives.

The false positives in our study are harder to characterize. The AI assisted device is designed to recognize disease rated as mild. Nine of the 16 cases labeled as false positives did have trace disease present on their echocardiogram. It is possible that the device recognized some of the trace disease as mild or that disease had worsened between the time of the echocardiogram and the index visit where Eko recordings were taken. Another possibility is that the false positives stemmed from lower-quality recordings that were still processed by the AI but excluded from human review. In our study, recordings were evaluable by human annotators in only 72 of the 99 patients, whereas the AI was able to analyze nearly all recordings. This discrepancy suggests that the AI screened a broader denominator of patients, an advantage in real-world settings, but one that may also contribute to its lower specificity. Human annotators' more cautious exclusion of noisy or poor-quality recordings could partly explain their higher

specificity. Future work should examine the characteristics of recordings deemed uninterpretable by human reviewers to better understand the impact of recording quality on AI performance.

There are many examples of conditions where prompt recognition of a murmur can be beneficial in the emergency department. Aortic sclerosis is common, but as it progresses to aortic stenosis, symptomatic disease can carry a two-to-three-year life expectancy if not intervened upon (Gottlieb 2018). Infective endocarditis will lead to heart failure in most patients and devastating neurological complications in many if not treated (Phillip, 2022). Acute mitral insufficiency in the setting of acute myocardial infarction can lead to rapid heart failure and unlike aortic stenosis where the murmur gets louder as it becomes more clinically significant mitral regurgitation murmurs can be quite subtle (Watanabe 2019). Hypertrophic obstructive cardiomyopathy has caused sudden cardiac death in athletes both famous and little known and yet most patients with it are undiagnosed (Maron, 2018). Increasing the effectiveness of screening for murmurs in the emergency department could allow for earlier treatment for many of our patients

Beyond its diagnostic capabilities, AIAA may also have important applications in emergency medicine education. Learners often have limited exposure to pathologic murmurs, and the busy emergency department environment can make recognition of subtle auscultatory findings particularly difficult. AI-assisted bedside examinations may provide real-time feedback regarding murmur identification and underlying cardiac pathology. This could strengthen physical examination skills, support learner development throughout training, and help maintain high-quality patient care in demanding clinical settings.

Although our results using AIAA provide evidence of improved detectability of VHD in the emergency department, there are still certain confounding conditions that can make this difficult. AIAA detection of valvular heart disease will still be limited for patients on positive airway pressure breathing such as BiPAP or CPAP because those devices increase noise internal to the patient. While Eko stethoscopes are designed to help filter out ambient noise external to the patient they are not designed to filter noises internal to the patient

Limitations

This study was performed upon a wide cross section of emergency department patients. It was not focused on specific murmurs; rather we sought to evaluate the device at a broad level. As it was done pragmatically in the ED, contemporaneous echocardiogram data was not available for many patients. One of our main comparisons was to annotator evaluation of the heart sounds; we did not attempt to compare to the interpretation of the heart sounds by the clinical team.

Conclusions

We found the AI interpretation of sounds to be more sensitive than that of human ears. It was very good for detection of disease audible to reviewing cardiologists. There remained, however, structural heart

disease that was not audible, though of relatively mild clinical significance.

Declarations

Declaration of competing interest

The Office of Medical Education at Corewell-Lakeland supported the subscription to the Eko SENSORA product. The authors declare they have no known competing financial interests or personal relationships that influenced this work. The authors have approved the publication of this manuscript.

Ethics and Consent to participate

This study was carried out in compliance with relevant laws and institutional guidelines and was approved by the Lakeland Hospitals Niles and St. Joseph, IRB# 1 as study #1634 on August 25, 2023. Informed consent was obtained from every participant for obtaining the recordings and review of medical records. The privacy rights of human subjects were observed by storing data on protected hospital servers using a study ID once the records were extracted. Generative AI was not used in the creation of this paper.

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The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Credit authorship contribution statement

Matthew Hysell: Supervision, Methodology, Conceptualization, Writing - Review and editing, Formal analysis. **Zara Chaudhry:** Writing – original draft. **Monique Luna:** Investigation. **Rachelle Pichot:** Investigation, project administration. **Zachary Heeringa:** Investigation. **AhnTuan Tong:** Investigation. **Michelino Mancini:** Funding acquisition, Writing – Review and editing. AI was not used in the preparation of this manuscript.

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