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Computer-Aided Auscultation of the Heart: From Anatomy and Physiology to Diagnostic Decision Support

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Abstract—**There is a clear and present need for computer-aided auscultation of the heart which arises from the highly informative nature of heart sounds, the inherent difficulty of auscultation and increasing pressure in healthcare for rapid, accurate, objective, documented and cost-effective patient evaluation and diagnostic decision making. There are advanced signal processing technologies that hold promise for developing computer-aided auscultation solutions that are intuitive, efficient, informative and accurate. Computer-aided auscultation offers an objective, quantitative and cost-effective tool for acquiring and analyzing heart sounds, providing archival records that support the patient evaluation and referral decision as well as serial comparisons for patient monitoring. There is the further promise of new quantitative acoustic measures and auscultatory findings that have more precise correlation with underlying physiological parameters. These solutions are being developed with the benefits of a rich literature of clinical studies in phonocardiography, the added insights derived from echocardiography, and advances in signal processing technology.**

I. Introduction

In the current continually developing healthcare context, there are emerging opportunities to provide diagnostic decision support to physicians and other medical personnel who must evaluate patients and make referral and treatment decisions that are critical to the health of their patients under circumstances of increasing pressure. These pressures arise from a rapidly accelerating body of knowledge about anatomy, physiology, biochemistry, genetics, therapeutic methods and agents, clinical studies and outcomes; evolving standards of care, growing risk of litigation, increased oversight by payers, cost-effectiveness considerations and consequent needs for greater patient throughput.

Particularly in evaluating the functional status of a complex system such as the heart, there is an opportunity to provide diagnostic decision support tools at various stages in the healthcare process, which include home health-care, sports screening, point-of-care referral decisions, post-surgical and critical-care patient monitoring.

One opportunity of particular interest is computer-aided auscultation of the heart (and lungs). Since the development of the stethoscope in 1816, the sounds of the heart have been carefully studied and related to physiological events within the heart. The interpretation of heart sounds has been made with increasing accuracy, especially since the advent of the sound spectrograph (1942), of which the encyclopedic work of McKusick on the spectral properties of heart sounds provides a rich example [1].

There is a substantial literature in phonocardiography, which records and correlates signals from various modalities to demonstrate the relationship of various heart sounds and murmurs with different parameters of cardiac physiology. A particularly clear and informative example of such studies is Harris [2]; other studies include Tavel [3], Levine and Harvey [4], Luisada [5] and Leatham [6]. With the availability of the increasingly high-resolution visual and quantitative information provided by cardiac ultrasound, the process of the generation of heart sounds has been established in great detail.

The opportunity for computer-aided auscultation of the heart is partly established by the inherent difficulty in hearing and correctly interpreting heart sounds. The sounds of the heart, which are reflective of hemodynamical processes, are often barely audible, involving dominant frequencies at the lower frequency edge of the threshold of hearing, and brief, transient sounds, the sequence of which is difficult to discern and the exact separation of which is hard to estimate. Auscultation is necessarily subjective, and the determination of spectral energies, splitting intervals and event sequences are hard to quantify upon listening. Moreover, archival recording of heart sounds is not currently part of standard clinical practice, and there are no methods generally used for supporting referrals to echocardiography with objective, instrumented auscultatory findings, nor readily available means for serial comparison of heart sound recordings.

A further factor is the decline of teaching of auscultation in medical schools [7] and a consequent lack of confidence and accuracy in identifying heart sounds and murmurs commonly encountered in clinical practice [8]. Renewed efforts at teaching auscultation as well as the use of teaching tapes and online resources will surely be helpful, but there are inherent limits to human performance. The economic consequences for the healthcare system are measurable in part by the number of referrals to echocardiography for evaluation of patients with heart murmur of unknown origin; audits of such referrals suggest that a very large proportion are reasonably considered unnecessary [9],[10]. Nonetheless, it is possible for someone with sufficient training and experience to accurately make

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referral decisions on the basis of auscultation [11], [12]; which suggests that the acoustic cues exist for reliable decision making. The goal, then, is to detect and quantify these cues for the benefit of the medical decision maker.

I. Computer-aided auscultation systems

A. Sensors

A necessary first step in computer-aided auscultation is the acquisition of heart sound signals through an appropriate sensor. The electronic stethoscope is an attractive solution to this need, as it provides an electrical transducer in the form factor of a standard stethoscope and delivers heart sounds with amplification and adjustable volume to the eartips along with selectable filtering that simulates the bell and diaphragm modes.

Several commercially available electronic stethoscopes also support recording of heart sounds, either by local a/d conversion and wireless transmission, or by an analog output which can be connected to the sound card of a laptop computer or workstation.

Electronic stethoscopes are generally designed to replicate as closely as possible the acoustic characteristics of mechanical stethoscopes, with the added advantage of controlled amplification and some filtering of background noise. The frequency response of these stethoscopes, however, varies considerably [13] which has implications for signal processing and classification. Moreover, the frequency response is intended to minimize the difference between the electronic and mechanical scope rather than to provide a flat response across a range of frequencies that may extend below the threshold of audibility. Furthermore, the controls and indicators of electronic stethoscopes are not (yet) ideally suited to the requirements of computer-aided auscultation; for example, there is typically no means for initiating the capture of heart sounds from the stethoscope, or support for an indication of completion of acquisition or data quality. In the future, changes in stethoscope design will likely reflect more closely the sensor goals of computer-aided auscultation.

B. Data Acquisition Protocols

Using an electronic stethoscope, a sequence of heart sound recordings can be obtained from standard auscultatory sites on the precordium; variations in the placement of the stethoscope can be accommodated for special purposes; however, for general examinations, the standard locations provide a useful starting point. In order to increase the likelihood of correct placement of the stethoscope and the correct labeling of site recordings, a voice-guided protocol has been developed that includes a graphical-user interface to indicate the auscultatory site to be recorded next (see Figure 1). Such methods have been found to be highly intuitive to users, quickly learned and accurately applied.

By recording 20 seconds of data, several respiratory cycles are captured even at the lower limit of adult respiration rates. Shorter recordings can be obtained in support of an even more streamlined protocol, with some (minimal) impact on performance.

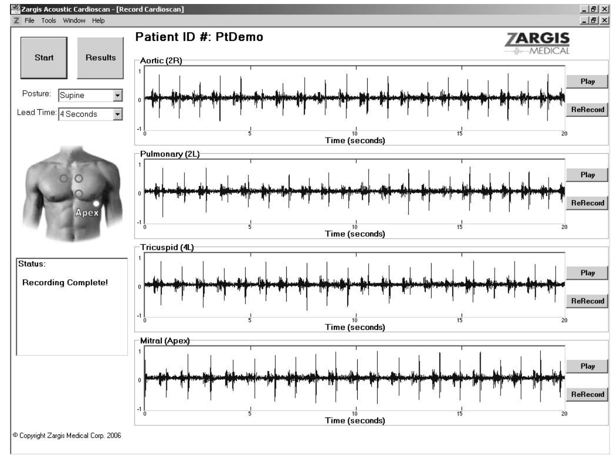

Fig. 1. Example graphical user interface in support of voice-guided auscultatory protocol for recording heart sounds.

C. Signal Processing

Realizing the potential of computer-aided auscultation is supported by decades of research and clinical studies in phonocardiography and advances in signal processing methods applied to heart sound analysis (for reviews, see Durand [14] and Rangayyan [15]). More specifically, advanced time-frequency methods, particularly wavelets, have been shown to have excellent properties for decomposition and representation of heart sounds [16]. These methods have been applied to the analysis of the first heart [17], second [18] and third heart sounds [19] and murmurs [20],[21].

Recent advances in nonlinear adaptive methods for classification have been applied to advantage to heart sound detection [22]-[25]. The ability to identify the first and second sounds enables the determination of systolic and diastolic intervals and the classification of murmurs on the basis of the heart sound signal alone; this capability obviates the need for a synchronizing ECG signal, which has positive implications for system design and results in a simplified clinical workflow.

Heart sounds are the product of a complex dynamical system, the states of which are unobservable. The heart beats in a quasi-regular manner and traverses its state space cyclically; the continual beating of the heart leads to well-defined temporal structure of heart sounds, which, to use an analogy to speech, is similar to someone speaking the same word repeatedly with minor variations. This insight provides the basis for applying advanced methods of statistical modeling and signal processing developed for speech recognition, chiefly hidden Markov models, to the interpretation of heart sounds [26]-[28].

All data driven methods depend for their success and applicability on statistically representative data sets for training, validation and testing. In the case of heart sounds, this requirement results in the need to obtain very large databases in order to capture the signal variations across patient characteristics, including age and gender, disease characteristics, including a wide range of valvular and congenital anomalies which vary widely in prevalence, as well as recording characteristics such as patient posture, recording sites and sensors. It is essential that these recordings be made under clinically realistic conditions, which will include motion artifacts and various endogenous and exogenous noises such as breath noise, bowel sounds and background speech. There are currently no widely available large scale databases for development or evaluation purposes; the Johns Hopkins Cardiac Auscultation Recording Database is an excellent resource for research purposes, although it contains predominantly pediatric subjects, but there is no publicly available resource similar to those which are available for evaluation and comparison of ECG algorithms.

II. Clinical applications

A. Patient evaluation and referral decision-support

A major opportunity for computer-aided auscultation of the heart is found in the evaluation and management of patients by primary-care physicians, particularly with regard to the treatment of patients with heart murmurs. Heart murmurs may be present in individuals of any age and are particularly common among children. Estimates of the prevalence of heart murmurs among children range from 72% to 80% [29] and from 29% to 60% among the elderly [30]. Among children, murmurs of non-pathological origin are overwhelmingly predominant, as are murmurs often heard in late pregnancy.

Referral to a specialist or to echocardiography for evaluation of asymptomatic patients with heart murmurs is very common and the outcome of such referrals is often a finding of non-pathological murmurs [9], [10]. The economic and social cost of such referrals is non-trivial and diagnostic decision-support tools which could enable more accurate referral decisions at the point of care would be expected to have a significant positive impact on healthcare costs. It has been shown that innocent systolic murmurs can be differentiated from pathological murmurs on the basis of the mid-systolic energy level [31]. A recent clinical study has shown that computer-aided auscultation enabled seven primary care physicians listening to a set of 100 heart sound recordings to reduce their average false positive referral rates from 36.5% to 21.4% ($p<0.001$) while reducing their false negative rates from 13.3% to 7.1% [32].

B. Pre-participation sports screening

The American Heart Association has published recommendations for preparticipation screening of young athletes which includes precordial auscultation of the heart as a component of the physical examination [33]. However, these AHA recommendations are unevenly and incompletely implemented; in a recent audit, only 26% of NCAA schools and only 17 of 43 states surveyed for compliance at the high school level were found to use adequate history and physical examination forms [34]. When performed, auscultation of the heart is often performed by personnel less skilled than a physician in less than acceptable acoustic environments.

To date, there have not been extensive studies assessing the effectiveness of computer-aided auscultation for sports screening, although the detection of systolic and diastolic murmurs would provide useful information and would already represent an improvement of the current situation.

One recent pilot study found a high degree of concordance between judgments of murmur grade by a cardiologist and spectral measures of systolic energy which enabled the correct detection of murmurs which were louder in standing than reclining postures. This difference in systolic murmur loudness is an auscultatory finding that is indicative of obstructive hypertrophic cardiomyopathy, a congenital condition that is implicated in about 35% of cases of sudden cardiac death in young athletes [35].

C. Diagnostic decision support

In addition to the broader screening and referral decision support applications, computer-aided auscultation has also been applied to specific diagnostic questions involving the severity of aortic stenosis [36] and pulmonary hypertension [37], among others. In the first example, the duration of the mid-systolic murmur energy above 300 Hz. was found to be highly correlated with the peak transvalvular pressure gradient, an indication of the severity of aortic stenosis. In the second example, the splitting interval between the aortic and pulmonic components of the second heart sound, as measured by a method of spectral dechirping and normalized by heart rate, was found to correlate well with systolic mean pulmonary arterial pressure. These studies provide acoustic measures (spectral energy and splitting) that are objective, quantitative, repeatable and more precise than is possible for human listeners to achieve.

Other well-established auscultatory findings with diagnostic significance suggest opportunities for diagnostic decision-support applications: the splitting of S2 in relationship to the diagnosis of atrial septal defect, the detection of the third and fourth heart sounds in relation to diastolic dysfunction and the presence of mid-systolic clicks indicative of mitral valve prolapse are several examples.

D. Other applications

In addition to screening and diagnostic decision-support, there are opportunities for computer-aided auscultation of the heart to contribute to improve healthcare and patient management. Examples of these applications include the assessment of implanted bio-prosthetic heart valves, long-term monitoring of patients with valvular or congenital heart disease and post-surgical follow-up. There is also the possibility of establishing new correlations between physiological parameters and acoustic features that would enable rapid assessment of specific aspects of patient health.

III. Future Directions

As the field of computer-aided auscultation matures, we expect that new electronic stethoscopes will be developed that are specifically designed to acquire high-fidelity heart sound recordings over a broader range of frequencies and provide optimal amplifications, controls and indicators. Systems will emerge that support a full inventory of canonical auscultatory findings in support of patient evaluation and referral decisions. New algorithms will be developed that derive quantitative auscultatory findings that are correlated with physiological variables. Clinical studies showing the cost-effectiveness of computer-aided auscultation of the heart will persuade payers to reimburse the use of decision support systems at the point of care. Extended clinical applications will be developed that leverage computer-aided auscultation in a variety of healthcare contexts.

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