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The Impact of Computer-assisted Auscultation on Physician Referrals of Asymptomatic Patients with Heart Murmurs

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Summary

Background: As many as 50–70% of asymptomatic children referred for specialist evaluation or echocardiography because of a murmur have no heart disease.

Hypothesis: Computer-assisted auscultation (CAA) can improve the sensitivity and specificity of referrals for evaluation of heart murmurs.

Methods: Seven board-certified primary care physicians were evaluated both without and with use of a computer-based decision-support system using 100 prerecorded patient heart sounds (55 innocent murmurs, 30 pathological murmurs, 15 without murmur). The sensitivity and specificity of their murmur referral decisions relative to American College of Cardiology/American Heart Association (ACC/AHA) guidelines, and sensitivity and specificity of murmur detection and characterization (innocent versus pathological) were measured.

Results: Sensitivity for detection of murmurs significantly increased with use of CAA from 76.6 to 89.1% ($p < 0.001$), while specificity remained unaffected (80.0 versus 81.0%). Computer-assisted auscultation improved sensitivity of correctly identifying pathological murmur cases from 82.4 to 90.0%, and specificity of correctly identifying benign cases (with innocent or no murmurs) from 74.9 to 88.8%. ($p < 0.001$). Referral sensitivity increased from 86.7 to 92.9%, while specificity increased from 63.5 to 78.6% using CAA ($p < 0.001$).

Conclusions: Computer-assisted auscultation appears to be a promising new technology for informing the referral decisions of primary care physicians.

Key words: computer-assisted auscultation, cardiac auscultation, heart murmurs

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Introduction

Studies suggest that as many as 50–70% of asymptomatic children referred for specialist evaluation or echocardiography because of a murmur have no heart disease, although it is widely held that the distinction of innocent from pathologic murmurs should and could be reliably made at the point of care using auscultation and other basic clinical skills.[1–6] Several investigators have reported that patients are over-referred for specialist evaluation or echocardiography.[2,7,8] Over-referral and over use of echocardiography are likely due at least in part to declining expertise in cardiac auscultation among referring physicians, resulting in diminished certainty about the presence or absence of disease.

Among various strategies that are being pursued to compensate for declining auscultatory skills, computer-assisted auscultation (CAA) of the heart is an emerging and promising technology. Automatically derived characteristics of heart sounds have been shown to provide a basis for accurate detection of pathological murmurs,[9] and identification of systolic murmurs that are louder in standing than supine position.[10] What has not yet been established is the potential improvement in clinical decision-making by physicians that can be achieved

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using computer-based analysis of heart sounds obtained at the point of care.

The objective of this study was to assess the impact of CAA on primary care physicians' accuracy of murmur detection and characterization as well as their decisions to refer asymptomatic patients with murmurs, as compared with the American College of Cardiology/American Heart Association (ACC/AHA) referral guidelines (Table 1).[11] Physicians were evaluated using prerecorded heart sounds from actual patients without and with the use of CAA provided by Cardioscan (Zargis Medical Corp., Princeton, N.J., USA), a new diagnostic decision support system.

Methods

Seven primary care physicians were recruited to participate, including three pediatricians, two internal medicine specialists and two family practitioners. All were board-certified with 16.0 ± 8.6 years in practice (mean ± SD; range 5–25). They reported no hearing deficits and provided auscultatory skill self-assessments of 7.1 ± 1.2 (mean ± SD, range 5–8) on a scale of 1–10 (with 1 being "not best strength" and 10 being "near perfect"). The Johns Hopkins University School of Medicine's Institutional Review Board (IRB) Executive Committee reviewed the protocol and determined that it qualified for an exemption from full review.

A total of 100 heart sound recordings were chosen from the Johns Hopkins University Cardiac Auscultatory Recording Database (CARD), which contains anonymized clinical histories, expert auscultatory findings, echocardiographic diagnoses, and digital heart sound recordings from over 1,200 patient cases with and without heart disease.[12] The auscultatory findings were entered into the CARD database by an experienced cardiologist (WRT) well in advance of the present study. None of the heart sound recordings chosen for use in this study were used to develop the CAA tool and no recording was selected with prior knowledge of its CAA analysis profile.

A set of heart sound criteria (Table 2) was defined to include all of the auscultatory findings referenced in the AHA guidelines. The majority of the recordings contained murmurs (85 cases) of either Class I or Class III types and the majority (55) of murmur cases included innocent murmurs, of which 30 were intensity grade I and 25 were intensity grade II, early-mid systolic murmurs. Examples of each type of Class I murmur identified in the AHA guidelines were also included in the set of 30 pathological cases. Cases were selected

TABLE 1 Recommendations for echocardiography in asymptomatic patients with cardiac murmurs.[11] (Class I: Conditions for which there is evidence and/or general agreement that echocardiography is useful and effective. Class IIa: Conditions for which there is conflicting evidence and/or a divergence of opinion about the usefulness/efficacy of echocardiography. Weight of evidence/opinion is in favor of usefulness/efficacy. Class III: Conditions for which there is evidence and/or general agreement that echocardiography is not useful and in some cases may be harmful)

Indication		Class
1	Diastolic or continuous murmurs	I
2	Holosystolic or late systolic murmurs	I
3	Grade 3 or greater midsystolic murmurs	I
4	Murmurs associated with abnormal physical findings on cardiac palpation or auscultation	IIa
5	Murmurs associated with an abnormal ECG or chest x-ray	IIa
6	Grade 2 or softer midsystolic murmur identified as innocent or functional by an experienced observer	III
7	To detect "silent" aortic regurgitation or mitral regurgitation in patients without cardiac murmurs, then recommend endocarditis prophylaxis	III

TABLE 2 Study group descriptions

Study group	Auscultatory findings	Pathologic status	ACC/AHA murmur referral class	# of pts
A	Normal heart sounds, no murmur	Normal	(NA)	15
B1	Grade 1/6, systolic ejection murmur	Normal	III (indication 6)	25
B2	Grade 2/6, systolic ejection murmur	Normal	III (indication 6)	30
C1	Grade 3/6, midsystolic murmur	Pathologic	I (indication 3)	14
C2	Grade 2/6, holosystolic murmur	Pathologic	I (indication 2)	7
C3	Grade 2/6, diastolic murmur	Pathologic	I (indication 1)	7
C4	Grade 2/6, continuous murmur	Pathologic	I (indication 1)	2
			TOTAL	100

at random from the CARD database to satisfy these inclusion criteria.

The CAA tool performs spectral and temporal analysis of heart sounds, graphically displays murmur energy profiles, and relates the data statistically to ACC/AHA referral guidelines (Fig. 1). The system applies advanced signal processing methods to heart sound analysis.[13,14] The system was developed using actual heart sound recordings obtained under a variety of conditions from normal volunteers or patients at multiple clinical sites, and none of the recordings used for algorithm development was included in this study. Cardioscan has been cleared by FDA (K060197, K042128, and K031517) for providing support to the physician in the evaluation of heart sounds in conjunction with physician over-read as well as consideration of all other relevant patient data.

The physician participants were provided with a 15-min orientation to the CAA heart sound analysis system and an explanation of the graphical user interface (GUI) (Fig. 1). Each physician, having completed the orientation, was provided a quiet office environment in which to listen to the recorded heart sounds using high-quality headphones. The participants could adjust the playback volume and listen to each recording as many times as

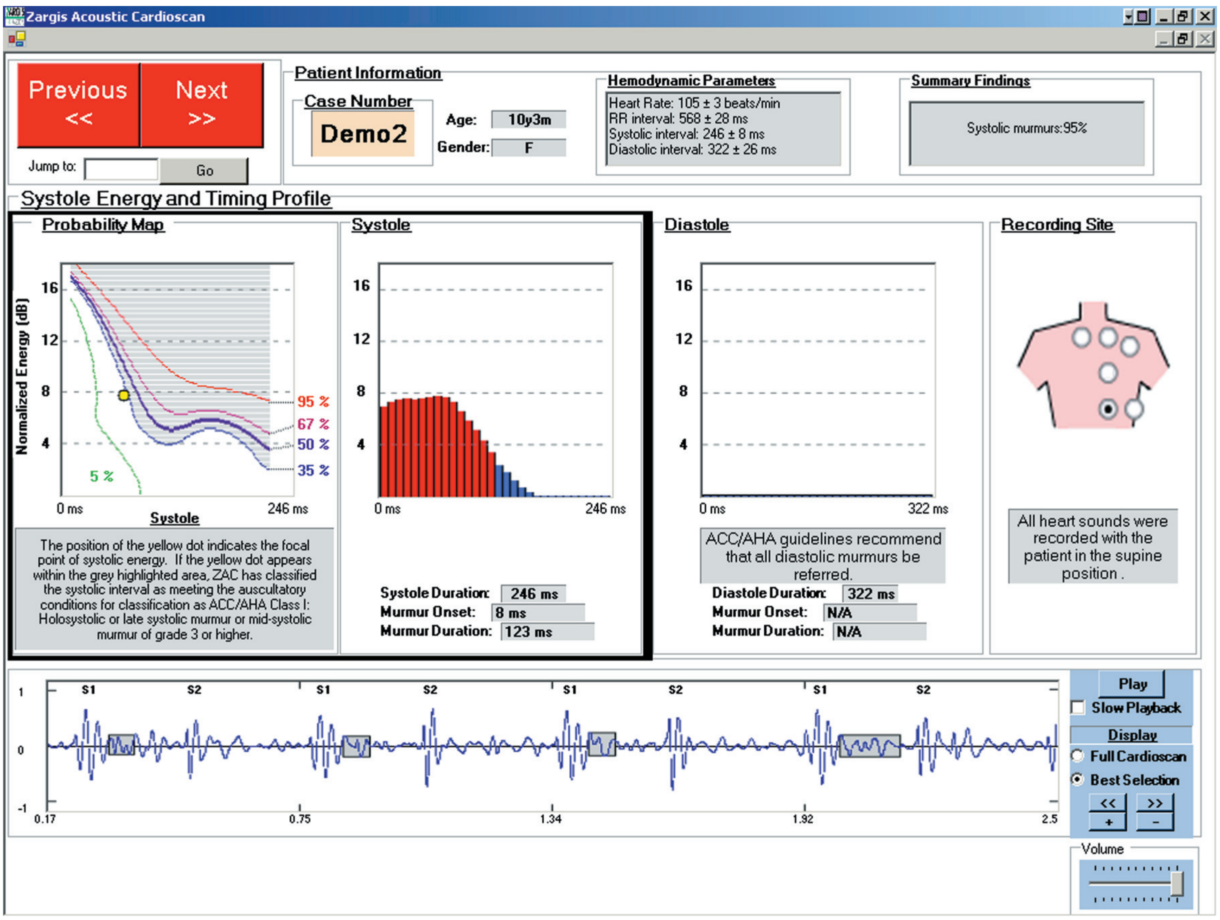

FIG. 1 Cardioscan graphical user interface. Based on the automatic detection of the first and second heart sounds, the subject heart rate, heart rate variability, and systolic/diastolic durations are reported as "Hemodynamic Parameters." The probability of systolic and diastolic murmurs being present is reported in the "Summary Findings" box. The energy profiles (middle panels) display (in blue) the median midfrequency energies for systole and diastole, normalized by the total signal energy. Any portions of the energy profile corresponding to systolic or diastolic murmurs detected are shown in red. The referral probability map depicts (by a yellow dot) the focal point of systolic energy as the maximum systolic energy at the normalized time point corresponding to the energy-weighted time index. Superimposed on this energy-time plot are the contours of a probability function that provides the relative probability of the systolic interval meeting the auscultatory definition of Class I versus Class III. Shown in gray is that region of energy/timing which exceeds a decision-threshold of 35%; using this probability as the criterion for Class I leads to a referral sensitivity of 95% with a specificity of 80% on the basis of another, independent data base. In this example, a grade I early systolic innocent murmur is depicted. In the bottom panel, a segment of the heart sound recording is shown as a traditional phonocardiographic time series which contains four heart beats that best exemplify the auscultatory findings derived from the 20-s recording. The first and second heart sounds are annotated, and any murmurs that may be present are surrounded by a shaded box.

desired. The case report form (CRF) questions asked, given only the patient's age, gender, and this heart sound recording, whether: (i) they heard a heart murmur, and, if they heard a murmur, whether (ii) they judged the murmur to be innocent or pathologic, and whether, (iii) assuming the patient is asymptomatic, they would refer that patient for cardiology evaluation or echocardiogram (or both).

Each physician listened to the entire set of 100 heart sound recordings in a randomized order, without CAA, and completed the CRFs for each. Each physician then listened to the same set of recordings in a different randomized order, and was additionally provided the CAA analysis of the recording prior to completing the CRFs.

Performance measures included the sensitivity and specificity of: murmur detection, discrimination between benign and pathologic cases, and referral decisions. The statistical significance of these measures was evaluated using a generalized linear mixed effects model[15] (logistic regression), where modality was a fixed effect and both case and physician were random effects. Statistical significance was inferred at $p < 0.05$ using a two-sided test.

Results

Among the 7 physicians, sensitivity for detection of murmurs significantly increased with the use of CAA from 76.6 to 89.1% (n = 85 murmur cases, $p < 0.001$; Table 3), while specificity remained unaffected (80.0 vs 81.0%, n = 15 cases without murmur). Improvement in sensitivity was due exclusively to better detection of innocent murmurs.

The CAA improved sensitivity of correctly identifying pathologic cases (group C; n = 30) from 82.4 to 90.0% ($p < 0.001$) and specificity of correctly identifying benign cases (groups A and B; n = 70) from 74.9 to 88.8% ($p < 0.001$).

The average physician referral accuracy (Table 4) increased from 70.4 to 82.9% using CAA ($p < 0.001$). The physicians were able to reduce their average false positive referral rate for nonmurmurs and innocent murmurs (n = 70) from 36.5 to 21.4% ($p < 0.001$), while simultaneously reducing their false negative referral rate for pathological murmurs (n = 30) from 13.3 to 7.1% ($p < 0.001$).

The greatest improvement in correct referral decisions was seen in the innocent murmur group, particularly those with grade 2 intensity systolic ejection murmurs. Referral decisions were not always concordant with designations of pathologic murmurs. There were 64 instances without and 55 with use of CAA in which cases designated as containing only innocent murmurs were nevertheless marked for referral, either for cardiologist or echocardiogram evaluation; most of these cases were from innocent murmur groups B1 or B2.

TABLE 3 Murmur detection without and with CAA

Reader	CAA	Sensitivity (n = 85) (%)	Specificity (n = 15) (%)
1	Without	82.4	100
	With	90.6	100
2	Without	51.8	86.7
	With	89.4	60.0
3	Without	69.4	86.7
	With	81.2	100
4	Without	77.6	66.7
	With	91.8	93.3
5	Without	85.9	93.3
	With	83.5	100
6	Without	87.1	33.3
	With	98.8	26.7
7	Without	82.4	93.3
	With	88.2	86.7
Average	Without	76.6	80.0
	With	89.1[a]	81.0[b]

[a] $p < 0.001$.
[b] Not statistically significant.
CAA = computer-assisted auscultation

TABLE 4 Impact of CAA on referral decisions

Reader	CAA	Accuracy (n = 100) (%)	Sensitivity (n = 30) (%)	Specificity (n = 70) (%)
1	Without	67	100	52.9
	With	90	96.7	87.1
2	Without	72	76.7	70.0
	With	80	83.3	78.6
3	Without	82	50.0	95.7
	With	90	83.3	92.9
4	Without	86	96.7	81.4
	With	91	93.3	90.0
5	Without	56	100	37.1
	With	85	100	78.6
6	Without	45	93.3	24.3
	With	54	96.7	35.7
7	Without	85	90.0	82.9
	With	90	96.7	87.1
Average	Without	70.4	86.7	63.5
	With	82.9[a]	92.9[a]	78.6[a]

[a] $p < 0.001$.
CAA = computer-assisted auscultation

Discussion

The present study assesses the incremental value of simultaneously examining a graphical representation and analysis of heart sounds to auscultation alone. In this study, murmur detection, characterization, and referral decisions improved with use of the graphical interface; these improvements were achieved with very limited (15 minutes) prior experience using the tool. In addition, the heart sound recordings chosen for use in this study were not used to develop the CAA tool and were selected without prior knowledge of their CAA analysis profile.

Using CAA, the sensitivity for identifying pathologic murmurs rose from 82.4 to 90.0%, while the specificity rose from 74.9 to 88.8%. The resulting likelihood ratio for a positive result (LR+) is 3.3 without and 8.0 with CAA; physical exam findings typically correspond to an LR+ ratio of approximately 2.0 for prediction of disease.

Interestingly, in several instances both without and with CAA, participants chose to refer cases in which they identified the detected murmur as innocent, likely reflecting the tendency of many primary care physicians to refer not only cases in which they are certain pathology exists, but also some cases which they feel are most likely normal but pathology cannot be excluded. There was a trend, though not statistically significant, toward decreased referrals of cases determined by the physicians as having only innocent murmurs with use of CAA: the percentage of innocent murmurs deemed innocent yet referred decreased from 18.9% (52/275) to 13.2% (44/333). Had the physicians not referred murmurs they considered innocent, the average sensitivity with CAA would have decreased slightly from 92.9 to 90.5%, while the specificity would have increased from 78.6 to 88.8%.

A limitation of the study is the relatively small number of physicians and cases evaluated. This was mitigated in part by specifying both cases and physicians as random effects in the multivariate regression analysis. In addition, the study used prerecorded heart sounds rather than live patients. This approach was advantageous in that the referral decisions were based on heart sounds alone, all physicians evaluated the same prerecorded heart sounds, and 100 cases could be assessed in a single day. However, in practice, referral decisions are influenced by many factors, including the patient history, symptoms and other exam findings, as well as nonmedical issues such as anxiety level of the patient or parent. The results of this or any auscultation assist device would need to be considered in the context of these various factors to arrive at a patient-specific, referral decision.

While the tool has yet to be validated in larger scale, prospective clinical trials, the improved performances of the small group of primary care physicians in the controlled environment of this study suggests the potential benefit of CAA.

Conclusions

Computer-assisted auscultation provides increased objectivity to a traditionally subjective, difficult clinical skill. In addition, graphical representation, quantification, and archiving of auscultation may reduce uncertainty in the continuity of care of patients with heart murmurs. A diagnostic decision support tool that could increase both the sensitivity and specificity of the echocardiography referral decisions would facilitate more efficient use of healthcare resources. The results of this study suggest that CAA shows promise of providing such a tool.

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