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Beyond auscultation – acoustic cardiography in the diagnosis and assessment of cardiac disease

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Summary

Auscultation has long been an important part of the evaluation of patients with known and suspected cardiac disease. The subsequent development of phonocardiography provided an analogue visual display that permitted a more detailed analysis of the timing and acoustical characteristics of heart sounds, murmurs, clicks and rubs. In addition, the measurement of systolic time intervals enabled a valuable non-invasive assessment of left ventricular function. Acoustic cardiography, a much more recently developed technology, has enabled the simultaneous acquisition of ECG and cardiac acoustical data. This user-friendly and cost-effective technology permits acquisition of detailed information regarding systolic and diastolic left ventricular function and provides both a computerized interpretation and a visual display of the findings. Its clinical applications include the evaluation of patients with suspected heart failure, ischaemia and cardiac arrhythmias and the optimization of cardiovascular drug and device therapies. It can also be used in a wide variety of ambulatory and inpatient monitoring applications.

Key words: heart sounds; electrocardiogram; cardiovascular diagnosis

History of auscultation and phonocardiography

Since the invention of the stethoscope by Rene Laennec in 1816, auscultation has been an important tool for evaluating patients with known or suspected cardiac disease [1]. Many investigators have described the diagnostic and prognostic value of the third heart sound (S3) in left ventricular dysfunction [2–15]. However, other studies have demonstrated the limitations of the stethoscope per se in the clinical evaluation of patients [16–19].

In recognition of these limitations, phonocardiography was developed to facilitate the evaluation of heart sounds and murmurs [20]. The analogue visual display of acquired acoustic data enables more precise assessments with respect to the timing and acoustical features of heart sounds and murmurs than does auscultation. It is possible to derive accurate measurements of timing relationships (eg to distinguish the S3 from an opening snap and document the presence and direction of splitting of S2) and to obtain accurate information about the duration, relative intensity and contour (eg crescendo/decrescendo *vs* "plateau-shaped") of cardiac murmurs.

The work of Weissler and colleagues increased the usefulness of phonocardiography still further by combining phonocardiography with external recordings of the carotid pulse to derive the systolic time intervals [21–25]. This has enabled precise non-invasive assessments of left ventricular systolic function. The systolic time intervals include the following:

- Q-S2 interval – the interval from the onset of the QRS to the aortic component of the second heart sound.
- Left ventricular ejection time (LVET) – the interval from the beginning of the carotid upstroke to the dicrotic notch.
- Pre-ejection period (PEP) – the interval from the onset of the QRS to the beginning of the carotid upstroke (ie PEP = (Q-S2) – LVET). The PEP has two components, namely the interval from QRS onset to S1 followed by the isovolumic contraction period (ie the interval from S1 to the beginning of the carotid upstroke).
- The ratio of PEP to LVET

Further refinement of the systolic time intervals was achieved with the development of numerical corrections for heart rate and gender. Investigators showed that the systolic time intervals

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could discriminate normal individuals from patients with heart failure and that these values were influenced by contractility, preload, afterload and intraventricular conduction abnormalities [26].

Acoustic cardiography

Despite their clinical value, the use of systolic time intervals as a non-invasive method of haemodynamic evaluation diminished. This was partly because their acquisition was labour-intensive and partly because of the increasing popularity of echocardiography and radionuclide studies. Acoustic cardiography (Audicor®, Inovise Medical, Inc., Portland, OR) has been developed much more recently. This diagnostic technique consists of recording and algorithmically interpreting contemporaneous digital ECG and cardiac acoustical data. This is accomplished by using electrodes placed in the same positions as those used for a standard electrocardiogram (ECG). However, in the V3 and V4 precordial positions it employs dual-purpose sensors that simultaneously acquire ECG and sound data from each of these locations. In addition to a full report of the diagnostic interpretation resulting from a computerized analysis of the ECG and heart sounds, the technology provides a printout of the ECG and heart sound raw data. Figure 1 shows an acoustic cardiographic report that includes a 12-lead ECG. For other types of applications, smaller numbers of ECG leads may be used.

The Audicor® technology uses sophisticated wavelet-based signal processing techniques to evaluate the heart sound data and feed the diag-

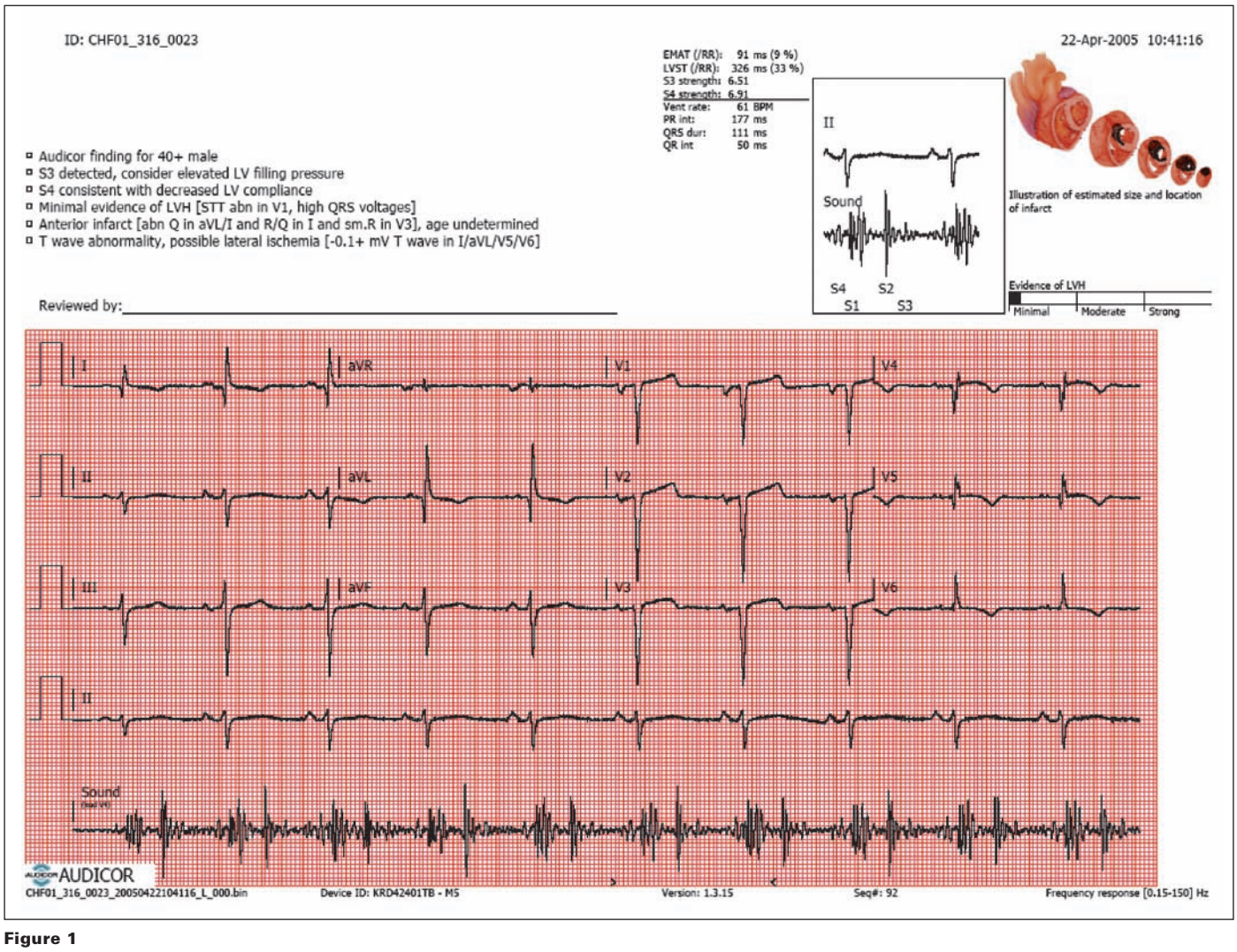


Figure 1

Example of an Acoustic Cardiographic Tracing and Report.
An acoustic cardiographic recording that includes a 12-lead ECG is shown. Below the ECG is a simultaneous sound tracing that reveals both an S3 and an S4. A segment of this sound tracing is also shown near the top right corner of the report and this segment includes labelling of the S3 and S4. At the top left of the report is the printed algorithmic interpretation of both the ECG and the heart sound findings. The ECG findings include an anterior myocardial infarction and evidence of left ventricular hypertrophy. The three dimensional image of the heart in the top right corner of the report indicates the location of the myocardial infarction in black ink. Immediately below the image of the heart is a horizontal bar graph that indicates the relative strength of the ECG evidence for the left ventricular hypertrophy.
Abbreviations: int – interval; LVH – left ventricular hypertrophy; mV – millivolt; S3 – third heart sound; S4 – fourth heart sound; EMAT – electromechanical activation time; LVST – left ventricular systolic time.

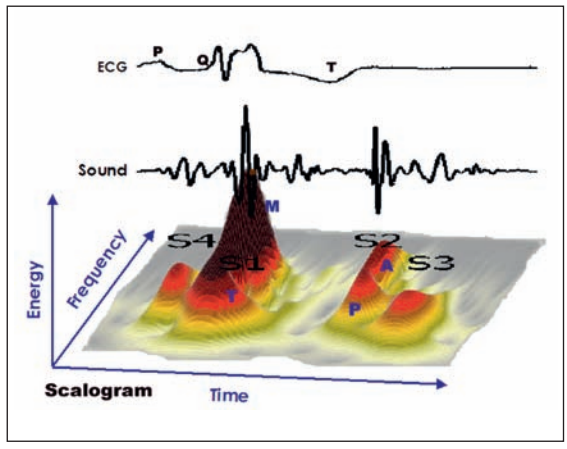
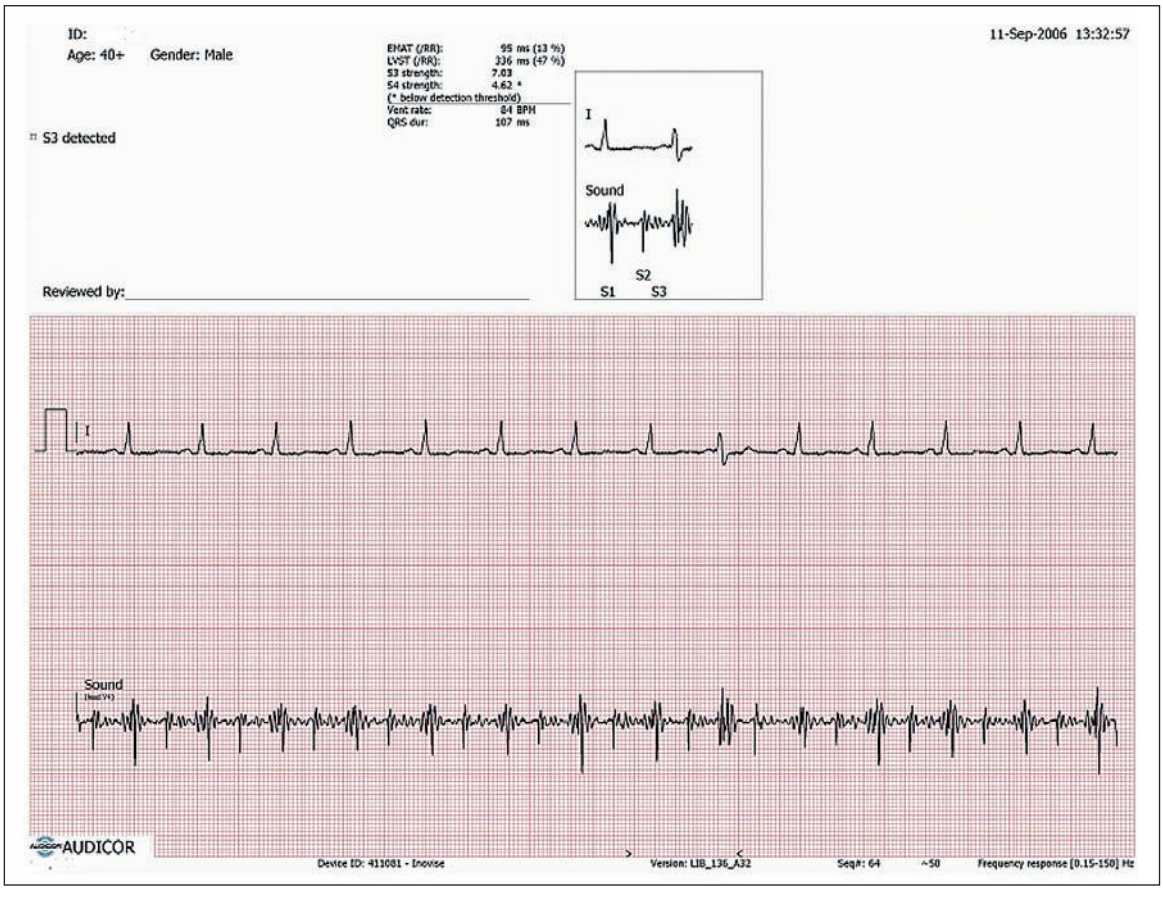


Figure 2

Time-Frequency Analysis of Heart Sounds.
The figure presents a schematic of a single heart beat showing a simultaneous ECG and sound recording in the time domain (upper two traces) as well as the wavelet filter based time-frequency representation of the heart sound recording (scalogram).
Abbreviations: P – ECG P wave; Q – ECG Q wave; T – ECG T wave; S1 – First heart sound; M – Mitral component; T – Tricuspic component; S2 – Second heart sound; A – Aortic component; P – Pulmonary component; S3 – Third heart sound; S4 – Fourth heart sound.

Figure 3

Acoustic cardiography report and time-frequency analysis of heart sounds for a subject with a third heart sound.
The upper panel (a) shows an acoustic cardiography report for a subject with a third heart sound, and the panels below illustrate the 2D (b) and 3D (c) scalogram views for three beats of the same recoding as in the upper panel. The third heard sound can be most easily identified in the 3D scalogram view, which is used by the sound algorithm for the detection and calculation of the heart sound intensity.



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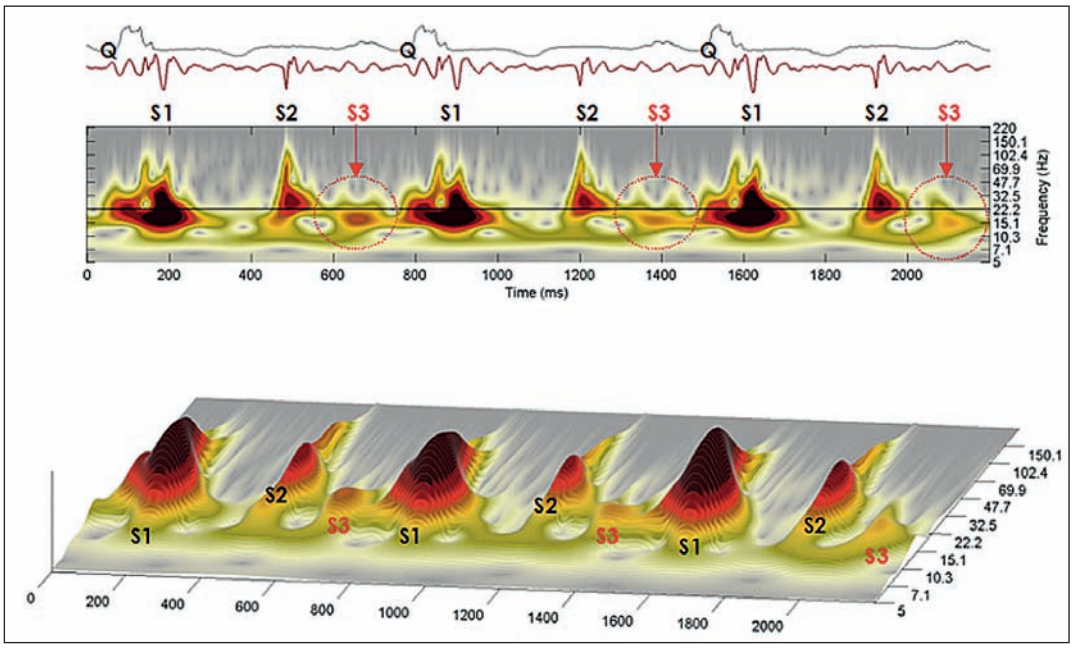

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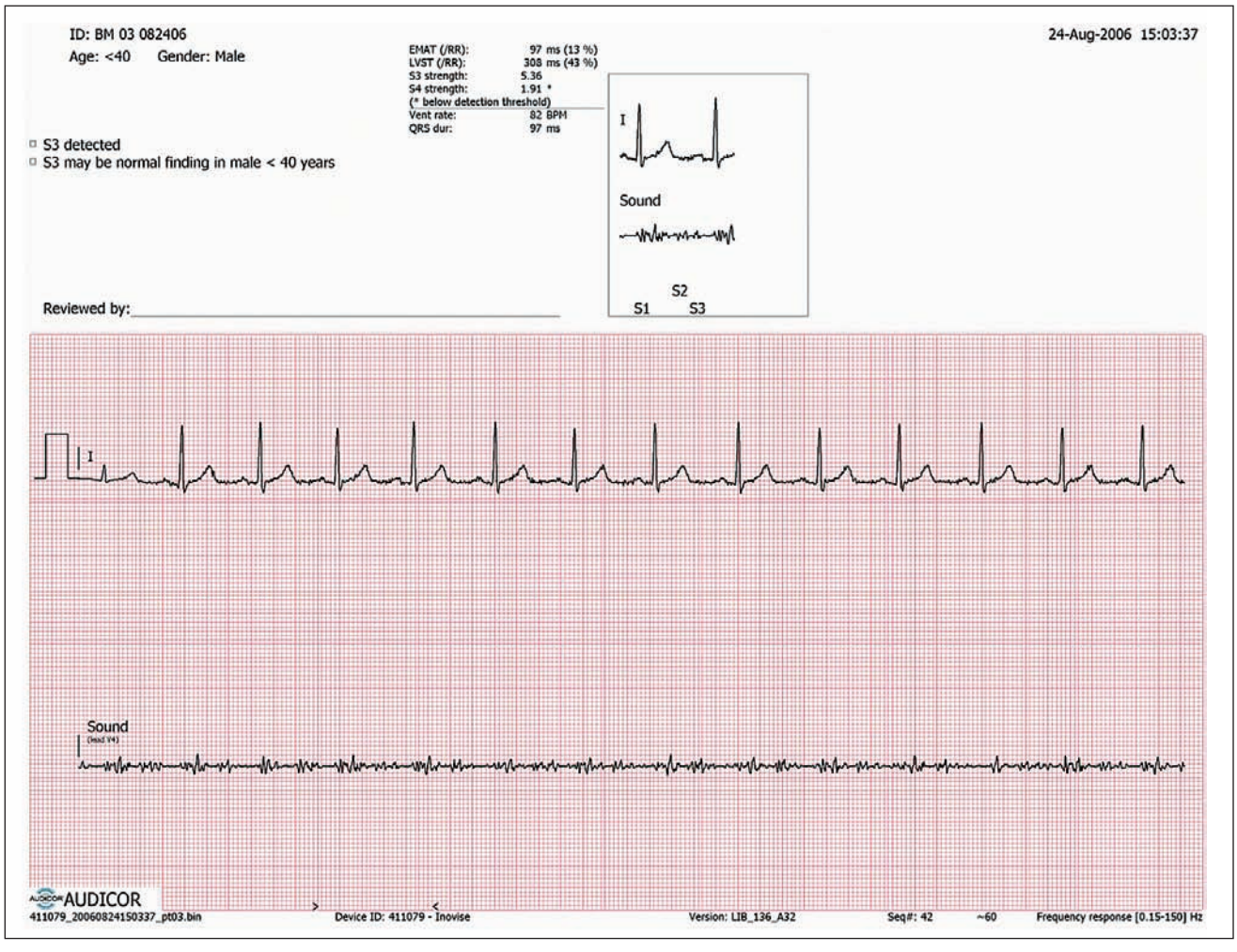

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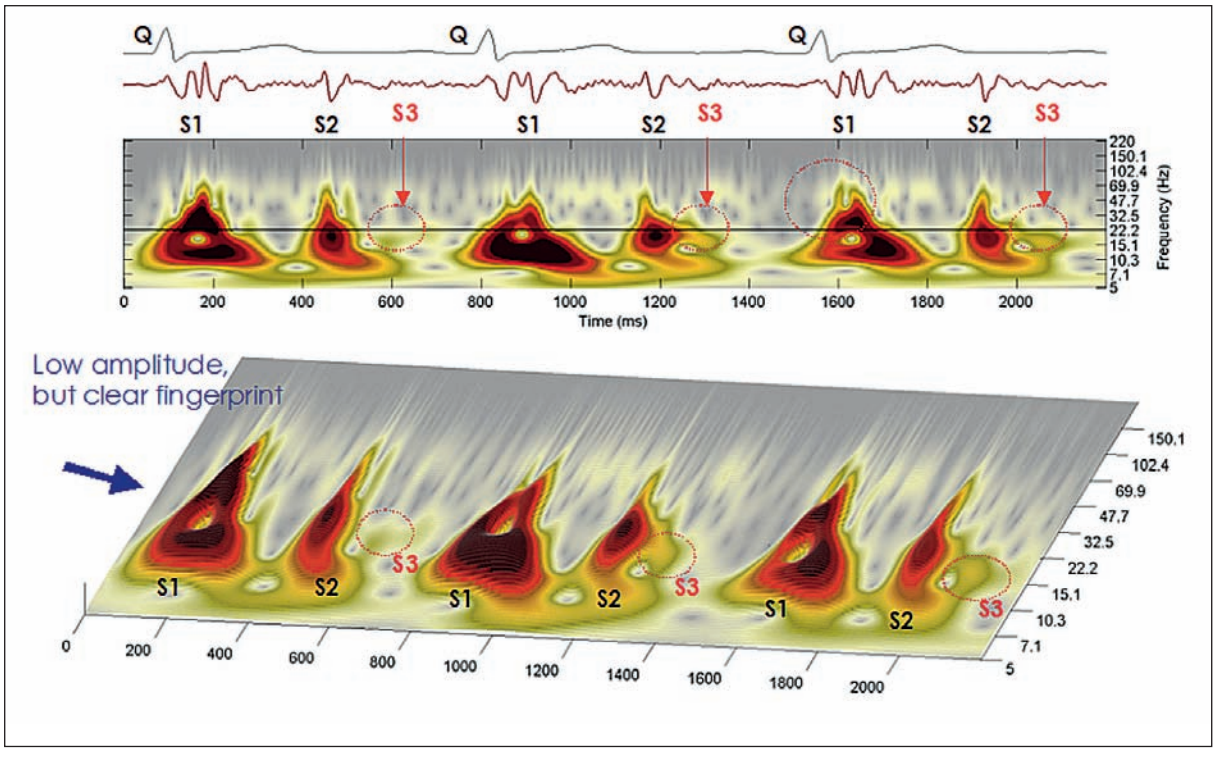

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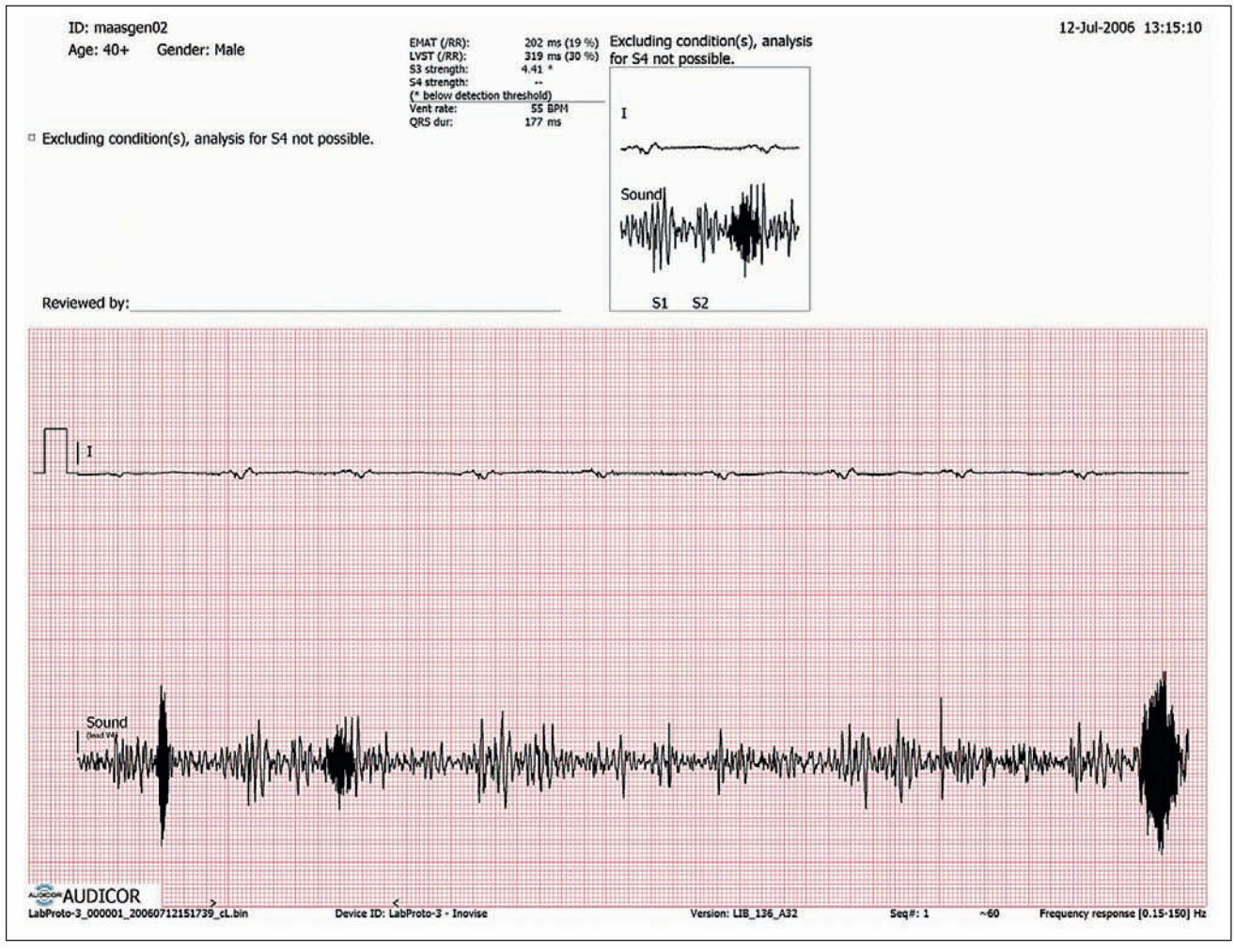
Figure 4

Acoustic cardiography report and time-frequency analysis of heart sounds for a subject with high body mass.
The upper panel (a) shows an acoustic cardiography report for a subject with high body mass (male, 560 pounds), and the panels below illustrate the 2D (b) and 3D (c) scalogram view for three beats of the same recoding as in the upper figure. While the intensity of the heart sounds is drastically lower than in subjects with normal weight, the "fingerprint" for each heart sound is the same as in normal weighted subjects, and therefore, allows an accurate analysis of the heart sounds by acoustic cardiography.



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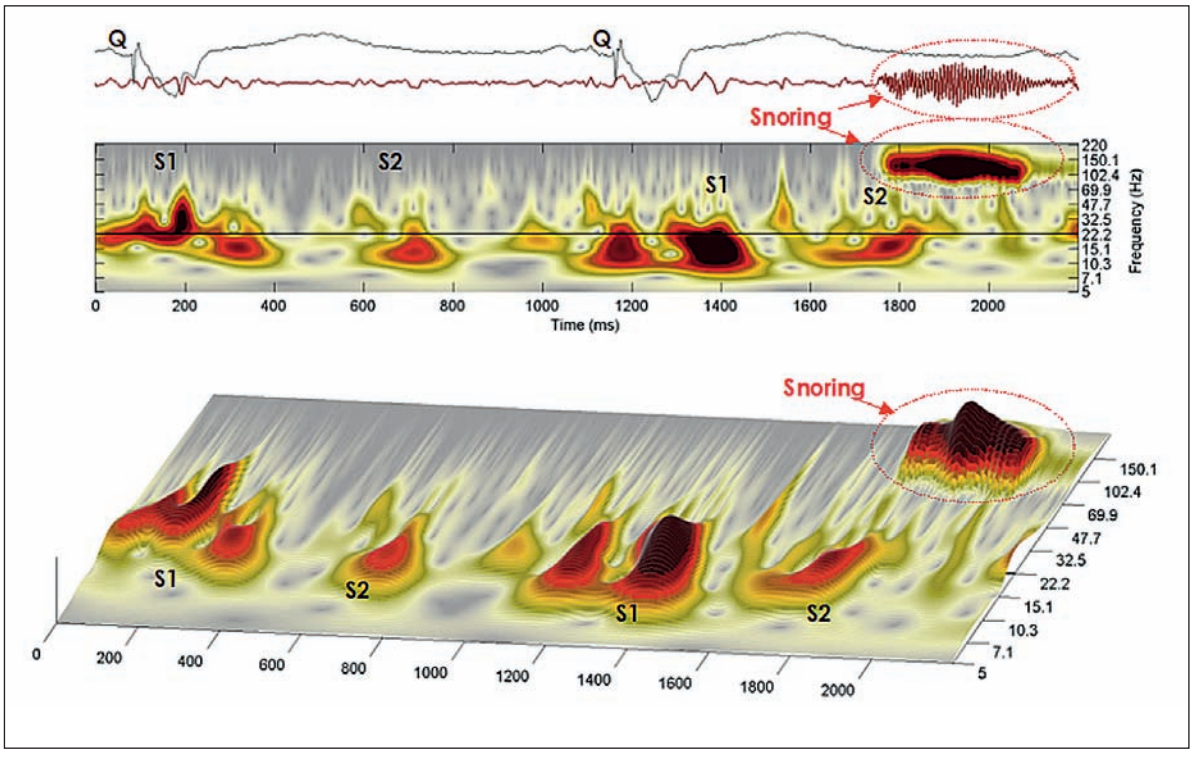

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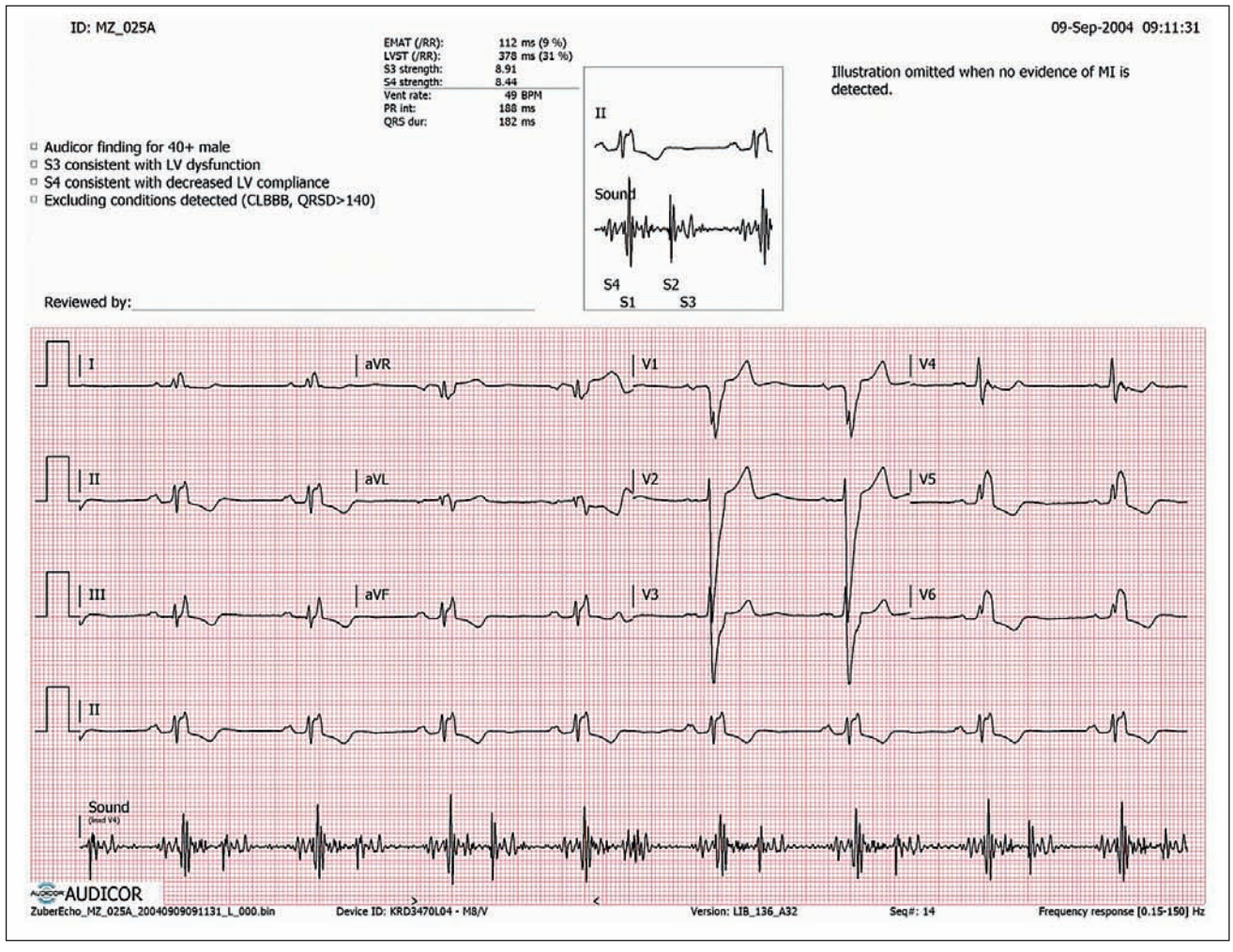
Figure 5

Acoustic cardiography report and time-frequency analysis of heart sounds for a subject with episodes of snoring.
The upper panel (a) shows an acoustic cardiography report for a subject with episodes of snoring, and the panels below (b) illustrate the 2D and 3D scalogram views for two beats from the acoustic cardiography rhythm strip shown above. The "fingerprint" of the snoring as well as other pulmonary sounds is very different from the heart sounds in the scalogram view, and while it is hard to verify in the time domain view, the algorithm can easily filter out those artefacts.



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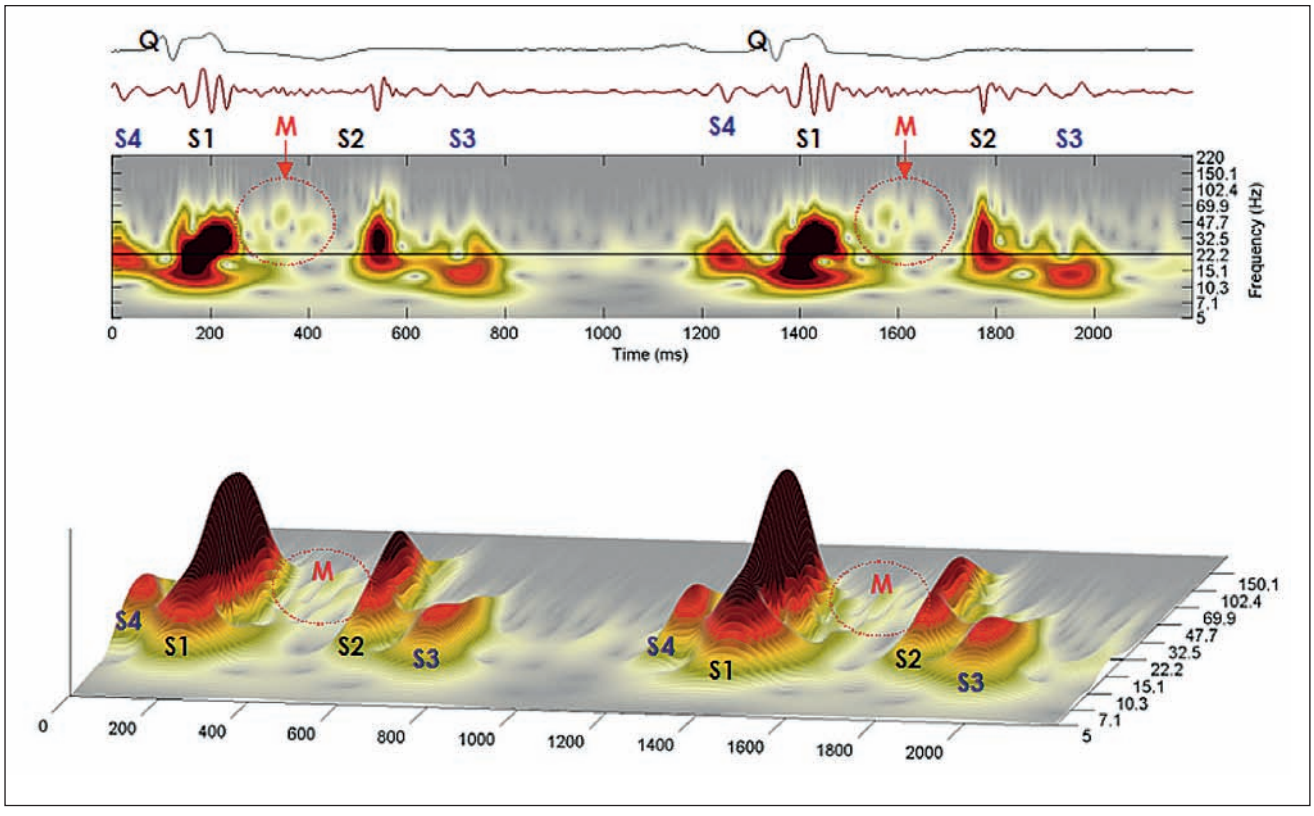

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Figure 6

Acoustic cardiography report and time-frequency analysis of heart sounds for a subject with a systolic murmur.
The upper panel (a) shows an acoustic cardiography report for a subject with a systolic murmur and the panels below (b) illustrate the 2D and 3D scalogram views for a few beats from the acoustic cardiography rhythm strip shown above. Since murmurs have higher frequency components than diastolic heart sounds, they do not have to be high in intensity to be detected by the human ear. Thus in this case, it will be easier for the human ear to detect the murmur than the low frequency third and fourth heart sound.

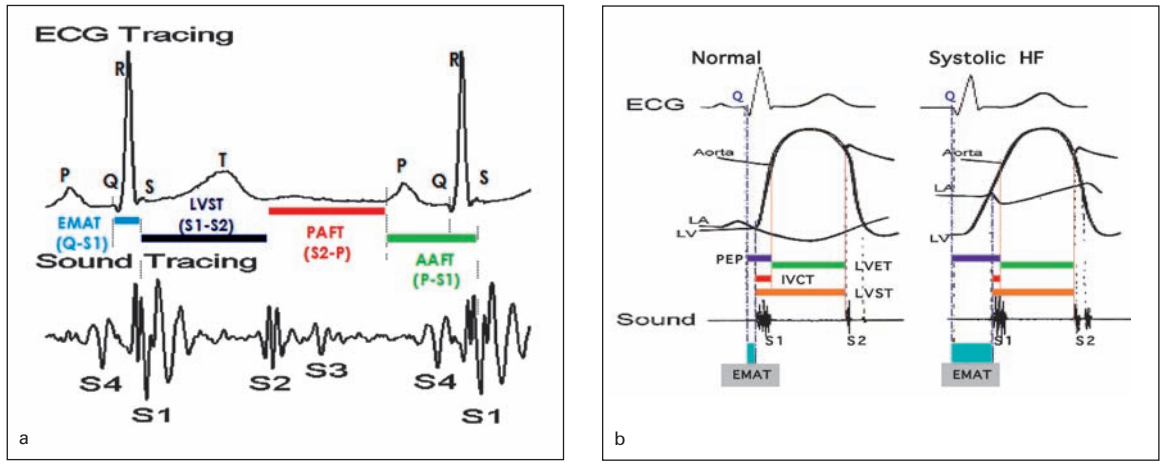


Figure 7

Relationship between ECG and heart sounds.
The upper panel (a) presents a schematic of the key landmarks of the ECG and heart sound recordings in the cardiac cycle and the main acoustic cardiographic parameters. The lower panel (b) presents a schematic of the relationships among the ECG, the aortic, left ventricular and left atrial pressures, the traditional systolic time intervals and several acoustic cardiographic parameters for a normal and systolic heart failure subject. A comparison of the right and left panels shows that with systolic heart failure, both the PEP and EMAT are prolonged.
Abbreviations: ECG – electrocardiogram; EMAT – electromechanical activation time; IVCT – isovolumic contraction time; LA – left atrium; LV – left ventricle; LVET – left ventricular ejection time; LVST – left ventricular systolic time; PAFT – preatrial filling time; AAFT – accelerated atrial filling time; S1 – first heart sound; S2 – second heart sound; S3 – third heart sound; S4 – fourth heart sound; Q – ECG Q wave; P – ECG P wave; R – ECG R wave; S – ECG S wave; T – ECG T wave; HF – heart failure.

nostic algorithm, which were tested and refined over the years using large, independently validated clinical databases. The raw sound data undergoes a time-frequency analysis (fig. 2), which allows not only the separation of heart sounds from murmurs and artefacts, but also the separation of left and right-sided events (ie the detection of the mitral, tricuspid, aortic and pulmonary valve closure, since each of those components has a very specific time-frequency "fingerprint" after the special wavelet-based filters are applied). As illustrated in figures 3–6, the algorithm is not confounded by external noise, speech, pulmonary sounds or murmurs, and the sounds can be detected even in subjects with high body mass index for whom no other non-invasive test can be employed reliably.

Comparing acoustic cardiography and traditional phonocardiography

Phonocardiography and acoustic cardiography provide visual records of recorded sounds. Therefore, both techniques facilitate the identification of heart sounds, permit accurate measurements of timing relationships (with respect to the ECG and to other heart sounds) and display the duration, relative intensity and contour of murmurs. Both also permit the non-invasive evaluation of left ventricular systolic function.

However, there are important differences between phonocardiography and acoustic cardiography. Acoustic cardiography uses digital, rather than analogue data. This permits a computerized, rather than a merely visual, interpretation of the findings and thus eliminates the need for user expertise in interpreting either heart sound or ECG data. Acoustic cardiography uses standardized sensor locations on the chest and employs uniform filtering and processing of the data. These factors increase the uniformity of the data collected from multiple patients and reduce the number of variables that would affect diagnostic interpretation. However, if clinically useful, the sound sensors can be moved to any location (eg to pulmonary or aortic areas). Acoustic cardiography is less labour-intensive than traditional phonocardiography and does not require a specially trained technician or cardiologist to obtain recordings. Therefore, compared with the analogue phonocardiogram, acoustic cardiography results in fewer interruptions of clinical workflow, lower personnel costs and a greater speed with which diagnostic results are available to the clinician. Additionally, unlike the systolic time intervals that are obtained using traditional phonocardiography, acoustic cardiography provides assessment of left ventricular systolic function without the need of carotid artery sensors.

Other advantages of Audicor® technology include the ability to continuously record simultaneous sound and ECG data over short, intermediate and long periods. This permits the use of acoustic cardiography in cardiovascular monitoring and in the optimization of the settings of cardiac synchronization therapy devices. In such applications, one may choose to acquire the ECG data using only one or two leads. Acoustic cardiography also permits the simultaneous acquisition of the heart sound data and a complete 12-lead ECG. This facilitates the detection of ischaemia, myocardial infarction and left ventricular enlargement. The combination of recorded heart sounds and ECG data constitutes a set of diagnostically orthogonal data. The non-redundancy of the ECG and the sound data increases the reliability of the diagnoses that Audicor® technology helps to make.

Auscultation and traditional phonocardiography are similar in that they provide only qualitative information about the S3 and the S4 (ie whether either or both are present or absent). In contrast, because acoustic cardiography uses digi-

tal data, it records these sounds as continuous parameters. The computerized algorithm determines if there is sound energy that has the timing and acoustical frequency consistent with the presence of an S3 and/or an S4. If such energy is present and exceeds a predetermined threshold value, then the computerized algorithm declares that either or both of these sounds are present. An advantage of recording S3 and S4 energy as a continuous, rather than as a dichotomous, variable is that recorded changes in the magnitude of the energy can be used to determine if the patients' haemodynamic status is improving or worsening.

Acoustic cardiography also offers an important opportunity for researchers in cardiovascular disease. The ease of acquisition and accessibility of the digital data along with the ability to export them to various types of analytic software render it possible to perform a wide variety of clinical investigations.

Acoustic cardiographic parameters

Acoustic cardiography records a variety of parameters that assess both systolic and diastolic left ventricular function (fig. 7a).

Systolic parameters

Electromechanical Activation Time (EMAT) – the interval in ms from the onset of the QRS to the point of peak intensity of S1. EMAT measures the amount of time that the left ventricle requires to generate sufficient force to close the mitral valve. As figure 7b shows, EMAT constitutes the initial portion of the traditional phonocardiographic parameter PEP.

- %EMAT – the ratio of EMAT to the RR interval. It indicates the proportion of the cardiac cycle that EMAT occupies.
- Left Ventricular Systolic Time (LVST) – the interval in ms from S1 to S2.
- %LVST – the proportion of the RR interval that the LVST occupies.
- EMAT/LVST Ratio – the proportion of the LVST that EMAT occupies.

Haemodynamic significance:

Figure 7b shows that both EMAT (and its derivatives) and PEP are prolonged in systolic heart failure. Although EF is widely used as a measure of systolic function, unlike both EMAT and PEP, it fails to measure the time required for left ventricular contraction. Recent work has shown that EMAT is more closely related to left ventricular dP/dt maximum than is left ventricular EF [27–28].

Diastolic parameters

- S3 Strength – the S3 energy is expressed on a scale of intensity from 0 to 10. If the intensity is >5.0, an S3 is considered to be present.
- S4 Strength – the S4 energy is expressed on a scale of intensity from 0 to 10. If the intensity is >5.0, an S4 is considered to be present.
- Left ventricular diastolic time (LVDT) – the interval in msec from S2 to the next S1.
- %LVDT – the proportion of the RR interval that the LVDT occupies.
- Pre-atrial filling time (PAFT) – the interval in msec between S2 and the onset of the next P wave on the ECG. It measures the duration of the passive phase of left ventricular diastolic filling, ie the portion of diastole prior to atrial contraction.
- %PAFT – the proportion of the LVDT that the PAFT occupies
- Accelerated atrial filling time (AAFT) – the interval in msec between the onset of the P wave and the subsequent S1. It measures the duration of the active phase of left ventricular diastolic filling, ie the portion of diastole that is associated with atrial contraction.

Haemodynamic significance:

The S3 is often present in systolic dysfunction, especially when the left ventricular filling pressure is elevated [5–15]. The S4 is often detected in patients with diminished left ventricular compliance (eg in acute myocardial infarction and ischaemia) [29–33]. Decreased left ventricular compliance also results in decreased left ventricular filling times, especially the passive phase of diastolic filling and the proportion of diastole that the PAFT occupies.

Clinical applications of acoustic cardiography

The ease of use and low cost of acoustic cardiography makes it useful for the evaluation and monitoring of patients with known or suspected heart disease in a variety of clinical settings and there are a wide variety of both clinical and investigational applications.

Rapid identification and assessment of heart failure patients

Studies have shown that its ability to assess both systolic and diastolic function makes acoustic cardiography a particularly useful technique for detecting and evaluating a broad spectrum of

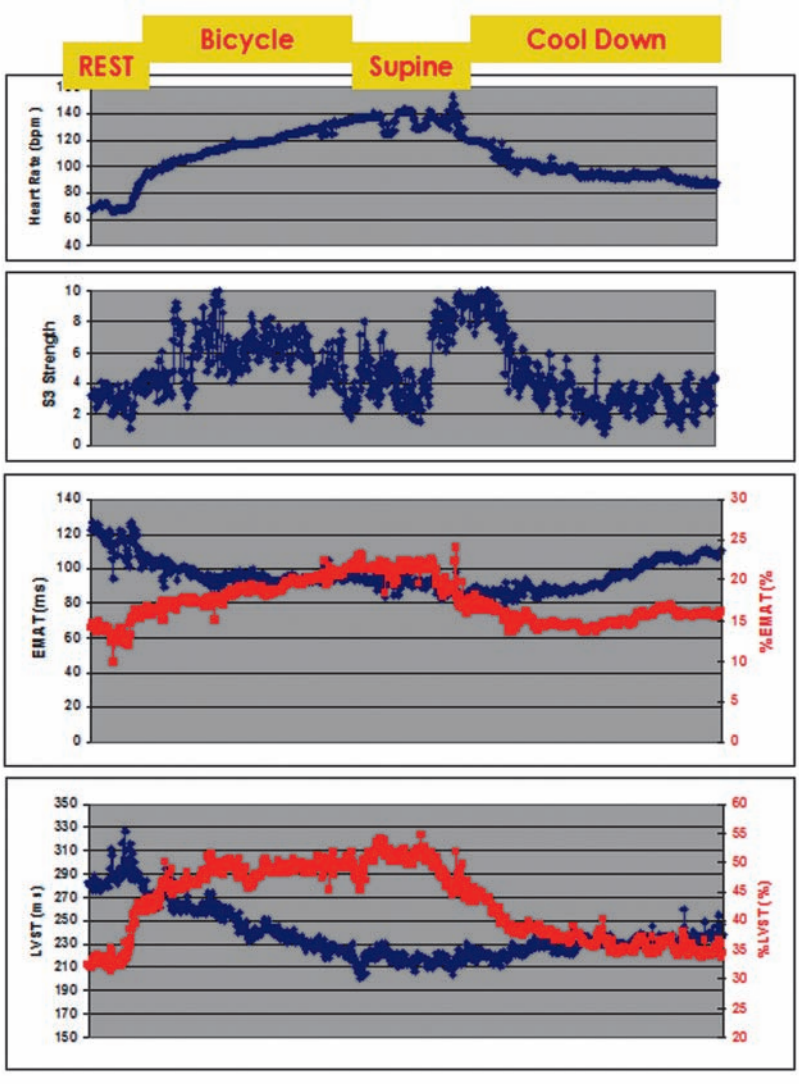


Figure 8

Continuous recording of acoustic cardiography parameter throughout a cardiac bicycle stress test.
The recording of acoustic cardiography parameters during physical stress testing reveals the ability of the cardiovascular system to adapt to the increased metabolic demand. With an increase in the heart rate the cardiac cycle becomes shorter; hence systole needs to shorten in order to allow sufficient time for diastole and therefore, diastolic coronary perfusion.
Abbreviations: EMAT – electromechanical activation time, %EMAT – the proportion of the RR interval that the EMAT occupies; LVST – left ventricular systolic time; %LVST – the proportion of the RR interval that the LVST occupies; S3 – third heart sound.

heart failure patients [34–38]. Roos et al. studied 37 patients undergoing cardiac catherization with contemporaneous acoustic cardiography. There were strong correlations between S3 strength and LV end-diastolic pressure (R = 0.982 in patients with LV systolic dysfunction) and EMAT and LV maximum dP/dt (R = –0.961 in patients with LV systolic dysfunction). In addition, the technology augments B-type natriuretic peptide [39] in the identification of patients with heart failure [40–42]. In a study of 164 outpatients with suspected heart failure, Zuber et al. [40] found that 42% of the patients had BNP in the non-diagnostic region and the use of acoustic cardiography improved the positive likelihood ratio from 2.3 for BNP alone to 69 for detection of LV dysfunction. Further, since all the acoustic cardiographic parameters are continuous measurements, the technology can be used to determine changes in the haemodynamic status of patients (eg in response to spontaneously changing clinical conditions or following the administration of therapy). In a study of 376 patients presenting to the emergency department with suspicion of heart failure, Collins et al. found that 58% of patients with heart failure had an S3 while after treatment with diuretics or vasodilators the proportion of heart failure patients with an S3 was 29% [44]. A specific example of the value of detecting changes in haemodynamic status would be the ability to follow patients who are receiving cardiotoxic chemotherapeutic agents such as doxorubicin and other anthracycline derivatives, which at present involves repetitive echocardiographic studies.

Besides the utility in the management of chronic heart failure patients, Collins et al. [43–44] have shown that acoustic cardiography is useful in the early and accurate detection of acutely decompensated heart failure (ADHF) patients in the emergency unit. Collins et al. concluded that the acoustic cardiographic S3 is highly specific for primary heart failure when they compared the performance of an acoustic cardiographic S3 to physician auscultation of an S3 in a population of 343 patients admitted to the emergency room with undifferentiated dyspnoea (sensitivity, specificity, positive predictive value, negative predictive value for acoustic cardiograph were 34%, 93%, 66%, 7% and for auscultation were 16%, 97%, 84%, 3%) [43]. Comorbidities such as COPD, obesity, heavy smoking and other pulmonary issues make the initial diagnosis difficult for the physician. The third heart sound helps with the early identification of ADHF and its presence in these patients has significant prognostic [9, 45] and economic implications [46].

Detection of ischaemia

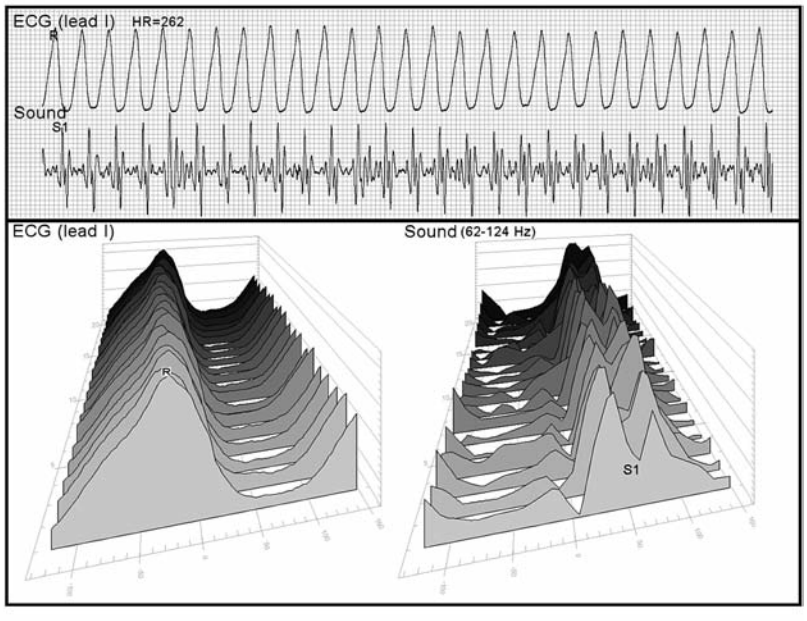
Since acute myocardial ischaemia exhibits both ECG and haemodynamic abnormalities, acoustic cardiography is an ideal method of evaluating patients with chest pain. Such an application includes using the technology in stress testing. ECG and heart sound data constitute orthogonal types of diagnostic data that can independently corroborate the presence of ischaemia. Employing this strategy is analogous to the well-established practice of using echocardiographic or radionuclide data to augment the ECG in stress testing. As shown in figure 8, acoustic cardiography yields reliable results under stress testing. Not only the absolute values of acoustic parameters at maximum heart rate but also the trends help to distinguish between patients with normal physiological responses to stress versus the pathological trends specific for ischaemic patients. Preliminary results by Zuber et al. [47] show promise that the trends in acoustic cardiography can increase the diagnostic value of the ECG stress test significantly. In a study population of 426 patients who had 12-lead ECG, acoustic cardiography, echocardiography and BNP testing, Efstratiadis et al. found that patients with anterior ischaemia

had greater echocardiographic (ejection fraction, end-diastolic volume index, left atrial volume) and acoustic cardiographic abnormalities (percent EMAT) compared to those with inferior ischaemia or no ischaemia on the ECG [72].

In patients with spontaneously occurring chest pain, acoustic cardiography can detect both angina (whether stable or unstable) and acute myocardial infarction. This application contrasts with the use of biomarkers such as troponin and creatine phosphokinase that require myocardial necrosis to become elevated. In addition to its value in improving the diagnosis of ischaemia, the haemodynamic information that acoustic cardiography provides can determine if an episode of either angina or myocardial infarction is accompanied by systolic dysfunction [48]. Such a determination would help physicians stratify patients with respect to their risk of adverse outcomes.

Figure 9

ECG and sound tracings in tachycardia.
The upper panel (a) shows an ECG tracing of a rapid wide-complex supraventricular tachycardia. The sound tracing beneath shows that the S1s associated with each beat are both uniform and of high amplitude. The lower panel shows contour maps that also reveal uniformity of both the QRS complexes and the S1s. The lower panel (b) shows an ECG tracing of ventricular tachycardia. The sound tracing beneath shows that the S1s associated with each beat are highly variable and many of them have very low amplitude. The lower panel shows contour maps that also reveal uniformity of the QRS complexes, but marked variability of the S1s.
Abbreviations: ECG – electrocardiogram; HR – heart rate; S1 – first heart sound.



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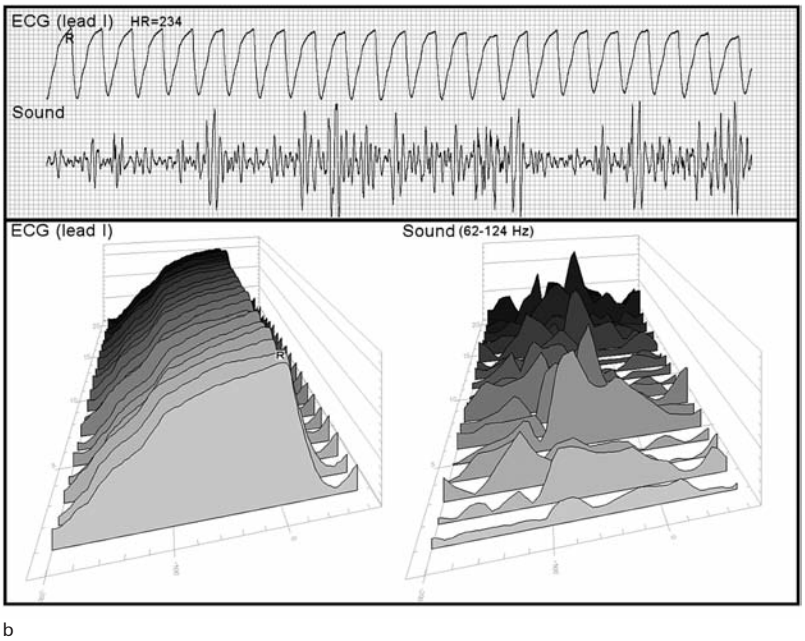

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Detection and evaluation of murmurs

A frequent application of traditional phonocardiography has been the identification, timing and characterization of heart murmurs. Since acoustic cardiography provides a printed display of the sound tracing, it also permits the reader to visually identify both systolic and diastolic murmurs and to analyze their relationships to both the ECG and the heart sounds. Although the sound sensors are placed in the V3 and V4 positions for most purposes, they can easily be moved to any location on the body (eg in the aortic and pulmonary areas of the precordium).

Mass diagnostic screening

The ease of use and low cost of acoustic cardiography makes it highly practical for mass screening large populations of patients. Marijon et al., [49] proposed echocardiographic screening for early detection of rheumatic heart disease in areas where the disease is endemic (eg sub-Saharan Africa and Southeast Asia). However, the reality of conducting systematic echocardiographic screening in such countries is limited because of resource constraints. Although acute rheumatic fever is no longer common in developed countries, idiopathic hypertrophic subaortic stenosis remains the most common cause of non-traumatic sudden death in young people [50]. By readily providing simultaneous ECG and heart sound data, acoustic cardiography could be useful in screening young people for this disease (eg prior to their participation in strenuous sports).

In addition, for screening of patients for left ventricular systolic dysfunction, acoustic cardiography has improved performance as compared to the standard criterion of QRS duration >= 120 msec. Warner et al. found that the sensitivity of QRS duration >=120 msec was 23% with specificity of 97% for detection of echocardiographic LV ejection fraction <50% whereas %EMAT at similar specificity had significantly improved sensitivity of 37% ($p < 0.02$), and the presence of either had a sensitivity of 53% at similar specificity ($p < 0.001$) [73].

Evaluation and detection of sleep apnoea

Obstructive and central sleep apnoea are associated with an increased risk of both heart failure and myocardial ischaemia [51–53]. With its ability to reveal both ECG and haemodynamic abnormalities, acoustic cardiography performed during sleep could reveal evidence that sleep apnoea is present. Besides ECG and haemodynamic parameters, acoustic cardiography is capable of

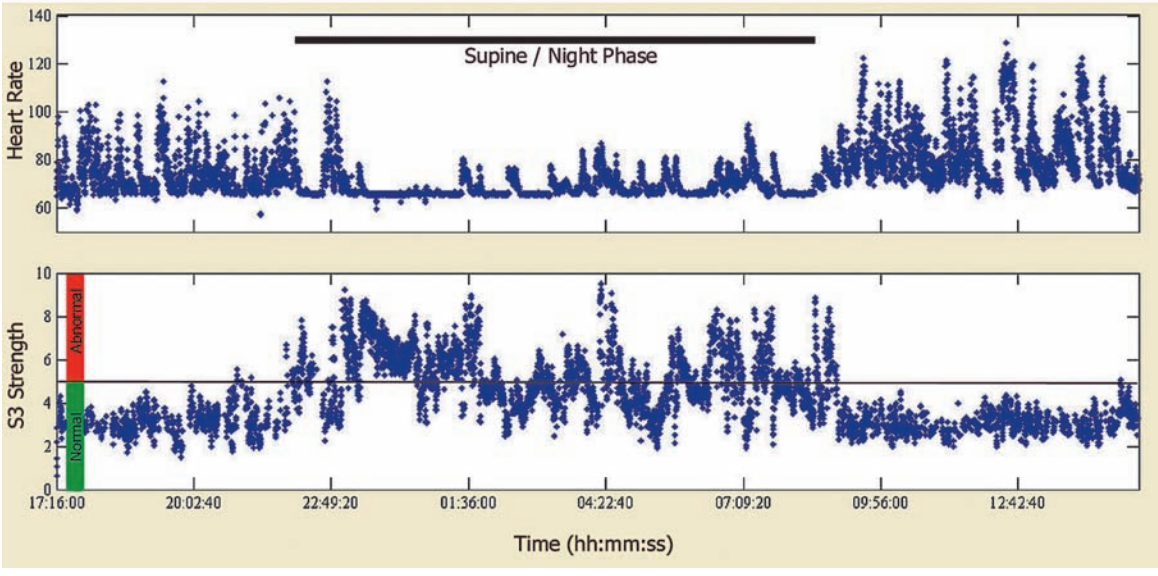

Figure 10

22-hour continuous Holter recording of acoustic cardiography parameter in a subject with systolic heart failure on optimized diuretic therapy.
The strength of the third heart sound is normal during the day (below the threshold of 5) indicating that fluid levels are adequately adjusted. During the night phase, when the subject is at rest in supine position, the strength of the third heart sound increases drastically, which suggests that the heart is not able to handle the increased volume adequately.
Abbreviations: S3 – third heart sound; hh – hours; mm – minutes; ss – seconds.

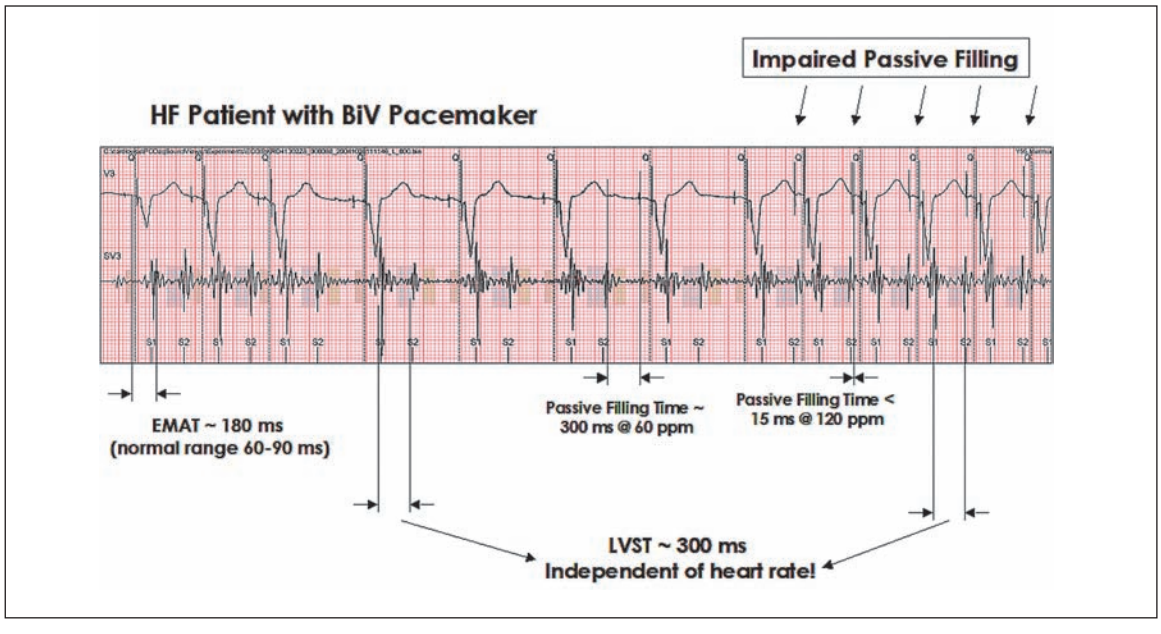

Figure 11

Acoustic cardiography recording on a subject with a biventricular pacemaker at two different pacing rates.
The figure illustrates that the selection of the appropriate base rate or the rate-adaptive for a pacemaker patient with systolic dysfunction can be critical to avoid impairment of diastole and therefore the risk for severely reduced diastolic cardiac perfusion. As shown in the figure, the pre-systole time (EMAT) as well as the systole time (LVST) does not shorten at higher heart rates; hence diastole, in particular the passive filling time, becomes severely impaired.
Abbreviations: ECG – electrocardiogram; EMAT – electromechanical activation time; LVST – left ventricular systolic time; S1 – first heart sound; S2 – second heart sound; Q – ECG Q wave.

measuring apnoeic phases, since respiration-induced intra-thoracic pressure differences will influence acoustic cardiography parameters such as the amplitude of the first heart sound. Thus, ambulatory acoustic cardiography is likely able to improve the screening for sleep apnoea patients as well as the assessment of treatment efficacy.

In addition to providing an inexpensive and convenient initial test for sleep apnoea, acoustic cardiography could be used in the sleep laboratory to augment other data obtained during polysomnography. A preliminary case study has shown the relationship between episodes of sleep apnoea and an increasing S3 [74]. Evidence that episodes of sleep apnoea are accompanied by either haemodynamic deterioration or ischaemia would aid risk assessment and indicate a need for specific cardiovascular treatment.

Characterisation of arrhythmias

A persistent clinical challenge is the differential diagnosis of wide complex tachycardia. Although it may be critical to distinguish ventricular tachycardia from supraventricular tachycardia with aberrant intra-ventricular conduction, the ECG alone is sometimes unreliable [54]. Unreliability of the ECG is especially likely to be true when only one or a few leads of ECG data are available (eg during monitoring, or when the caregivers have not had extensive training and ex-

perience in electrocardiography). However, the availability of heart sound data can be important. Firstly, since ventricular tachycardia is associated with greater ventricular dyssynchrony than SVT, ventricular contraction at similar heart rates is weaker [55]. This diminishes the intensity of S1 because of the decreased forcefulness of mitral closure. Secondly, the AV dissociation that characterizes most cases of VT produces beat-to-beat variations in S1 intensity [56].

The upper panels within figures 9a and 9b show linear recordings of simultaneous ECG and sound data as would be displayed in routine acoustic cardiographic recordings [57]. The lower panels of these figures show contour maps of the amplitudes of both the ECG and sound recordings. In figure 9a, the ECG reveals a rapid wide complex that during electrophysiological study had been shown to be supraventricular. Both the linear recording and the contour map show that the recorded S1's are of uniformly high amplitude. In figure 9b, the ECG shows a slightly slower wide complex that during electrophysiological study had been determined to be ventricular with atrioventricular dissociation. In figure 9b, both the linear recording and the contour map show that the amplitudes of the S1 recorded vary greatly and that many of these amplitudes are lower than those observed in figure 9a.

Cardiovascular monitoring

In addition to its use in individual or serial brief recordings, acoustic cardiography can easily be employed in cardiovascular monitoring, either in the hospital or in the ambulatory setting. As discussed above, the heart sound data augments the ECG, for example, in the detection of ischaemia and/or arrhythmias. Unlike the continuous measurement of pulmonary arterial and wedge pressures, acoustic cardiography is a non-invasive method of detecting changes in haemodynamic status. Other non-invasive methods of haemodynamic assessment (eg echocardiography) are not feasible for intermediate or long term monitoring.

In particular, the areas of ambulatory – as well as home – monitoring are in need of a haemodynamically relevant parameter with prognostic value, such as the third heart sound, to improve the management of heart failure patients. As suggested in the 22-hour ambulatory trend of the third heart sound in a patient with systolic dysfunction and on optimized diuretic therapy (fig. 10), the problem of decompensation through fluid overload might be best monitored during the night when the patients are lying down with low heart rates and the cardiovascular system is unable to handle the increased venous return.

Pacemaker therapy

Although the main application of implantable pacemakers and defibrillators is the treatment of conduction problems and arrhythmia, their roles in the monitoring and treatment of heart failure and ischaemia is increasing. Over the years, implantable pacemakers offered more and more physiology pacing features such as AV synchronous pacing and rate adaptation, mode switch etc. However, these features require complex programming and fine tuning and are greatly underused in clinical practice, one of the reasons being the lack of simple, reliable tools to assess the impact of various pacemaker settings on haemodynamic parameters relevant for patient quality of life and prognosis. Acoustic cardiography provides the relevant prognostic information [9, 45, 58] and is easy enough to incorporate into the standard pacemaker follow-up workflow. Specific areas where the technology has the potential to make a difference include: the optimization of rate adaptive parameters, particularly in patients with systolic heart failure (fig. 11); tilt testing on patients with vasovagal syndrome; the assessment of the haemodynamic burden of arrhythmia (fig. 9) and success of arrhythmia therapy including ablation; the monitoring of the patient's haemodynamic condition over time to apply appropriate upgrades in device and drug therapy.

Cardiac resynchronization therapy

Cardiac Resynchronization Therapy (CRT) is a prominent example in pacing therapy for which the optimization of device parameter is critical for patient outcome. CRT has proven to be an effective method to decrease morbidity and mortality and to increase quality of life in patients with severe and moderate heart failure and mechanical dyssynchrony [59–60]. The implantation of a biventricular pacemaker in such patients leads to a more synchronous, simultaneous contraction pattern of the right and left ventricle and to an improvement in systolic performance of the heart. The response rate of patients to CRT will depend on how well the patients are pre-selected, good placement of the ventricular pacing leads during device implant and optimization of pacing delays to maximize preload and minimize intraventricular dyssynchrony. Acoustic cardiography has proven to be a reliable and cost-efficient alternative to echocardiographic methods [61–63]. Toggweiler et al. [58] showed that the optimization of pacing delays using acoustic cardiography not only improves the systolic function in CRT patients but also yields improvements in exercise tolerance, and therefore quality of life in these patients. In this study of 14 patients undergoing CRT optimization using acoustic cardiography, ejection fraction rose significantly (from 26.5% to 31.3%) and left ventricular outflow tract increased significantly from 10.8 to 13.0 (relative difference 20.4%), and oxygen uptake at anaerobic threshold improved from 12.8 to 14.9 mL.min.kg (16.5%). Furthermore, promising results suggest that the technology can help with a better selection of CRT candidates [64], the placement of the left ventricular lead to optimize

systolic performance [65] and the avoidance of phrenic nerve stimulation [66–67].

Potential to enable new heart failure therapy concepts

A number of device-based therapies have been developed to prevent the progression of heart failure and improve systolic function in those patients. Examples are Left Ventricular Assist Devices (LVAD) [68] for patients with severely failing hearts waiting for heart transplants, Cardiac Contractility Modulation (CCM) [69] with very low systolic strength and no dyssynchrony and External Counter Pulsation Therapy (ECPT) [70]. Acoustic cardiography does not have the potential to exhibit the same capacity for the optimization of therapy relevant parameter in those therapies as for the assessment of therapy efficacy as in CRT. However, it could become the central element in open and closed loop therapy systems (ie the smart use of asymptomatic diaphragmatic stimulation to improve cardiac output in patients with severe heart failure [71]).

Conclusions

We conclude that heart sounds and murmurs provide valuable diagnostic information. The visual displays provided by phonocardiography increased the amount and accuracy of this information. Deriving the systolic time intervals from the phonocardiogram and the carotid pulse tracing has provided detailed, non-invasive haemodynamic data. The recent development of acoustic cardiography has further increased both the ease of use and the cost effectiveness of the acoustical information that can be recorded from the heart. This new technology offers a wide variety of both clinical and investigational applications.

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References

1 Morris JS. Laennec's stethoscope – the Welsh connection. R Soc Med. 2004;97:137–41.
2 Potain P. Adherence du pericarde: triple bruit du coeur; implusion diastolique. Bull Soc Anat Paris. 1856;31:378.
3 Potain P. Concerning the cardiac rhythm called gallop rhythm (Fr). Bull Soc Med Hop Paris. 1876;12:137–66.
4 Pierre-Carl Potain (1825–1901) cardiovascular physician. JAMA. 1966;196:1086.
5 Rame JE, Dries DL, Drazner MH. The prognostic value of the physical examination in patients with chronic heart failure. Congest Heart Fail. 2003;9:170–5, 178.
6 Reddy PS. The third heart sound. Int J Cardiol. 1985; 7(3):213–21.
7 Stevenson LW, Perloff JK. The limited reliability of physical signs for estimating hemodynamics in chronic heart failure. JAMA. 1989;261(6):884–8.
8 Sloan A. Cardiac gallop rhythm. Medicine. 1958; 37:197–215.
9 Drazner MH, Rame JE, Stevenson LW, Dries DL. Prognostic importance of elevated jugular venous pressure and a third heart sound in patients with heart failure. N Engl J Med. 2001;345:574–81.
10 Drazner MH, Rame JE, Dries DL. Third heart sound and elevated jugular pressure as markers of the subsequent development of heart failure in patients with asymptomatic left ventricular dysfunction. Am J Med. 2003;114:431–7.
11 Shah PM, Gramiak R, Kramer DH, Yu PN. Determinants of atrial (S4) and ventricular (S3) gallop sounds in primary myocardial disease. N Engl J Med. 1968;278(4):753–8.
12 Glower DD, Murah RL, Olsen CO, Rankin JS. Mechanical correlates of the third heart sound. J Am Coll Cardiol. 1992;19(2):450–7.
13 Kono T, Rosman H, Alam M, Stein PD, Sabbah HN. Haemodynamic correlates of the third heart sound during the evolution of chronic heart failure. J Am Coll Cardiol. 1993;21 (2):419–23.
14 Tribouilloy CM, Enriquez-Sarano M, Mohty D, Horn RA, Bailey KR, Seward JB, et al. Pathophysiologic determinants of third heart sounds: a prospective clinical and Doppler echocardiographic study. Am J Med. 2001;111(2):96–112.
15 Ozawa Y, Smith D, Craige E. Origin of the third heart sound. II. Studies in human subjects. Circulation. 1983;67(2):399–404.
16 Ishmail AA, Wing S, Ferguson J, Hutchinson TA, Magder S, Flegel KM. Interobserver agreement by auscultation in the presence of a third heart sound in patients with congestive heart failure. Chest. 1987;91:870–3.
17 Lok CE, Morgan CD, Ranganathan N. The accuracy and interobserver agreement in detecting the "gallop sounds" by cardiac auscultation. Chest. 1998;114:1281–8.
18 Davie AP, Francis CM, Caruana L, Sutherland GR, McMurray JJ. Assessing diagnosis in heart failure: which features are any use? QJM. 1997;90(5):335–9.
19 Wang CS, Fitzgerald JM, Schulzer M, Mak E, Ayas NT. Does this dyspneic patient in the emergency department have congestive heart failure? JAMA. 2005;294(15):1944–56.
20 Leatham A. Phonocardiography. Brit Med Bull. 1952;8:333.
21 Lewis RP, Rittgers SE, Forester WF, Boudoulas H. A critical review of the systolic time intervals. Circulation. 1977;56:146.
22 Weissler AM, Harris WS, Schoenfield CD. Bedside technics for the evaluation of ventricular function in man. Am J Cardiol. 1969;23:577.
23 Stack RS, Sohn YH, Weissler AM. Accuracy of systolic time intervals in detecting abnormal left ventricular performance in coronary artery disease. Am J Cardiol. 1981;47:603–9.
24 Weissler AM, Harris HS, Schoenfeld CD. Systolic time intervals in heart failure in man. Circulation. 1968;37:149–59.
25 Garrard CL, Weissler AM, Dodge HT. The relationship of alterations in systolic time intervals to ejection fraction in patients with cardiac disease. Circulation. 1970;62:455–62.
26 Weissler AM, Peeler RG, Roehll WH. Relationships between left ventricular ejection time, stroke volume, and heart rate in normal individuals and patients with cardiovascular disease. Am Heart J. 1961;62:367–78.
27 Roos M, Toggweiler S, Jamshidi P, Zuber M, Kobza R, Meier, R, et al. Non-invasive Detection of Left-Ventricular Systolic Dysfunction by Acoustic Cardiography in Cardiac Failure Patients. J Card Fail. 2008;14(4):310–9.
28 Jamshidi P, Roos M, Kobza R, Toggweiler S, Zuber M, Erne P. Impact of Preload Changes on Positive and Negative Left-ventricular dP/dt and Systolic Time Intervals. Submitted for publication.

29 Siegel, W, Lim JS, Proudfit WL, Sheldon WC, M.D, Loop FD. The spectrum of exercise test and angiographic correlations in myocardial revascularization surgery. Circulation. 1975; 52(2 Suppl):1156–62.

30 Thompson PL. Physical Examination in ischaemic heart disease. Med J Aust. 1976;1(14):492–5.

31 Perez GL, Luisada AA. When does a fourth sound become an atrial gallop? Angiology. 1976;27(5):300–10.

32 Upton MT. Detecting abnormalities in left ventricular function during exercise before angina and ST-segment depression. Circulation. 1980;62(2)341–9.

33 Ishikawa M, Sakata K; Maki A, Mizuno H, Ishikawa K. Prognostic significance of a clearly audible fourth heart sound detected a month after an acute myocardial infarction. Am J Cardiol. 1997;80(5):619–21.

34 Gerber IL, McKeown BH, Marcus G, Vessy J, Jordan MV, Huddleston M, et al. The third and fourth heart sounds are highly specific markers for elevated left ventricular filling pressure and reduced ejection fraction. J Card Fail. 2004;10(4):S36.

35 Marcus GM, Gerber IL, McKeown BH, Vessey JC, Jordan MV, Huddleston M, et al. Association between phonocardiographic third and fourth heart sounds and objective measures of left ventricular function. JAMA. 2005;293(18):2238–44.

36 Peacock WF, Harrison A. The utility of heart sounds and systolic intervals across the care continuum. CHF. 2006;(4 Supple 1):2–7.

37 Shah SJ, Michaels AD. Haemodynamic correlates of the third heart sound and systolic time intervals. CHF. 2006;12(4 Supple 1):8–13.

38 Roos M, Toggweiler S, Zuber M, Jamshidi P, Erne P. Acoustic Cardiographic Parameters and their Relationship to Invasive Haemodynamic Measurements in Patients with Left Ventricular Systolic Dysfunction. CHF. 2006;12(4 Supple 1):19–24.

39 Mueller C, Breidthardt T, Laule-Kilian K, Christ M, Perruchoud AP. The integration of BNP and NT-proBNP into clinical medicine. Swiss Med Wkly. 2007;137(1-2):4–12.

40 Zuber M, Kipfer P, Attenhofer-Jost Ch. Usefulness of Acoustic Cardiography to Resolve Ambiguous Values of B-Type Natriuretic Peptide Levels in Patients With Suspected Heart Failure. Am J Cardiol. 2007;100(5): 866–9.

41 Moyers B, Shapiro M, Marcus GM, Gerber IL, McKeown BH, Vessey JC, et al. The Performance of Phonoelectrocardiographic Left Ventricular Systolic Time Intervals and B-type Natriuretic Peptide Levels in the Diagnosis of Left Ventricular Dysfunction. Ann Noninvasive Electrocardiol. 2007;12(2):89–97.

42 Lainscak M, Keber I. Heart failure clinic in a community hospital improves outcome in heart failure patients. Swiss Med Wkly. 2006;136(17-18):274–80.

43 Collins SP, Lindsell CJ, Peacock WF, Hedger VD, Eckert DC, Askew J, et al. The Combined Utility of an S3 Heart Sound and B-type Natriuretic Peptide Levels in Emergency Department Patients with Dyspnea. J Cardiac Fail. 2006;12(4):286–92.

44 Collins SP, Lindsell CJ, Peacock WF, Hedger VD, Storrow AB. The Effect of Treatment on the Presence of Abnormal Heart Sounds in Emergency Department Patients with Heart Failure. Am J Emerg Med. 2006;24:25–32.

45 Maisel A, Peacock WF, Clopton P, Daniels L, Collins S. The Presence of an S3 is Associated with an Increased Rate of Adverse Cardiac Events. J Cardiac Fail. 2007;13(6):143.

46 Zuber M, Attenhofer-Jost Ch, Kipfer P, Collins S, Michota F, Peacock F. Acoustic Cardiography Augments Prolonged QRS Duration for Detecting Left Ventricular Dysfunction. Ann Noninvasive Electrocardiol. 2007;12(4):316–28.

47 Zuber M, Kipfer P, Attenhofer Jost Ch, Erne P. Utility of Acoustic Cardiography to Improve the Diagnosis of Acute Coronary Syndrome. Personal communication.

48 Harris I, Lee E, Yeghiazarians Y, Drew BJ, Michaels AD. Phonocardiographic Timing of Third and Fourth Heart Sounds during Acute Myocardial Infarction. J Electrocardiology. 2006;39:305–9.

49 Marijon E, Ou P, Celermajer DS, Ferreira B, Mocumbi AG, Jani D, et al. Prevalence of rheumatic heart disease detected by echocardiographic screening. N Engl J Med. 2007;357:470–6.

50 Yetman A, McCrindle B, Freedom R, Gow R. Myocardial bridging in children with hypertrophic cardiomyopathy – a risk factor for sudden death. N Engl J Med. 1998;339:1201–9.

51 Javaheri S. Sleep disorders in systolic heart failure: a prospective study of 100 male patients. Int J Cardiol. 2006;106:21–8.

52 Mutlu GM, Rubinstein I. Obstructive Sleep Apnoea Syndrome-Associated Nocturnal Myocardial Ischemia Chest. 2000;117:1534–5.

53 Thurnheer R. Obstructive sleep apnoea and cardiovascular disease – time to act! Swiss Med Wkly. 2007;137(15-16):217–22.

54 Isenhour JL, Craig S, Gibbs M, Littman L, Rose G, Risch R. Wide-complex tachycardia – continued evaluation of diagnostic criteria. Acad Emerg Med. 2000;7:769–73.

55 Kolettis TM, Kyriakides ZS, Popov T, Mesiskli T, Papalambrou A, Kremastinos DT. Importance of the site of ventricular tachycardia origin on left ventricular hemodynamics in humans. Pacing Clin Electrophysiol. 1999;22:871–9.

56 Garratt CJ, Griffith MJ, Young G, Curzen N, Brecker S, Rickards AF, et al. Value of physical signs in the diagnosis of ventricular tachycardia. Circulation. 1994;90:3103–7.

57 Kobza R, Roos M, Toggweiler S, Zuber M, Erne P. Recorded Heart Sounds for Identification of Ventricular Tachycardia. Submitted for publication.

58 Toggweiler S, Zuber M, Kobza R, Roos M, Jamshidi P, Maier R, et al. Improved Response to Cardiac Resynchronization Therapy Through Optimization of Atrioventricular and Interventricular Delays Using Acoustic Cardiography: A Pilot Study. J Card Fail. 2007;13(8):637–42.

59 Cazeau S, Leclercq C, Lavergne T, Walker S, Varma C, Linde C, et al. Effects of multisite biventricular pacing in patients with heart failure and intraventricular conduction delay. N Engl J Med. 2001;344:873–80.

60 Sticherling C, Schaer B, Coenen M, Kühne M, Ammann P, Osswald S. Cardiac resynchronization therapy in chronic heart failure. Swiss Med Wkly. 2006;136(39-40):611–7.

61 Hasan A, Abraham WT, Quinn-Tate L, Brown L, Amkieh A. Optimization of Cardiac Resynchronization Devices Using Acoustic Cardiography: a Comparison to Echocardiography. Congest Heart Fail. 2006;12(4 suppl 1):25–31.

62 Zuber M, Toggweiler S, Roos M, Kobza R, Jamshidi P, Erne P. Comparison of Different Approaches for Optimization of Atrioventricular and Interventricular Delay in Biventricular Pacing. Europace. 2008;10:367–73.

63 Zuber M, Toggweiler S, Quinn-Tate L, Brown L, Amkieh A, Erne P. A Comparison of Acoustic Cardiography and Doppler Echocardiography for Optimizing Pacemaker Settings in Cardiac Resynchronization Therapy. Submitted for publication.

64 Kontos M, Haney A, et al. Are Systolic Time Intervals Superior to QRS Duration for Detection of LV Dyssynchrony? J Card Fail. 2007;13(6):173.

65 Corbisiero R, Wjasow C, et al. Impact of Intra-Operative CS Lead Placement and Post-Operative AV Optimization on Systolic Function in CRT Patients as Measured by Acoustic Cardiography. J Card Fail. 2007;13(6):133.

66 Toggweiler S, Kobza R, Roos M, Erne P. Visualizing Pacemaker-Induced Phrenic Nerve Stimulation with Acoustic Cardiography. Pacing Clin Electrophysiol. 2007;30:806. 2007.

67 Zuber M, Roos M, Kobza R, Toggweiler S, Meier M, Erne P. Detection and Haemodynamic Significance of Cardiac Pacemaker-Induced Phrenic Nerve Stimulation. Submitted for publication.

68 Navia J, McCarthy PM, Hoercher KJ, Smedira NG, Banbury MK, Blackstone EH. Do left ventricular assist device (LVAD) bridge-to-transplantation outcomes predict the results of permanent LVAD implantation? Ann Thorac Surg. 2002;74:2051–63.

69 Borggrefe MM, Lawo T, Butter C, Schmidinger H, Lunati M, Pieske B, et al. Randomized, double blind study of non-excitatory, cardiac contractility modulation electrical impulses for symptomatic heart failure. Eur Heart J. 2008;doi:10.1093/eurheartj/ehn020

70 Soroff HS, Hui JCK, Giron F. Historical Review of the Development of Enhanced External Counterpulsation Technology and its Physiologic Rationale. Cardiovasc Rev Reports. 1997; 18(11):34–6, 39.

71 Roos M, Zuber M, Bauer P, Erne P. Improved Cardiac Performance Through Pacemaker–Induced Phrenic Nerve Stimulation – A Novel Electrophysiological Approach in Heart Failure Management? Personal communication.

72 Efstratiadis S, Warner RA, Kontos MC, Zuber M, Arand P, Michaels AD. Acoustic cardiographic electromechanical activation time correlates with echocardiographic parameters of left ventricular contractility in patients with myocardial ischemia. International Society for Computerized Electrocardiography Scientific Sessions. J Electrocardiol. 2008, in Press.

73 Warner RA, Arand PA. An Improved Screening Test for Left Ventricular Systolic Dysfunction. International Society for Computerized Electrocardiography Scientific Sessions, J Electrocardiol. 2008, in Press.

74 Naqvi TZ, Bauer P, Castillo E, Innes T, Manzoor B, Zhang J, Wheeler T. Insight into Cardiac Hemodyamics Using A Novel Ambulatory Monitoring Device in a Patient with CHF and Sleep Apnea. Personal Communication.

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