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Review

Beyond auscultation: Acoustic cardiography in clinical practice

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ABSTRACT

Cardiac auscultation by stethoscope is widely used but limited by low sensitivity and accuracy. Phonocardiogram was developed in an attempt to provide quantitative and qualitative information of heart sounds and murmurs by transforming acoustic signal into visual wavelet. Although phonocardiogram provides objective heart sound information and holds diagnostic potentials of different heart problems, its examination procedure is time-consuming and it requires specially trained technicians to operate the device. Acoustic cardiography (AUDICOR, Inovise Medical, Inc., Portland, OR, USA) is a major recent advance in the evolution of cardiac auscultation technology. The technique is more efficient and less operator-dependent. It synchronizes cardiac auscultation with ECG recording and provides a comprehensive assessment of both mechanical and electronic function of the heart. The application of acoustic cardiography is far beyond auscultation only. It generates various parameters which have been proven to correlate with gold standards in heart failure diagnosis and ischemic heart disease detection. Its application can be extended to other diseases, including LV hypertrophy, constrictive pericarditis, sleep apnea and ventricular fibrillation. The newly developed ambulatory acoustic cardiography is potentially used in heart failure follow-up in both home and hospital setting. This review comprehensively summarizes acoustic cardiographic research, including the most recent development.

1. History of cardiac auscultation

Before the 19th century, cardiac physical examination was limited to inspection and palpation. With the invention of stethoscope by Rene Laennec in 1816, cardiac auscultation was introduced into clinical practice for cardiovascular examination [1]. For two centuries, physicians have been using this method to interpret physiological and pathological changes of the heart. However, it has been reported that auscultation by stethoscope has low diagnostic sensitivity and accuracy [2,3]. Clinical disagreement and skill discrepancy among examiners result in non-objective and unreliable auscultation data [4,5]. As reported by Avendano-Valencia et al., human ear limitation is another explanation to the deficiency of traditional physical auscultation [6].

Phonocardiogram was developed in an attempt to provide quantitative and qualitative information of heart sounds and murmurs. The phonocardiogram records heart sound through a microphone, which is placed on the chest wall of subjects. The acoustic signal is transformed into visual wavelet and recorded graphically [7]. Mathematical methods to improve the diagnostic quality of phonocardiogram data have evolved in recent years [3,8–10]. With the advance of digital techniques, phonocardiogram is now capable of characterizing heart sounds and murmurs by their acoustic components, pattern, timing, frequency and intensity [2]. Data obtained from phonocardiogram can refine cardiologists' understanding of the mechanism and origin of heart sounds and may aid in clinical diagnosis. The results of phonocardiogram have been used as reference standard to judge physicians' auscultation skill [11]. The application of phonocardiogram was further extended to the diagnostic evaluation of left ventricular (LV) dysfunction and myocardial ischemia. Systolic time interval, i.e., the interval between peak intensity of the first (S1) and second heart sounds (S2), has been shown to correlate with impaired LV systolic function and coronary heart disease [12–21]. Phonocardiogram, when combined with echocardiography, electrocardiography (ECG) and carotid pulse tracing offers a non-invasive measure of systolic time intervals to evaluate LV function [12,16,18,19] and to detect coronary artery insufficiency [14,17,20,21]. Although phonocardiogram provides objective heart sound information and holds diagnostic potentials of different heart problems, its examination procedure is time-consuming and requires specially trained technicians to operate the device. Consequently, a more efficient and less operator-dependent technique is needed for routine clinical practice, and as a result, acoustic cardiography (Audicor, Inovise Medical, Inc., Portland, OR) was developed.

2. The technology of acoustic cardiography

Acoustic cardiography is a major recent advance in the evolution of cardiac auscultation technology. The technique synchronizes cardiac

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auscultation with ECG recording and provides a comprehensive assessment of both mechanical and electronic function of the heart. The Audicor system consists of three components: an acoustic/ECG console with two chest sensors, a computer for signal processing and analysis, and a printer to generate a full report of acoustic and ECG data. The acoustic information is processed with wavelet signal reprocessing techniques and uses time-frequency analysis to detect heart sound, as well as the intervals between sounds (Figs. 1–7). Unlike traditional phonocardiogram, acoustic cardiography has the advantage of requiring minimal training in its operation. The examination procedure is even simpler and faster than a traditional 12-lead ECG recording. By placing two sensors on the V3 and V4 positions of the chest and attaching 2 standard electrodes on limb leads positions of standard ECG, both the heart sounds and ECG data are captured, algorithmically analyzed, stored, and displayed. Traditional phonocardiogram required trained clinicians or experienced technicians to interpret the acoustic signals, increasing its inter- and intra-observer variability. In contrast, in acoustic cardiography a detailed report of computerized analysis of the acoustic and ECG information is automatically generated within seconds after data acquisition (Fig. 8), simplifying clinical workflow.

The latest advent of acoustic cardiography is the development of ambulatory monitoring technology (Audicor AM) to allow continuous surveillance of acoustic and ECG data for detection of infrequent events such as transient ischemia, ventricular dysfunction, arrhythmia as well as sleep apnea. The Audicor AM device and data collection process are similar to that of conventional Holter monitoring. Signal acquisition is achieved by attaching 3 electrodes to the chest wall of patients and having the patients to carry a small recorder unit for a period of 24–48 h. Through a wireless connection to a computer, data can be previewed while on recording. A removable smart card within the recorder unit is used to save up to 48 h of data. Data is then transferred to computer for algorithmic analysis. Compared with snapshot acoustic cardiogram, which records only isolated events, ambulatory monitoring device shows the trending of heart failure and therefore evaluates the therapeutic response. Ambulatory acoustic cardiography not only provides acoustic and electrical information, but also respiratory events. With another automated algorithm, the ambulatory recorder unit simultaneously acquires respiratory data, which includes respiration rate, episodes of snoring and sleep apnea [22] (Fig. 9). While a 3-second snapshot acoustic cardiography can be too brief to capture infrequent events, the Audicor AM ambulatory recording device may allow detection of silent ischemia, LV dysfunction, filling status, responses to therapeutic measures and sleep apnea by allowing continuous out-of-hospital monitoring.

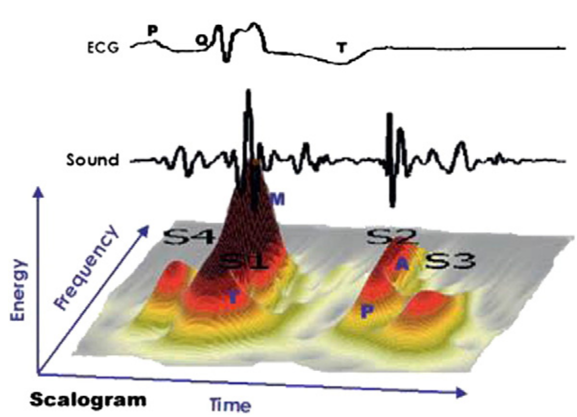

Fig. 1. 3D sound fingerprint. This figure shows the heart sound analysis with wavelet techniques, resynchronized with ECG. Each heart sound has its own time, frequency and energy distribution.

3. Parameters of acoustic cardiography

Acoustic cardiography generates a number of parameters in connection of p wave and QRS complex in every cardiac cycle from ECG to represent LV systolic and diastolic functions (Table 1 and Fig. 10). Among them, the diagnostic value of EMAT, SDI, S3 and S4 in heart failure have been validated in clinical studies and their cut-off values are also established (Table 2) (Fig. 11).

3.1. EMAT and %EMAT

EMAT represents the time required to generate force by LV to close mitral valve and is therefore related to the acceleration of the pressure in LV. Previous studies have indicated that:

- Longer EMAT or increased %EMAT indicates impaired LV function [23];
- Shorten EMAT correlated with improved LV contractility and short electromechanical delays [23];
- Increased %EMAT predicted re-hospitalization in heart failure [24].

3.2. SDI (QRS duration ∗ QR interval ∗ %EMAT ∗ S3 strength)

SDI is a multiplicative combination of ECG and acoustic parameters to predict LV systolic dysfunction with high specificity. It has been shown that:

- SDI> = 5 suggested LV systolic dysfunction (EF < 50%);
- SDI > 7.5 suggested severe LV systolic dysfunction (EF <35%) [25].

3.3. S3

Acoustic cardiography objectively and sensitively detects S3 and expresses it in a value of 0 to 10. S3 strength ≧5 declares the presence of S3. In patients over 40 years, S3 is considered pathological and associated with elevated LV filling pressure and impaired LV contractility. Utilizing acoustic cardiography, studies show that:

- S3 had a positive likelihood ratio of 4.8 to predict LV dysfunction [27];
- S3 correlated with increased LV end-diastolic pressure [27,29];
- S3 assisted BNP to increase diagnostic accuracy of acute heart failure [26].

3.4. S4

Similar to S3, acoustic cardiography derived S4 strength is also provided in a value of 0 to 10. Presence of S4 (≧5) is generally pathological and suggests increased LV stiffness. It was shown that

- S4 was associated with LV stiffness and elevated LVEDP [27].
- The nocturnal increase in S4 strength in asymptomatic older patients indicates diastolic impairment consistent with echocardiographic diastolic filling patterns with increasing age [49].

4. Clinical application of acoustic cardiography

4.1. Heart failure diagnosis and monitoring

4.1.1. Evaluation of left ventricular function

Acoustic cardiography has been shown to correlate with invasive and non-invasive cardiac hemodynamic assessment of LV function. Previous research suggested that acoustic cardiography parameters detects LV dysfunction as precisely as echocardiographic parameters, including LVEF (28,29)and LVDP [30]. In a study of 161 heart failure patients conducted by Zuber et. al., EMAT, LVST, EMAT/LVST measured by acoustic cardiography strongly agreed with echocardiographic ejection fraction (EF) measurement to identify LV systolic dysfunction [28]. In a subsequent larger scale study in 433 heart failure patients, Kosmicki