FAST TRACK COMMUNICATION

Multi-point accelerometric detection and principal component analysis of heart sounds

To cite this article: S De Panfilis et al 2013 Physiol. Meas. 34 L1

View the article online for updates and enhancements.

Related content
- An open access database for the evaluation of heart sound algorithms
  Chengyu Liu, David Springer, Qiao Li et al.
- A simplicity-based fuzzy clustering approach for detection and extraction of murmurs
  V Nigam and R Priemer
- Beat-to-beat systolic time-interval measurement from heart sounds and ECG
  R P Paiva, P Carvalho, R Couceiro et al.

Recent citations
- A survey on signals and systems in ambulatory blood pressure monitoring using pulse transit time
  Dilpreet Buxi et al
FAST TRACK COMMUNICATION

Multi-point accelerometric detection and principal component analysis of heart sounds

S De Panfilis\textsuperscript{1,2}, C Moroni\textsuperscript{3}, M Peccianti\textsuperscript{1}, O M Chiru\textsuperscript{1}, V Vashkevich\textsuperscript{3}, G Parisi\textsuperscript{4} and R Cassone\textsuperscript{5}

\textsuperscript{1} Centro Studi e Ricerche e Museo Storico della Fisica ‘E. Fermi’, P.le del Viminale 1, Roma I-00184, Italy
\textsuperscript{2} Centre for Life Nano Science IIT@Sapienza, Istituto Italiano di Tecnologia, V.le Regina Elena 291, Roma I-00161, Italy
\textsuperscript{3} Dipartimento Scienze Cardiovascolari—Sez. Cardiologia e Pneumologia, Universit\`a di Roma ‘Sapienza’, V.le del Policlinico 155, Roma I-00161, Italy
\textsuperscript{4} Dipartimento di Fisica, Universit\`a di Roma ‘Sapienza’, P.le Aldo Moro 5, Roma I-00185, Italy
\textsuperscript{5} Centro per l’innovazione tecnologica in cardiologia e ricerca scientifica nel settore cardiovascolare ONLUS, Via di Villa Massimo 3, Roma I-00161, Italy

E-mail: simone.depanfilis@roma1.infn.it

Received 18 September 2012, accepted for publication 30 January 2013
Published 12 February 2013
Online at stacks.iop.org/PM/34/L1

Abstract

Heart sounds are a fundamental physiological variable that provide a unique insight into cardiac semiotics. However a deterministic and unambiguous association between noises in cardiac dynamics is far from being accomplished yet due to many and different overlapping events which contribute to the acoustic emission. The current computer-based capacities in terms of signal detection and processing allow one to move from the standard cardiac auscultation, even in its improved forms like electronic stethoscopes or hi-tech phonocardiography, to the extraction of information on the cardiac activity previously unexplored. In this report, we present a new equipment for the detection of heart sounds, based on a set of accelerometric sensors placed in contact with the chest skin on the precordial area, and are able to measure simultaneously the vibration induced on the chest surface by the heart’s mechanical activity. By utilizing advanced algorithms for the data treatment, such as wavelet decomposition and principal component analysis, we are able to condense the spatially extended acoustic information and to provide a synthetical representation of the heart activity. We applied our approach to 30 adults, mixed per gender, age and healthiness, and correlated our results with standard echocardiographic examinations. We obtained a 93% concordance...
rate with echocardiography between healthy and unhealthy hearts, including minor abnormalities such as mitral valve prolapse.

Keywords: heart activity, phonocardiography, biosignal processing, medical imaging

(Some figures may appear in colour only in the online journal)

1. Introduction

The heart auscultation method is a well known and widely used low-technology and inexpensive diagnostic indicator for cardiac morpho-functional abnormalities. Heart sound classification and analysis play an important role in the auscultative diagnosis. Although modern imaging techniques such as echocardiography, magnetic resonance imaging, computed tomography have partially overcome the clinical cardiac auscultation, the detection of heart sounds still appears to be the best compromise in terms of cost effectiveness, flexibility and large screening approach (Zipes et al 2005). The coupling of modern detection devices and of advanced algorithms for signal processing provided a robust impulse to the detection of heart sounds (e.g. see Watrous (2006), Semmlow and Rahalkar (2007), Amit et al (2009) and references therein). Nowadays, modern phonocardiography (PCG) can be defined as the method of recording all vibrations of the precordium by means of generic transducers, in opposition to the old bare auscultation which dealt with only the clinically audible vibrations (Abbas and Bassam 2009).

Generally speaking, a PCG signal is a waveform produced by recording vibrations on the precordium (anterior chest wall). Processing this measurement with the support of other signal inputs, such as ECG, provides a complete description of the electromechanical event of the cardiac cycle. The PCG waveform can be interpreted by physicians in much the same way as electrocardiograms are interpreted. But despite the improvements in the PCG detection system and/or signal processing, there have been very poor advances in the methodology of automated waveform analysis of phonocardiograms.

The main issue in the systematics of PCG comes from the intimate nature of the measurement itself. The displacement of the chest wall over the precordial area is the result of a periodic complex wave, which is the superposition of signals generated by a spatially extended and inhomogeneous source, the heart. The processing of this signal represents a challenging issue, as the positioning of the sound detector is often critical and non-reproducible. Still, there exists a need for using PCG waveforms in automated systems (e.g. see Cathers (1995)) to differentiate heart failures from other common clinical conditions and to further implement high throughput screening programmes.

Array PCG is largely unexplored. A non-clinical test was attempted on a urethane phantom model (Owsley 2000), mainly to localize turbulences in the blood vessel. A dedicated study on a human subject is still lacking, though. Previous works along this line were attempted by our group in the past few years (Cassone 2008, Moroni 2010). The aim of this communication is to illustrate a novel approach to the study of phonocardiographic signals, which combines a simultaneous multi-point PCG detection over the entire precordium, with a computer-assisted data treatment. The main outcome of this work is a low-cost user-friendly tool to extract the most relevant informative content distributed over the multidimensional dataset and to condense it as a synthetical image able to represent the heart activity, irrelevant to the spatial extension of the heart itself.
2. Heart sounds

In the most heuristic definition, the heart can be seen as a mechanical pump, with the corresponding aspirating and ejecting valves. The cardiac cycle itself can be divided into a ventricular contraction phase, *systole*, while blood is propelled out of ventricles, and a further phase, called *diastole*, which is the period of time when the ventricles relax after contraction filling again with blood, in preparation of the next systolic period (Zipes *et al.* 2005).

Due to the purely mechanical nature of the heart, the blood flows into the cardiac chambers and is further ejected out towards the blood vessels. The cardiac cycle is characterized by sounds (basic tones and murmurs). Heart sounds travel through the internal tissues from the heart to the chest surface, where physicians (or devices) can detect them. Several physiological variables (e.g. air trapping in lungs, thickness of adipose tissue, chest muscles mass) can alter both the amplitude and the phase of the sound signal, and this often represents a strong limitation to the general validity of both human and non-human detection of heart sounds. Non-physiological variables (pressure applied on the transducer at the physical positioning of the detector on the chest) as well can hamper the systematic reproducibility of PCG measurements.

Normal heart sounds can be divided into two components, called first tone and second tone. While the first one is associated with the beginning of ventricular contraction, closing of atrio-ventricular valves (mitral and tricuspid) and opening of the ejecting valves (aortic and pulmonary), the second tone is related to the closure of the aortic and pulmonary valves at the end of the ventricular *systole* (the beginning of the following diastole) and the reverberation of blood pushing against the closed valves. These two auscultatory events establish a framework within which further heart sounds (third and fourth tones) and murmurs can be placed and timed. The occurrence of extra sounds and murmurs with respect to the first two can be related to a variety of physiological or pathological states (Zipes *et al.* 2005).

3. Mathematical framework

Wavelet transforms have been proved to be very useful in many scientific and engineering applications, including signal processing, communication, video and image compression, medical imaging and scientific visualization. The concept of wavelets can be viewed as a synthesis of ideas originated in the contiguous domains of mathematics, physics and engineering (Kaiser 2003). A prominent example is the 1D continuous wavelet transform (CWT) where a signal is analysed by calculating inner products with test functions (Daubechies 2006).

Wavelet analysis of phonocardiographic signals has been already introduced over the last few years (e.g. see Debbal and Bereksi-Reguig (2008) and references therein). The approaches are often different, but it is an established concept that the wavelet decomposition of the PCG signals is a stable method for the localization and investigation of the temporal/frequency characteristics of heart sounds.

Still, the idea at the origin of this communication, i.e. combining the wavelet analysis of PCG signals simultaneously collected at different positions of the chest through a principal component analysis (PCA) of the multidimensional dataset, is largely unexplored.

The main purpose of PCA (Joliffe 2002) is to reduce the dataset dimensionality *p*, while accounting at the same time for as much information as in the original dataset as possible. With PCA, one transforms the data to a new set of coordinates or variables that are the linear
PCA is used for dimensionality reduction in many biomedical and clinical measurements by retaining those characteristics of the data that contribute the most to its variance. In many cases, it is enough to keep only the lowest-order (principal) component of the decomposition, thus reducing the large dimensionality of the dataset to a single parameter. The discriminating parameter to this is the portion of the total dataset variance which is kept in the first component.

For the purposes of this work, the multi-dimensionality of the acquisition is the product of the \( n \) number of accelerometers placed on the patient chest by the \( m \) number of heart beats collected during a single acquisition, i.e. \( p = n \times m \). By combining all the valid heart beats and the signals from all the accelerometric detectors, we redistribute the physiological information of the dataset, and we concentrate the largest portion of it on the very first component of the PCA decomposition. Spurious physiological arrhythmic beating, such as ventricular extrasystoles, is eliminated from the datasets by excluding all the beats whose time duration differs by more than 30% of the average beat duration. Physiological fluctuation of the heart beat length during apnea or normal breathing is then safely taken into account by the segmentation algorithm.

An identical CWT analysis is then applied to the ensemble of the experimental signals, i.e. to all of the \( n \times m \) datasets, through complex Morlet test functions. A logarithmic semi-tonal scale is used for the scale \( s = S/\omega \) of the CWT, where \( S \) is the sampling rate of the acquisition (typically 10 kHz) and \( \omega \) covers 0.8 Hz to 1 kHz range.

For each one of the scale \( s \), or, equivalently, of the frequency \( \omega \), we calculate the first principal component of the CWT moduli by projecting the multi-detector \( n \)-dimensional space of the PCG signals onto a single vector containing the largest informative content. The datasets are then reduced to a single matrix for each heart beat whose columns are the first principal component calculated for each frequency \( \omega \). The fraction of the total variance transferred onto the first component is a function of \( n \): it is typically in the 80%–90% range per \( n = 4 \), while it decreases down to \( \sim 60\% \) when \( n = 10 \).

The different heart beats are finally averaged to obtain the typical scalogram shown in figure 1. For comparison, the lower panel of figure 1 shows the ECG and PCG curves corresponding to one of the \( m \) heart cycles. The oscillations corresponding to the first and second tones are clearly visible and they are well reproduced in the time/frequency decomposition of the upper panel. As the various accelerometers (four for this particular acquisition) are spatially distributed on the chest of the subject under investigation, their signals are not superposed, as expected. The overall time distribution of the vibrating energy, though, is correctly registered by all of them.

4. Experimental details

The heart sound acquisition system consists in large bandwidth vibration detectors placed in contact with the patient skin on the chest. Elastic bands hold the detectors in places. The vibrations induced on the chest surface by the heart sounds are converted into electrical signals by a set of integrated electronic piezo-electric (IEPE) Brüel&Kjær single-axis accelerometer type 4507. The sensitivity of the accelerometric sensors is 100 mV g\(^{-1}\) and the response is guaranteed to be linear in the 0.2–6000 Hz interval. Their resonance frequency is above 18 kHz. A combination of high sensitivity, low mass and small physical dimensions make them ideal for modal measurements of extended sources, such as the precordium. These miniature vibration detectors consist of a ThetaShear\textsuperscript{®} accelerometer and a DeltaTron\textsuperscript{®} preamplifier in a lightweight titanium housing, which prevent any allergic reaction from the patients. An
Figure 1. First principal component in the time-frequency space of ten heart beats registered by four accelerometers placed on the chest of a normal male (upper panel). The well separated first and second tones are represented by the pronounced peaks extending to higher frequencies (upper panel). A single ECG signal from one of the heart beat is shown in the lower panel for comparison (black curve), as well as the PCG signals of the same heart cycle from the four accelerometers (coloured curves, shifted upwards for clarity).

Ultrasound gel solution can be used to optimize the sound contact between the detector support and the patient skin. In many cases, though, the acquisition can be equally made putting the sensors directly in contact with the chest skin.

A preliminary test to detect heart sounds with accelerometers (Padmanabhan et al. 1993) demonstrated the usability of these sensors. Yet, the increased quality of the commercial sensors available nowadays, plus the reduced costs, make these types of vibration detectors largely competitive with more conventional microphonic detectors. Indeed, at the early stage of our research, we used microphones, but we had to reject this choice as the systematic errors encountered during the positioning of the microphone array (the pressure applied on the microphones mainly) hampered the reproducibility of the results. In contrast, accelerometers demonstrated to be much less sensitive to systematic errors.

Simultaneously to the detection of the mechanical vibrations induced on the chest, the heart electrical activity is monitored by means of an ECG recorder, equipped with an analogue output, whose electrodes are usually placed in the standard lead I (right-arm/left-arm) configuration, but any other lead is also possible. This ECG has no diagnostic relevance, and its only use is to provide a precise clock to segment the heart beats by identifying the different QRS complexes. The common time origin of the different heart beats is then arbitrarily set to be 50 ms before the R peak. The PCG signals are segmented correspondingly.

All the analogue signals from the accelerometers and from the ECG device are digitalized through 24-bit 102 dB dynamic range multi-channel analogue–digital (A/D) NI-9234 acquisition modules hosted in an NI CompactDAQ 8-slot chassis. The maximum sampling rate per channel of each A/D module is above 50 kS s\(^{-1}\), tunable via software to
any desired smaller value. This capability allows for both apex cardiogram and conventional PCG to be recorded with a single instrument. For the purpose of this work, we focused our investigation to the low-frequency portion of the spectrum (below 250 Hz), as sound and noises that fall in this region come mainly by large moving masses (i.e. the mechanical activity of the heart). The sampled data are then transmitted via a standard USB connection to a personal computer, where a software interface has been designed to store the data in multi-columns ASCII files.

Thanks to the simultaneous recording of the mechanical and electrical heart activities, the acquired PCG from the auscultation points on the chest are synchronized with themselves and with the ECG pattern. A 10 s acquisition of the raw PCG signals collected by ten different accelerometers uniformly placed on the chest of a patient are shown in figure 2, together with the synchronous ECG signal (first curve from the bottom).

More than 30 subjects were investigated for this study, mixed per gender, age and pathologies. We welcomed about 30% of female patients; 35% of the total sample was younger than 40 and 15% was older than 70. The cardiac activity of the whole ensemble of patients was monitored by standard electrocardiography and echocardiography (Toshiba Aplio Artida™); 27% of the patients were healthy or presented mitral valve prolapse; 23% presented a moderate valvular regurgitation, while 23% showed left ventricle segmental wall motion abnormalities (hypokinesia); 17% presented idiopathic dilatative cardiomyopathy with overt heart failure. None of the studied patients presented previous myocardial infarction.

The patients were enrolled to this research study during routine diagnostic echocardiographic examinations. They were informed of the research protocol, and signed an informed consent. For the purposes of this study, unique identification codes were attributed to each subject, and the processed data were blinded to the members of the research team.
Figure 3. Principal component representations of the heart activity for four prototypical patients. The first and second heart sounds are clearly visible as black irregular patches superposed to a white background, even though they change shape and intensities. Intensities are normalized and a common colour axis has been adopted. Pathological hearts show altered patterns. (a) Healthy young female. (b) Male patient showing a systolic murmur due to aortic stenosis. (c) Patient with ischaemic heart disease and echocardiographically detected left ventricle segmental wall motion abnormality (hypokinesia). (d) Patient with overt heart failure (NYHA class III) due to dilatative cardiomyopathy.

5. Results and discussion

The results of our procedure are presented in figure 3 for four archetypical patients, showing different degree of pathological heart activity. These images are obtained through the procedure described above. They are the synthesis of the multi-site collection (four accelerometers placed on the main auscultation areas: aortic, pulmonic, mitral and tricuspid regions) during prolonged time acquisitions (typically 10 to 20 s) of the vibrations induced on the chest skin by the heart’s mechanical activity. All the acquisitions were made with supine patients in deep apnea (10 to 20 s), and the clinical assessments on the healthiness conditions of the patients were obtained through accurate echocardiographic examinations. In all the cases the variance portion expressed in these PCA images is above 85% of the total.

The characteristic pattern of a healthy subject as shown in figure 1 is well reproduced in figure 3(a) for a different patient, as per age and gender, reflecting the inevitable physiological variability of the clinical auscultation, but also confirming the main features of the first and
second tones. Two main modulations protruding to the high-frequency side of the image are shown, the second tone (0.5 to 0.6 s) being slightly pushed to higher frequencies with respect to the first one, and the first tone (0.15 to 0.3 s) being shallower and more long-lasting. As shown in figure 3(b), heart murmurs are easily detected in pathological patients, and they appear as further contributions to the two main heart sounds characteristic of a healthy subject. In this case, a systolic murmur due to the imperfect closure of the aortic valve provides a signal between 80 and 100 Hz as a grey region between the two main components. The effect of a left ventricle segmental hypokinesia is seen in figure 3(c) as a strongly reduced first tone and a moderately reduced second tone. Finally, in figure 3(d), the pattern corresponding to a severely impaired ventricular function is shown.

Quantitatively and qualitatively similar patterns were recorded with ten accelerometers uniformly placed on the anterior chest of the patients, with a variance fraction reduced to below 65% of the total. The four detector geometry provides an optimized use of the instrument in terms of the amount of information delivered, at the cost of a more delicate positioning of the detectors, which requires expert handling. In contrast, a uniform array of accelerometers allows the operator to make immediate measurement, with the drawback of reduced accuracy of the result. While the first scheme is suitable for diagnostic purposes, the regular array geometry is of better use for large screening or non-specialists.

The patterns shown in figure 3 provide the flavour of the capabilities offered by the instrument described in this work. In particular, we believe our approach is able to provide discriminating patterns between healthy and pathological subjects in a very visual manner, with a non-expensive, non-invasive and fast procedure. The overall time required for the acquisition and data treatment to deliver the diagnostic images shown in figure 3 does not exceed 1 to 2 min, even with limited computational capabilities.

With respect to the total ensemble of the studied patients, our method was able to discriminate between normal and abnormal hearts with a sufficient confidence level in 28 cases over 30 patients, corresponding to 93% of successful diagnosis confirmed by echocardiographic examinations. These include three cases where minor abnormalities, such as mitral valve prolapse, appeared as a blurring of the resulting image at low frequencies. For two patients the analysis was inconclusive.

6. Conclusions

A novel instrument for recording phonocardiographic signals has been presented. It combines a multi-site recording of the heart sounds on the chest skin through accelerometric detectors, and an advanced mathematical treatment of the PCG patterns. The multi-site PCG measurement is simultaneous with the collection of an ECG signal, used as time marker of the heart beat.

Final result of this complex procedure is a three-dimensional image in the time–frequency domain, showing intensity modulations corresponding to physiological and pathological heart activity. The shape of these modulations reveals in a synthetical way the state of the heart, and it provides a useful diagnostic tool to clinicians with a great confidence level.

This unique reconstruction of the heart behaviour as revealed by multi-point heart auscultation overcomes the usual drawback of non-human detection of heart sounds, due to the spatially extended nature of the source. Thanks to the combined used of CWT and PCA, we are able to condense in one single image the informative content dispersed on the chest.

The intrinsic simplicity of the device, few miniaturized accelerometers connected to a portable computer, may be easily reduced in a compact form without any loss of diagnostic capability. The instrument may then become suitable to be used in a number of different clinical
environments, including high throughput screening programmes and first aid and emergency treatments.

The sensitivity of the technique to major heart pathologies is almost immediate, but we are confident that a deeper analysis of the informative content provided by this approach may also deliver a non-invasive low-cost diagnostic tool to non-experts.

Acknowledgments

This research was completed thanks to the extensive funding made available by the Centro Studi e Ricerche e Museo Storico della Fisica 'E. Fermi' through the project ‘Suoni Cardiaci e Diagnosi Clinica’. It is a pleasure to thank Professor R D’Autilia for his fundamental contribution at the initial stage of the project and for enlightening discussions. SDP wishes to thank the Physics Department of the University of Rome ‘Sapienza’ for providing resources and hospitality during the entire duration of the research.

References

Daubechies I 2006 Ten Lectures on Wavelets (Philadelphia, PA: SIAM)