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Automated Cardiac Auscultation for Detection of Pathologic Heart Murmurs

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Abstract. Experienced cardiologists can usually recognize pathologic heart murmurs with high sensitivity and specificity, although nonspecialists with less clinical experience may have more difficulty. Harsh, pansystolic murmurs of intensity grade ≥3 at the left upper sternal border (LUSB) are likely to be associated with pathology. In this study, we designed a system for automatically detecting systolic murmurs due to a variety of conditions and examined the correlation between relative murmur intensity and likelihood of pathology. Cardiac auscultatory examinations of 194 children and young adults were recorded, digitized, and stored along with corresponding echocardiographic diagnoses, and automated spectral analysis using continuous wavelet transforms was performed. Patients without heart disease and either no murmur or an innocent murmur ($n = 95$) were compared to patients with a variety of cardiac diagnoses and a pathologic systolic murmur present at the LUSB ($n = 99$). The sensitivity and specificity of the automated system for detecting pathologic murmurs with intensity grade ≥2 were both 96%, and for grade ≥3 murmurs they were 100%. Automated cardiac auscultation and interpretation may be useful as a diagnostic aid to support clinical decision making.

Key words: Murmurs — Auscultation — Automated diagnosis

Innocent heart murmurs are common in clinical practice, present on at least one examination in 50% to 90% of children and 15% to 44% of young adults [6, 11, 18, 19, 22]. In contrast, the incidence of congenital heart disease is 0.5% to 0.8% [9], with most cases presenting in infancy and only 1 or 2 per 1000 previously unknown cases presenting in school-aged children [12]. In addition, the incidence of acquired heart disease in this population is low. Given the prevalence of innocent murmurs and the relatively low incidence of actual heart disease, the primary health care provider may have difficulty determining which patients with murmurs need specialist referral, especially when there are no other signs or symptoms of heart disease.

In studies of patients referred by primary care physicians because of heart murmurs either directly for echocardiography or for evaluation by the cardiologist, only 20% to 30% of the patients have pathology [6, 18]. This supports the conclusion that expensive testing based on clinical assessment by the primary provider is probably not cost-efficient when compared to a strategy of referral to the specialist prior to testing, but it also points out the need for improvements in the primary screening examination. However, recent evidence suggests that proficiency in cardiac auscultation among physicians in training may be in decline [10, 13, 14, 16, 23, 24], and few systemic remedies have been proposed. Nevertheless, screening for heart disease by cardiac auscultation remains an important part of general pediatric and adult care, preoperative assessment of anesthetic and surgical risks, and prescreening for heart disease prior to participation in athletics, according to policy statements of the American Academy of Pediatrics and the American Heart Association [2, 3, 17].

Recent advances in digital signal processing have led to a reexamination of the potential role of spectral analysis of heart sounds in cardiac diagnosis [4, 5, 7, 20, 25]. In this study, we investigated a new technique for evaluating heart murmurs in children and young adults using automated analysis of the systolic energy content found in digital recordings of cardiac auscultations. The spectral energy was compared to murmur intensity grade by clinical assessment and to echocardiographic diagnoses for a variety of cardiac diseases, and correlations were established. The goal of this study was to evaluate

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Table 1. Comparison of murmur intensity at the LUSB as judged by traditional stethoscope examination versus digital recording

Murmur intensity by stethoscope exam	Murmur intensity on digital recording				
	0	1	2	3	4
0	28	2			
1		10	2		
2	4	11	22		
3	1	2	15	10	
4			2	2	5
5			3		2
NA	41	12	12	8	
Total cases	74	37	56	20	7

NA: Not available.

automated spectral analysis for potential use as a diagnostic aid to assist the clinician in the detection and evaluation of heart murmurs.

Methods

Subject Population

All patients evaluated in the pediatric echocardiography laboratory for assessment of possible heart disease, follow-up of known heart disease, or cardiac evaluation in the setting of other systemic diseases during a 31-month period were considered potential candidates for digital recording of cardiac auscultation. Heart sound recordings were made if sufficient time and technical assistance were available, consent for participation was obtained, and the patient was cooperative enough to allow for minimal background noise. The protocol was approved by the Joint Committee for Clinical Investigation.

During a 31-month period, approximately 12,000 patients had complete two-dimensional echocardiography, 706 of which also had cardiac auscultation recordings digitized and stored. Cases for further study were identified by searching the database for (1) cases with echocardiographic diagnosis of normal, without further restrictions, and (2) cases with echocardiographic diagnosis of abnormal anatomy and the presence of a systolic murmur at the left upper sternal border (LUSB) by clinic physician stethoscope examination.

The binary data files were automatically scanned for adequacy of the electrocardiograph (ECG) signal and approximately 95% were acceptable, resulting in 229 cases for further review. Prior to spectral analysis, all files were converted to WAV digital audio format and listened to by a single cardiologist to ensure consistency of clinical auscultation data and murmur intensity assignment. For each case, the location and relative intensity grade (1–6) of the systolic murmur(s), when present, were determined. In cases in which the original stethoscope examination had also been performed by a cardiologist, the correlation between the intensity grade on the stethoscope exam compared to the digital recording was generally high ($r = 0.82$, $p < 0.0001$) (Table 1). Five cases without heart disease and no murmur were eliminated because of the presence of a systolic click. Sixteen cases with pathology by echocardiogram were eliminated due to the lack of an audible systolic murmur at the LUSB on the digital recording. Of the remaining 208 cases, 10 were eliminated because of unacceptably low quality of digital recording due to artifact noise, and 4 were unable to be processed due to other technical problems.

Data Acquisition

Digital Phonocardiography. Phonocardiography was performed on all subjects immediately following echocardiography. With the patient in the supine position, a piezoelectric contact sensor (Hewlett-Packard, Model 21050A) was firmly secured on the chest for a 20-second recording from each of at least five of the usual auscultatory areas. Three electrocardiographic leads were placed for recording the simultaneous ECG signal on a separate channel for cardiac cycle gating. The recording protocol took 3 to 5 minutes per patient to complete. A 12-bit PCMCIA analog-to-digital conversion board was used to digitize data at a sample rate of 8.13 kHz. Digital recordings, along with demographic, clinical, and echocardiography data, were stored in a relational database.

Echocardiography. All studies were performed with either a Hewlett-Packard Sonos 2000, 2500, or 5500 or an Acuson 128 XP echocardiographic system. The echocardiograms were interpreted independently without knowledge of phonocardiogram or spectral analysis. A study was considered normal if no pathologic diagnosis other than trace to mild tricuspid or pulmonary regurgitation or trace mitral regurgitation was made. All other studies with structural heart disease were considered abnormal.

Spectral Analysis

The heart sound signals were low-pass filtered at 1000 Hz and converted to timescale (analogous to time-frequency) domain using the continuous wavelet transform method. The derived energy values, expressed in decibels (dB), are relative. S_1 and S_2 were automatically detected for each cardiac cycle by reference to the QRS peak and used to define the systolic interval. Interrogation of the systolic interval for spectral energy content was limited to the middle portion, beginning at 32.5% and ending at 67.5% of the distance from S_1 to S_2. The effects of extraneous noise and artifact were minimized by using the median energy value derived from at least 15 cardiac cycles per recording. The range of variability of the relative energy values during a single clinic visit was ±1.2 dB, as determined in a separate series of cases in which nine duplicate recordings from the LUSB of the same patient on the same clinic day were analyzed for consistency of recording technique and spectral analysis.

Statistical Analysis

Data were analyzed using the one-tailed, two-sample unequal variance Student's *t*-test, with $p < 0.05$ considered significant. The median energy value was compared to the presence or absence of heart disease by echocardiography, and receiver-operating characteristic (ROC) curves were calculated.

Results

Population

The 194 binary files on which spectral analysis was performed were from 193 unique patients (one patient without heart disease was recorded on two separate visits 6 months apart). There were 95 cases without heart disease (median age 8.6 years, range 40 days to 40.8 years, 54% males) and either no murmur ($n = 74$) or an innocent

Table 2. Relationship between systolic murmur intensity grade and spectral energy values (in relative dB)

Intensity	Mean	Median	Low	High	SD	p value[a]
0 ($n = 74$)	4.4	4.0	−4.1	12.9	4.0	—
1 ($n = 37$)	7.3	7.4	1.2	15.2	3.6	0.0002
2 ($n = 56$)	15.7	15.0	2.7	31.1	5.9	<0.0001
3 ($n = 20$)	24.3	23.9	16.1	39.2	5.6	<0.0001
4 ($n = 7$)	25.5	29.2	15.0	32.2	7.1	0.3564

[a] p values compare the mean energy value with the value for the previous intensity level.

murmur audible at the LUSB ($n = 21$). The intensity of the innocent murmurs at the LUSB included grade 1 ($n = 18$) and grade 2 ($n = 3$), as determined by listening to the digital recording prior to spectral analysis. There were 99 cases with heart disease (median age 4.8 years, range 2 days to 31.2 years, 47% males) and a systolic murmur heard either best at ($n = 63$) or radiating to ($n = 36$) the LUSB. The intensity of the pathologic murmurs at the LUSB included grade 1 (15 best heard at the LUSB and 4 radiating to the LUSB), grade 2 (30 best heard at the LUSB and 23 radiating to the LUSB), and grade ≥3 (18 best heard at the LUSB and 9 radiating to the LUSB).

Analysis

The relationship between systolic murmur intensity grade and corresponding derived spectral energy is shown in Table 2. There was a significant increase in the mean energy value at each successive intensity grade except between grades 3 and 4. The mean energy value for all cases with no heart disease, including those with innocent murmurs, was 4.7 dB (range −4.1 to 12.9, SD 3.8), which was significantly lower than the mean value for cases with pathology by echocardiogram of 17.1 dB (range 1.6 to 39.2, SD 7.5, $p < 0.0001$). A comparison of the sensitivity and specificity of the energy value for predicting pathology at various cutpoints is shown in Table 3. Using an energy threshold of 7.0 dB, the sensitivity and specificity of the energy value for predicting pathology for the entire group of cases were 93% and 75%, respectively. If prediction was based on the subgroup of pathologic cases with murmur intensity grade ≥2 (group A), the sensitivity of 90% had an increased specificity of 89% at cutpoint 10.2 dB.

If all normal cases were compared to pathologic cases with murmur intensity grade ≥2 which were best heard at the LUSB (group B), the sensitivity and specificity increased to 96% for cutpoint of 11.6 dB. The ROC curve for group B is shown in Fig. 1A. The area under the curve is 0.986, which is the probability that the midsystolic energy level is higher for a randomly selected pathologic case than for a randomly selected case with no heart disease. The false-negative and false-positive rates for group B at different possible cutpoints are shown in Fig. 1B. The primary diagnoses of the 143 cases used to calculate the group B ROC curve are shown in Fig. 2 with the corresponding spectral energy values. As expected, the pathologic diagnoses included primarily ones commonly associated with murmurs heard at the LUSB. There were two false negatives in group B (using cutpoint of 11.6 dB)—a 2-day-old neonate with coarctation of the aorta (6.5 dB) and a 6-month-old infant with trivial pulmonary valve stenosis (8.4 dB). There were eight other pathologic cases under 12 months old in group B, all of whom were true positives with energy values >11.6 dB (mean 20.5, SD 4.9).

If only pathologic cases with murmur intensity grade ≥3 were compared to all normal cases (group C), the sensitivity and specificity of the algorithm for detecting the pathologic murmur increased to 100% at cutpoint of 13.0 dB. Thus, using the systolic murmur intensity criteria of McCrindle et al. [18] to correlate best with likelihood of pathology, the algorithm was able to discriminate normals from pathologic cases with no false negatives or false positives.

Innocent Murmurs

The specificity of the algorithm for labeling cases with innocent murmurs correctly as nonpathologic was high. There were 21 normal subjects with innocent murmurs only. Of these, there was only 1 case with energy value >11.6 dB, a 3-year-old with a grade 2 murmur (12.0 dB). The specificity of the algorithm among patients with innocent murmurs in this series was thus 95%, similar to the overall specificity of the entire group of normals. Of note, the mean energy value for the 19 pathologic cases with a grade 1 murmur was 9.2 dB (range 1.6 to 15.2, SD 3.4). This was significantly higher than the mean value of 4.4 dB for the 74 normal cases with no murmur (range −4.1 to 12.9, SD 4.0, p <0.0001) and the mean value of 5.3 dB for the 18 normal cases with a grade 1 innocent murmur (range 1.2 to 10.5, SD 2.7, $p = 0.0002$). The mean value from normal cases with a grade 1 innocent murmur was not significantly different from that found in cases with no murmur ($p = 0.1428$), suggesting that innocent murmurs may have less energy, as measured by the detection algorithm, than pathologic murmurs of the same relative intensity. More cases of higher intensity (grades 2 and 3) innocent murmurs must be analyzed before the true specificity of the algorithm for distinguishing innocent from pathologic murmurs of equal intensity can be established. However, this finding suggests the possibility of detecting characteristics of murmurs other than simple intensity that contribute to pathologic versus innocent midsystolic energy values.

Table 3. Comparison of the sensitivity and specificity of the energy value for predicting pathology at various cutpoints

	n	Sensitivity at energy cutpoint (dB)			
		7.0	10.2	11.6	13.0
All pathologies (95% CI)	99	0.93 (0.86–0.97)	0.83 (0.74–0.90)	0.78 (0.68–0.86)	0.68 (0.57–0.77)
Group A[a] (95% CI)	80	0.98 (0.91–1.00)	0.90 (0.81–0.96)	0.90 (0.81–0.96)	0.81 (0.71–0.89)
Group B[b] (95% CI)	48	0.98 (0.89–1.00)	0.96 (0.86–0.99)	0.96 (0.86–0.99)	0.83 (0.70–0.93)
Group C[c] (95% CI)	27	1.00 (0.87–1.00)	1.00 (0.87–1.00)	1.00 (0.87–1.00)	1.00 (0.87–1.00)
Specificity (95% CI)	95	0.75 (0.64–0.82)	0.89 (0.81–0.95)	0.96 (0.88–0.98)	1.00 (0.96–1.00)

[a]All abnormal cases with pathologic murmur intensity grade ≥2.
[b]Abnormal cases with pathologic murmur intensity grade ≥2, best heard at LUSB.
[c]All abnormal cases with pathologic murmur intensity grade ≥3.

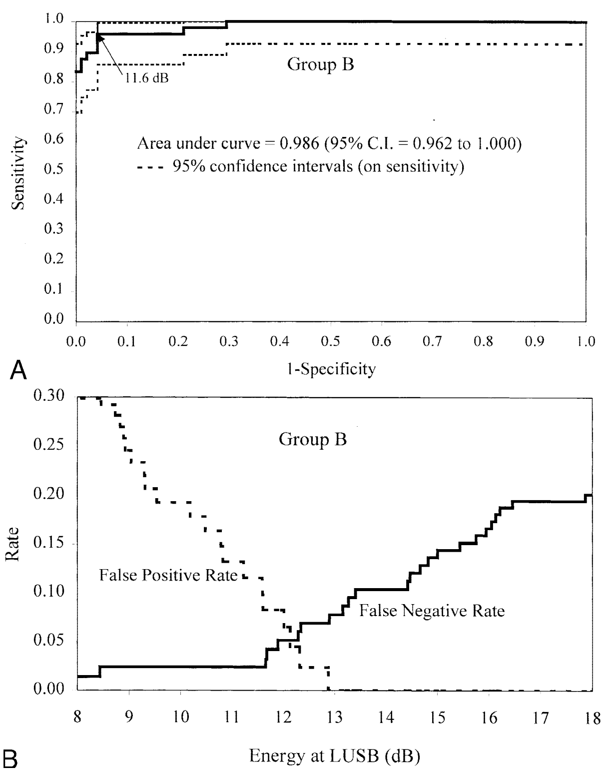

Fig. 1. (A) Receiver-operating characteristic (ROC) curve for group B. Group B includes all normal cases ($n = 95$) and only pathologic cases with murmur intensity grade ≥2 which were best heard at the LUSB ($n = 48$). Confidence intervals shown are for sensitivity; specificity confidence intervals were narrower. The arrow indicates the energy cutpoint that may afford a clinically reasonable trade-off between sensitivity and specificity. **(B)** The false-negative and false-positive rates for group B at different possible cutpoints are shown.

New Patients

Of the 194 cases examined, 37 (19%) were new referrals without previous diagnosis of heart disease. Of these, there were 28 cases without heart disease (median age 5.2 years, range 1 month to 15.7 years)—14 with no murmur and 14 with an innocent murmur, grade 1 ($n = 11$) or grade 2 ($n = 3$). Only 2 new patients with no pathology on echocardiogram had energy values >11.6 dB. One was the 3-year-old child with a grade 2 innocent murmur discussed previously and the other was a 5-year-old with no murmur (12.9 dB). Thus, the algorithm correctly identified as negative 13 of 14 innocent murmurs and 13 of 14 cases with no murmur among the new patients.

There were nine new cases found to have pathology on echocardiogram (ECG) (median age 1.2 years, range 3 days to 15.1 years), with murmur intensity grades 1 ($n = 1$), 2 ($n = 6$), and 3 ($n = 2$). Three of these had energy values less than 11.6 dB: a 5-year-old with a grade 1 murmur at the LUSB and an atrial septal defect (6.2 dB), a 6-month-old with a grade 2 murmur and trivial pulmonary stenosis (8.4 dB), and a 4-year-old with a grade 2 murmur and mild pulmonary stenosis (9.1 dB). The six true positives, with energy values >11.6 dB, included three cases with pulmonic stenosis, two with subaortic stenosis, and one with patent ductus arteriosus. If these cases had been screened using group B criteria (murmur intensity grade ≥2, best heard at the LUSB) with cutpoint 11.6 dB, there would have been only one false negative (trivial pulmonary stenosis) out of six pathologic cases.

Discussion

In a study of 222 consecutive patients referred for evaluation of a heart murmur, McCrindle et al. [18] found that six cardinal clinical signs on cardiac examination proved to be significant independent predictors of the presence of a confirmed cardiac lesion. The six signs were murmur intensity grade ≥3, best heard at the LUSB, harsh quality, pansystolic timing, the presence of a systolic click, or the presence of an abnormal second heart sound. The authors estimated that if referring clinicians were

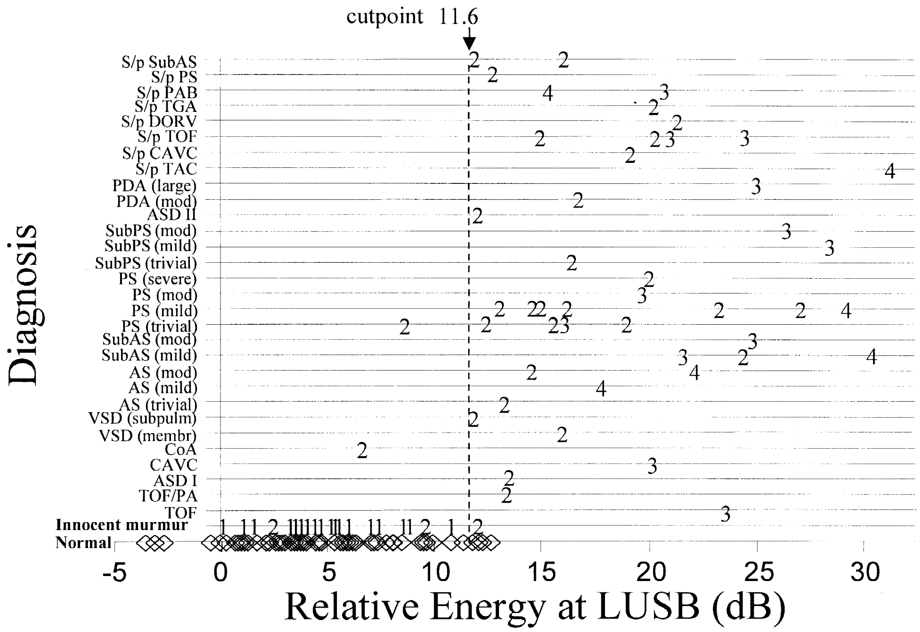

Fig. 2. Graph showing the relative midsystolic energy value for each of the 143 cases in group B (see legend to Fig. 1). The list of primary pathologic diagnoses is shown with the corresponding energy value for the case(s) with that diagnosis. The numbers on the diagnosis lines represent the murmur intensity grade at the LUSB. The dotted line shows the energy cutpoint of 11.6 dB. *AS,* aortic valve stenosis; *ASD,* atrial septal defect; *CAVC,* common atrioventricular canal; *CoA,* coarctation of the aorta; *DORV,* double-outlet right ventricle; *PAB,* pulmonary artery band; *PDA,* patent ductus arteriosus; *PS,* pulmonic valve stenosis; *S/p,* status postrepair of; *SubAS,* subaortic stenosis; *SubPS,* subpulmonic stenosis; *TAC,* truncus arteriosus communis; *TGA,* transposition of the great arteries; *TOF,* tetralogy of Fallot; *TOF/PA,* tetralogy of Fallot with pulmonary valve atresia; *VSD,* ventricular septal defect.

reliably able to recognize these six signs, referrals or direct ordering of echocardiograms might be reduced by approximately 50%.

Several studies have shown that clinical assessment by an experienced cardiologist can detect heart disease in children and adults with up to 96% sensitivity and 89% to 95% specificity, and that lesions missed by this assessment are likely to be less serious in nature [11, 15, 18, 22]. These studies have generally assessed the cardiologists' clinical skill in the selected population of patients referred to rule out heart disease, in which there is a higher preevaluation probability of disease than exists in the general population (25–30% vs 0.8%). In contrast, the task of primary health care providers to distinguish pathologic from normal cardiac findings is more difficult not only because the provider is less familiar with the characteristics of specific, uncommon cardiac lesions but also because of the much lower preevaluation likelihood of encountering disease. Given these challenges and recent concerns about the adequacy of training in cardiac auscultation among new residents, it is clear that improvements in detection methods and in teaching of traditional cardiac auscultation are needed.

In this study, a new technique involving spectral analysis of digital heart sound recordings was evaluated to assess whether pathologic heart murmurs could be automatically detected. The results show that for patients with a pathologic systolic murmur of intensity grade ≥2, best heard at the LUSB, digital recordings from that location could be screened for systolic interval energy content, and the relative energy level detected by automated analysis correlated highly with probability of pathology. Likewise, recordings from patients with either no murmur or innocent systolic murmurs of grade ≤2 had lower energy values that allowed correct identification of these cases as normal. Increasing energy level in midsystole, as automatically detected in this study, was both a sensitive and a specific predictor of pathologic murmurs.

It is interesting that the algorithm, which is designed to screen for only one of the six cardinal clinical signs of cardiac pathology, performs acceptably against a diverse group of cardiac pathologies as well as patient ages and sizes. Although the number of new patients evaluated was relatively small, the predictive value of the algorithm among this group was high. The one new patient with pathology that would have been missed by an application of the algorithm, if used to detect pathologic murmurs of intensity grade ≥2 best heard at the LUSB, was a 6-month-old infant with trivial pulmonary valve stenosis. It is estimated that heart murmurs first noted at 6 months of age carry a 1:7 risk of congenital heart disease, whereas those first heard at 12 months have only a 1:50 risk. However, if a murmur first detected at birth persists until 12 months, the risk is 3:5 [21]. For neonates with murmurs, the risk of structural heart disease may be as high as 54% to 84% [1, 8]. Thus, it would be prudent and appropriate to have a lower threshold for referral of infants less than 12 months of age with murmur when using this or any diagnostic support strategy for detecting congenital heart disease.

We speculate that with further development and testing, automated spectral analysis of auscultatory data may be of assistance to primary care providers, increasing the rate and accuracy of detection of occult heart disease. In addition, the ability to quantitatively assess heart sounds and murmur characteristics may be of use to the cardiologist for following certain patients with known heart disease to detect changes in disease severity without the use of serial echocardiography. We do not foresee the application of such a device in the role of screening for all forms of heart disease since some pathologic conditions may have only subtle or no abnormal auscultatory findings. Rather, the algorithm may be useful as a convenient, rapid, low-cost method whereby a nurse or health care associate could quantitatively detect and document the presence of higher intensity heart murmurs, which have a correspondingly higher likelihood of being due to pathology. Patients with a higher murmur intensity score could then be reviewed more carefully in the context of other historical and physical examination findings to develop a more consistent, informed basis for referral.

Limitations

In this initial study, we chose to analyze only recordings taken from the LUSB because of the observation that murmurs best heard at this area were more likely to be pathologic, according to McCrindle et al. [18]. It is not known how the analysis will perform at other auscultation areas, particularly at the left lower sternal border where Still's-type innocent murmurs are often heard. We expect that each area may have a different cutpoint for pathologic murmurs because the lesions most often associated with murmurs at those areas differ.

Importantly, this algorithm was designed to detect pathologic systolic murmurs and not necessarily all pathologic lesions. Many examples of severe heart defects exist without a related systolic murmur. Similarly, although most diastolic murmurs, other than the venous hum, are associated with pathology, this algorithm makes no attempt to detect them. We anticipate that future algorithms may eventually be able to detect additional pathologic features and diastolic murmurs. However, we do not expect automated spectral analysis to replace the need for careful attention to historical details, general physical findings, and cardiac auscultatory signs not detectable by automated analysis.

In addition, this study was by design limited in its analysis of innocent murmurs. The majority of patients in our practice with innocent murmurs are correctly diagnosed by the cardiologist on clinical evaluation and do not have echocardiography; thus, they were not eligible for participation in this study. The intention of this initial investigation was rather to focus on developing a process whereby murmurs could be automatically interrogated and analyzed for energy content. As such, the ability to distinguish innocent from pathologic murmurs of equal intensity was not a priority; therefore, the true specificity of the algorithm against innocent murmurs is currently unknown. However, the data do suggest that at least some innocent murmurs appear to have less energy than pathologic murmurs of the same relative intensity, possibly reflecting differences in spectral bandwidth. In any event, since murmurs with intensity grade ≥ 3 are more likely to be pathologic, restriction of the algorithm to detect only murmurs of this intensity or higher would likely provide for robust specificity against grade 2 innocent murmurs, if clinically desired. Louder-intensity innocent murmurs (grade ≥ 2) are much less common in clinical practice than grade 1 murmurs and would therefore be more appropriate for referral to the specialist and possibly for echocardiography if detected by the algorithm.

Finally, the performance of the algorithm against an unselected patient population, as would be found in the primary health care provider's practice, is currently unknown and may differ considerably from that reported here. A prospective trial to investigate performance in this setting is planned to determine the actual positive and negative predictive value of the algorithm, given the much lower pretest probability of disease in the primary care setting.

Conclusions

This study demonstrates a method for automated spectral analysis of heart murmurs in children and young adults. Midsystolic energy present in pathologic murmurs can be automatically detected and murmur intensity correlated with likelihood of pathology. Future refinements and testing of the algorithm may lead to a diagnostic assist device to support clinical decision making.

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References

1. Ainsworth SB, Wyllie JP, Wren C (1999) Prevalence and clinical significance of cardiac murmurs in neonates. *Arch Dis Child Fetal Neonatal Ed 80*:F43–F45
2. American Academy of Pediatrics (1996) Policy statement. Evaluation and preparation of pediatric patients undergoing anesthesia. *Pediatrics 98*:502–508
3. American Heart Association (1994) Guidelines for evaluation and management of common congenital cardiac problems in infants, children, and adolescents. Medical/scientific statement.
4. Balster DA, Chan DP, Rowland DG, Allen HD (1997) Digital acoustic analysis of precordial innocent versus ventricular septal defect murmurs in children. *Am J Cardiol 79*:1552–1555
5. Bulgrin JR, Rubal BJ, Thompson CR, Moody JM (1993) Comparison of short-time Fourier, wavelet and time-domain analyses of intracardiac sounds. *Biomed Sci Instrum 29*:465–472
6. Danford DA, Nasir A, Gumbiner C (1993) Cost assessment of the evaluation of heart murmurs in children. *Pediatrics 91*:365–368
7. Donnerstein RL (1989) Continuous spectral analysis of heart murmurs for evaluating stenotic cardiac lesions. *Am J Cardiol 64*:625–630
8. Du Z-D, Roguin N, Barak M (1997) Clinical and echocardiographic evaluation of neonates with heart murmurs. *Acta Paediatr 86*:752–756
9. Ferencz C, Rubin JD, McCarter RJ, et al (1985) Congenital heart disease prevalence at live birth—the Baltimore–Washington infant study. *Am J Epidemiol 121*:31–36
10. Gaskin PRA, Owens SE, Talner NS, Sanders SP, Li JS (2000) Clinical auscultation skills in pediatric residents. *Pediatrics 105*:1184–1187
11. Geva T, Hegesh J, Frand M (1988) Reappraisal of the approach to the child with heart murmurs: is echocardiography mandatory? *Int J Cardiol 19*:107–113
12. Henikoff LM, Stevens WA Jr, Perry LW (1968) Detection of heart disease in children. *Circulation 38*:375–385
13. Ishmail AA, Wing S, Ferguson J, et al (1987) Interobserver agreement by auscultation in the presence of a third heart sound in patients with congestive heart failure. *Chest 91*:870–873
14. Jordan MD, Taylor CR, Nyhuis AW, Tavel ME (1987) Audibility of the fourth heart sound. *Arch Intern Med 147*:721–726
15. Jost CHA, Turina J, Mayer K, et al (2000) Echocardiography in the evaluation of systolic murmurs of unknown cause. *Am J Med 108*:614–620
16. Mangione S, Nieman LZ (1997) Cardiac auscultatory skills of internal medicine and family practice trainees. *J Am Med Assoc 278*:717–722
17. Maron BJ, et al (1996) Cardiovascular preparticipation screening of competitive athletes: American Heart Association medical/scientific statement. *Circulation 94*:850–856
18. McCrindle BW, Shaffer KM, Kan JS, et al (1996) Cardinal clinical signs in the differentiation of heart murmurs in children. *Arch Pediatr Adolesc Med 150*:169–174
19. Newburger W, Rosenthal A, Williams RG, Fellows K, Miettinen OS (1983) Noninvasive tests in the initial evaluation of heart murmurs in children. *N Engl J Med 308*:61–64
20. Rangayyan RM, Lehner RJ (1988) Phonocardiogram signal analysis: a review. *CRC Crit Rev Biomed Eng 15*:211–236
21. Richards MR, Merritt KK, Samuels MH, et al (1955) Frequency and significance of systolic cardiac murmurs in the first year of life. *Pediatrics 15*:169–179
22. Smythe JF, Teixeira OHP, Vlad P, Demers PP, Feldman W (1990) Initial evaluation of heart murmurs: are laboratory tests necessary? *Pediatrics 86*:497–500
23. St Clair EW, Oddone EZ, Waugh RA, Correy GR, Feussner JR (1992) Assessing house staff diagnostic skills using a cardiology patient simulator. *Ann Intern Med 177*:751–756
24. Tavel ME (1996) Cardiac auscultation: a glorious past—but does it have a future? *Circulation 93*:1250–1253
25. Tavel ME, Brown DD, Shander D (1994) Enhanced auscultation with a new graphic display system. *Arch Intern Med 154*:893–898