Cardiac Auscultatory Recording Database: Delivering Heart Sounds Through the Internet

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Abstract

The clinical skill of cardiac auscultation, while known to be sensitive, specific, and inexpensive in screening for cardiac disease among children, has recently been shown to be deficient among residents in training. This decline in clinical skill is partly due to the difficulty in teaching auscultation. Standardization, depth, and breadth of experience has been difficult to reproduce for students due to time constraints and the impracticality of examining large numbers of patients with cardiac pathology. We have developed a web-based multimedia platform that delivers complete heart sound recordings from over 800 different patients seen at the Johns Hopkins Outpatient Pediatric Cardiology Clinic. The database represents more than twenty significant cardiac lesions as well as normal and innocent murmurs. Each patient record is complete with a gold standard echo for diagnostic confirmation and a gold standard auscultatory assessment provided by a pediatric cardiology attending.

Introduction

Despite rapid advances in sophisticated cardiac imaging tools, auscultation using a simple stethoscope remains a powerful and fundamental skill used by both the generalist and specialist to discriminate disease from health, yet acquiring the knowledge and experience required for effective auscultation of the heart is still one of the most challenging and elusive hurdles faced by the medical student and resident physician-in-training. Several studies have shown that an experienced cardiologist can accurately determine the innocence or pathologic significance of most murmurs heard in children using as few as six cardinal clinical signs, without relying on expensive testing (1-5). In contrast, many pediatricians and family practitioners are either unfamiliar with, or are unable to accurately identify these signs and therefore often refer patients with innocent murmurs either directly for an echocardiogram or to the cardiologist for a subspecialist's opinion.

Recently, the level of clinical auscultation skills in pediatric residents has been documented as sub-optimal (6). We suspect that the decline in this skill of auscultation is partly due to the difficulty in teaching auscultation. Standardization, depth, and breadth of experience has been difficult to reproduce for students due to time constraints and the impracticality of examining large numbers of patients with cardiac pathology. These circumstances are exacerbated by the fact that congenital heart disease or acquired valvular disease is rarely seen in an untreated state, and when present, patients are not in the hospital long enough for students to learn from their examinations. These needs provide specifications for a system that is easily accessible, reproducing actual patient heart sounds with clinical scenarios and confirmatory diagnostic test results.

There are electronic and computer-based auscultation tools that rely heavily upon synthesized heart sounds (6, 7, 8). While synthesized sounds offer flexibility in studying certain cardiac findings, they lack the realism that is important in developing actual skill in auscultation. Additionally, the cost, size, and need to purchase an independent, limited function device may be prohibitive.

There are CD-ROM based collections of actual heart sound recordings that teach a single representative case of each cardiac lesion. In contrast, cardiologists develop their auscultation skills over years of experience listening to hundreds of patients, thus becoming familiar with the variations in pathologic and normal heart sounds.

This article will describe the Cardiac Auscultatory Recording Database (CARD), a teaching and research tool designed to deliver digitized pediatric and adult heart sound recordings and comprehensive clinical scenarios over the Internet through a web browser.

Design Considerations

We developed the Cardiac Auscultatory Recording Database with the following considerations:

Teaching Tool

First, we aimed to accurately reproduce auscultation to enable students to develop their clinical skill. Secondly, we strove to build a case repository for teaching the

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common presentations of diseases in pediatric cardiology.

Research Tool
We planned to develop a dataset that was useful not only for teaching, but for the development of computerized algorithms for automated murmur recognition and diagnosis.

Clinical Tool
We envisioned the use of the website as a reference for clinicians, enabling the rapid and efficient comparison of recorded heart sounds from previous visits with current auscultations. In addition, new patients with unfamiliar examinations might also be compared with known patients to look for similarities with the heart sound signature. A comprehensive search mechanism would be needed to enable users to identify patients with specific or combinations of auscultatory findings, echocardiography diagnoses, or clinical history.

System Description

Website Development & Deployment
The Cardiac Auscultatory Recording Database is developed using Microsoft Access as the relational database backend. The website interface is written in Allaire's Cold Fusion language following a variant of the Fusebox software architecture style (9). The website is hosted on a Hewlett Packard LH3 NetServer running Microsoft Windows NT, Microsoft Internet Information Server version 4, and Allaire's Cold Fusion professional server version 4.01.

Collection of Heart Sounds
Digitization of patient auscultatory exams was performed by a technician. Clinical history, auscultation descriptions as reported by an attending physician, and echocardiography results were added to the database.

Each heart sound was recorded for twenty seconds through two Hewlett Packard 21050A microphones with simultaneous data capture from three ECG leads. Data acquisition was accomplished through LABVIEW software operating on a laptop with an analog-to-digital converter connected to the amplified output of the microphones and electrocardiogram leads. Auscultations were digitized at 16-bit resolution at a sample rate of 4 KHz. One microphone was placed at the point of interest with the other microphone placed on the abdomen or arm to record ambient, non-cardiac sounds.

Descriptions of auscultation findings were documented from the bedside assessment of pediatric cardiology attending physicians in the clinic and the additional assessment of a pediatric cardiology attending listening to the digital recordings alone. Since we did not assume that bedside auscultation and digital auscultation were identical, the auscultation based upon the digital recordings was selected as the gold standard description since it represents the findings known to be audible in the digital format. Correlation between the bedside and digital auscultation descriptions was high ($r=0.82$, $p<0.0001$) as documented in a separate report on these data (10). For diagnosis, all patients have echocardiography reports that serve as the gold standard.

The clinical history and echocardiography results were downloaded from the electronic medical record at Johns Hopkins Hospital. Identifying names were removed from the clinical history. Twelve-lead electrocardiograms, when available, were scanned from paper printouts and added to the website.

Signal Processing
After bedside heart sound recording was complete, a WAV audio file was extracted from the LABVIEW binary data. A graphic was generated showing simultaneous phonocardiogram, ECG tracing, and Fourier analysis (frequency vs. time). Subsequently, five filters were applied to the WAV audio file: high-pass, low-pass (to simulate the bell attachment of a stethoscope), time-stretch with pitch preservation, and combinations of high-pass with time stretch and low-pass with time stretch. These filtered versions allow a student to slow the rapid pediatric heartbeat and emphasize different aspects of the cardiac cycle with the hope that significant findings are more easily identified. The original and filtered audio files were then encoded into RealAudio and MP3 formats to facilitate audio playback through a web browser.

Security
Since CARD is designed to serve in the dual role of teaching and research, we control access to the website as well as access to patient identifiers.

Website use is restricted to individuals with approved username and password combinations. Website pages are encrypted using the secure sockets layer (SSL) feature of the webserver to minimize risk of interception. Upon successful login, the user's browser is given a non-permanent cookie for authentication against the server's session variables every time a webpage is retrieved. The ability to access certain website features is controlled through permission or privilege variables that are initialized on the server at login. Users are automatically logged out after approximately fifteen minutes of inactivity or if the browser is closed.

Following a role-based security model, patient names are removed from the clinical history and are masked from display for typical users. The website substitutes its own identification numbers for patients.

Sound Playback

The website interface allows a user to retrieve a patient visit, read anonymized clinical information, then auscultate. Audio file playback is triggered through JavaScript enhanced hyperlinks that invoke the RealAudio player, the Windows Sound Player, or an MP3 compatible sound player (figure 1). Graphics for each sound file include phonocardiograms, ECG tracings, and Fourier analysis.

Auscultations

When a user has finished listening, he or she may enter their auscultatory assessment through a series of forms that encourage the use of a standard vocabulary to describe key components of the cardiac cycle. These forms have common descriptors that may be checked as present. The user may also enter their own description in a free text field.

After the user has characterized a heart sound, he or she is asked to determine if a murmur is present. If present, a murmur is described through a similar form with common descriptors easily check marked.

Finally, each auscultator must make a diagnosis. He or she may simply indicate that the examination is normal or normal with an innocent murmur. If pathology is suspected, the user can indicate the suspected lesion through a client-side JavaScript "search-from-hundreds" routine which quickly retrieves diagnostic codes. These diagnostic codes correspond to those used for echocardiography findings.

The website typically operates in either of two modes depending upon the user's status. In an interactive learning mode, users are not permitted to view any auscultation description until they have completed their own assessment. Additionally, the echocardiography report and twelve-lead electrocardiogram (ECG) interpretation are suppressed. Once their auscultation has been entered, the gold standard auscultation description with findings made by an attending physician is made available with confirmatory echocardiography and ECG reports.

Search

In a reference mode, users are immediately granted full access to each patient record. The search feature allows for quick retrieval of relevant patient visits and heart sounds based upon auscultatory findings, echocardiography diagnosis, chief complaint, or clinical history. This feature might be useful at the bedside when a resident makes an auscultatory finding, but is unsure of the diagnosis. He or she can quickly retrieve stored heart sounds for comparison and development of a differential diagnosis.

The search interface allows multiple search terms with simple AND, OR, NOT logic within and between fields. This interface also provides a "lookup" that identifies search terms currently in use.

Every executed search is saved in each user's search history, allowing results to be stored and shared with other individuals. The search parameters are also stored to allow the future execution of identical searches, thereby retrieving newly added patients.

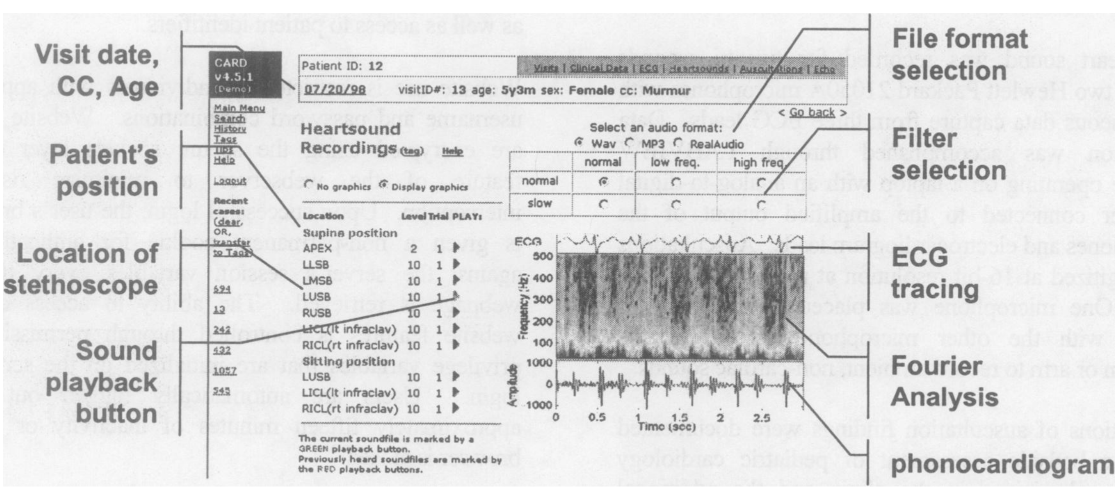

Figure 1. Auscultation interface. Each heart sound plays in the chosen format with the selected filter when the triangular play button is clicked.

Status

Patient Selection

Beginning in July 1997, patients of all ages seen at the Johns Hopkins Outpatient Center Pediatric Cardiology Clinic had their clinical exams digitized. Patients with and without heart disease were included; in particular, those with innocent or "functional" heart murmurs were included. Patients were excluded from the database if informed consent was not obtained, if examinations were marred by unacceptable noise artifact, or if echocardiography was not to be performed.

The Dataset

To date, we have collected and catalogued 5,038 individual recordings from 931 visits representing 867 different patients. Patients range in age from 1 day old to 80 years and represent a wide variety of congenital and acquired cardiac diseases. In some cases, CARD also provides heart sound recordings with the patient squatting, sitting, or standing. Table I identifies the frequency of selected cardiac abnormalities contained within the database.

TABLE I. Frequency of patients with abnormal cardiac exams.

Diagnosis	No. of Patients
Aortic Stenosis	70
Atrial Septal Defect:	
Not otherwise specified	2
Primum	3
Secundum	51
Sinus Venosus	3
Sino-septal	1
Bicuspid aortic valve	79
Dilated cardiomyopathy	12
Coarctation of the aorta	16
Common atrioventricular canal	8
Ventricular septal defect:	
Not otherwise specified	11
Conoventricular	4
Membranous	56
Muscular	28
Sub-pulmonary	3
Dextrocardia	5
Sub-aortic stenosis	26
d-Transposition of the great arteries	17
Double chambered right ventricle	3
Double outlet right ventricle	7
Double inlet left ventricle	4
Dysplastic pulmonary valve	6
Ebstein's anomaly of the tricuspid valve	3
Hypertrophic cardiomyopathy	7
Mitral regurgitation	95
Mitral stenosis	19
Mitral valve prolapse	53
Patent ductus arteriosus	57
Tetralogy of Fallot	12

The original 5,038 WAV files have been filtered and converted into a total of 90,671 sound files of twenty seconds duration each. In addition, a total of 4,981 graphic files comprised of ECG tracing, Fourier analysis, and phonocardiogram were generated.

The database contains 2400 echocardiography results, 696 twelve-lead electrocardiogram graphics, and 1710 auscultation reports.

Lessons Learned

After six months of implementation and management, the CARD system has grown significantly. The database currently occupies over 4.65 gigabytes of WAV files, which is nine times larger than a single-CD-ROM based heart sound collection. Managing a database of this size for the purposes of educating housestaff and fellows has identified two key areas that require additional research.

Bandwidth

Although we have addressed the issue of file size and bandwidth limitations, the practical deployment of CARD is restricted to those individuals in high bandwidth environments. The typical patient exam comprises of at least five heart sound recordings, each approximately 160 KB in size when in WAV format. Other formats such as MP3 or RealAudio are dramatically smaller, typically one-third the original size (table II). When tallying both the size of the graphics (150 KB) as well as the audio files, each patient encounter ranges from 252 KB to 950 KB in size, depending on the audio file format.

TABLE II. Audio file format comparison.

File format characteristics:		size
WAV	Streaming	160 KB
MP3	Non-streaming	60 KB
Real Audio	Streaming	104 KB
Jpeg (350x298)	Progressive	30 KB

In order to make the user experience as responsive as possible, the website is designed only to show graphics when desired and will download these graphics into the browser's cache during idle time. Table III reports ideal transmission times for 150 kilobyte (e.g. uncompressed WAV audio file or entire graphics set) and 60 kilobyte files (e.g. MP3 audio file).

For 56-kilobit modem users, CARD's ability to display graphics during auscultation is limited by the time required to download the necessary files (21.9 seconds). In the hospital setting, the website transmits both graphics and audio nearly instantaneously across a busy 10 Mbps Ethernet network. We believe that the bandwidth limitation imposed by a 56-kilobit modem will become less significant as broadband options such as Cable and DSL modems penetrate residential markets.

TABLE III. Theoretical transmission times.

Transmission	speed	150 KB file	60 KB file
28.8 Modem	28 Kbps	42.7	17.1
56k Modem	56 Kbps	21.9	8.8
ISDN	128 Kbps	9.6	3.8
Cable Modem	400 Kbps	3.1	1.2
DSL	768 Kbps	1.6	0.6
T1	1.5 Mbps	0.8	0.3

Sound Playback Hardware

Although we believe that auscultation through the website with standard headphones connected to a modern sound card is adequate for learning, reproduction of low (bass) frequencies is subjectively improved using a stethophone (a stethoscope shaped headphone) where sounds are directed down the ear canal. We have also observed differences in the ability of certain sound card configurations to reproduce our WAV files sampled at 4 KHz. On certain computers, these files will playback at approximately double the original speed. To address these variations, we offer MP3 and RealAudio sound file formats that achieve uniform playback across varying hardware. Although we feel strongly that no loss in quality can be appreciated, further study is necessary to quantify differences in sound reproduction.

Recent & Future Work

CARD is regularly used by us to conduct group teaching sessions and will be publicly available for this purpose. We have recently used CARD to conduct a faculty auscultation trial to validate the usefulness of the digital recordings for diagnostic purposes. A controlled trial testing the effectiveness of teaching clinical auscultation through this web-based multimedia platform and of quantitatively evaluating this clinical skill is planned.

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