Is there an Optimal Localization of Cardio-microphone Sensors for Phonocardiogram Analysis?

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Abstract— **Heart auscultation is one of the most useful medical diagnostic tools for getting valuable information of heart valves and heart hemodynamics functions. However, the information acquired by a traditional stethoscope can be inaccurate and insufficient. Phonocardiogram (PCG) was developed to improve accuracy through visual inspection and analysis. Digitally processed, PCG can then be analyzed by automated heart sound analysis systems. But there is no standardization for PCG data acquisition unlike electrocardiogram (ECG). This study aims at analyzing the influence of cardiomicrophone localization on the chest for the study of cardiac sounds S1 and S2. For that purpose, simultaneous acquisitions of 12 PCG signals with one ECG signal were realized and a comparative analysis of delays between R waves of ECG and detected S1 and S2 sounds was conducted. Results show that there are significant differences between R-S1 (or R-S2) intervals obtained from different areas of sensor placement on the chest. For future works on PCG, studies dealing with the analysis of heart sounds or proposing new heart sounds detection algorithms may pay attention to the location and attachment of PCG sensors.**

I. Introduction

According to World Health Organization report from 2015 [1], cardiovascular diseases (CVD) continue to be the leading cause of morbidity and mortality worldwide. One of the first steps in evaluating the cardiovascular system in clinical practice is physical examination. Heart auscultation is one of the most useful medical diagnostic tools for getting valuable information concerning the function of heart valves and hemodynamics and may reveal many pathologic cardiac conditions such as arrhythmias, valve disease, heart failure…. Heart sounds provide initial clues in disease evaluation and thus play an important role in the early detection for CVD.

However, heart sounds examination using traditional stethoscope is subjective and depends on the examiner experience. Highly trained personal can provide more accurate information, but they are still limited by human ear possibilities which is poorly suited for cardiac auscultation. Therefore, phonocardiography (PCG) was developed and many new possibilities for heart analysis was made. With development of computer-aided auscultation, algorithms can automatically detect even inaudible sounds and recognize pathological phenomena [2-4]. PCG is a diagnostic graphical method of recording sounds, echoes that accompany mechanical vibrations originating in the heart and vessels. It uses a microphone attached at the surface of the chest wall, and it is used to register heart sounds and murmurs in the diagnosis of heart disease. Among cardiac sounds, two, noted respectively S1 and S2, are particularly audible and correspond to the closure of respectively the atrial-ventricular valves (beginning of the ventricular systole) and the aortic and pulmonary valves (onset of the ventricular diastole).

One difficulty remains that unlike electrocardiogram (ECG), there is no standardization in PCG acquisition and even if new methods of features detection are still coming there is no common way how to measure PCG. In most methodological articles dealing with S1 and S2 sounds detection [5-12], the location of cardio-microphones is not precisely mentioned. Only a few articles dating from several years now have explored the influence of several sites for heart sounds auscultation, using simultaneous PCG acquisition [13-15]. But conclusions were not clear about the differences between sites and whether one site is better than another. It appears that there are some variations of energy between sites. The cause is the localization of sensors (microphones), but the pressure of the sensor on the skin cannot be neglected.

Considering the recent advanced methodological results to process PCG signals and detect heart sounds, it is of interest for accurate PCG data acquisition, to study the placement and fixation of the microphone on the chest. In this study, we investigate different auscultation sites and ways of attaching the microphones to analyze their influence on PCG signals quality. The comparison is carried out considering S1 and S2 sounds detection over several acquisitions.

II. Material and methods

A. Data acquisition

Acquisitions of simultaneous PCG and ECG signals were performed on 2 healthy volunteers at TIMC-IMAG laboratory (La Tronche, France), using a PowerLab data acquisition system (ADInstruments). All signals were sampled at 1 KHz.

Each subject was equipped with 3 Disposable electrodes (Ag/AgCl) for a DI lead ECG and 12 cardiac microphones (MLT201, AD Instruments) put on the skin for PCG

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acquisitions. The PCG auscultation sites are shown on Figure 1. The location of the PCG sensors was chosen to include 4 standard auscultation areas (red points) and well map the heart area. The points were also chosen so that they were easily identifiable and descriptive and allowed to repeat the same sensor placement for other measurements and subjects. For reference we considered intercostal areas and distance from the sternum. Similar sensor deployment was also used in a previous energy measurement study [13]. In the following, PCG auscultation sites are named from 1 to 12, starting from the top right of the heart and while moving right to left and top to down.

Each measurement was performed in a quiet laboratory (without special acoustic shielding) at the sitting position of the subject. The appropriate auscultation places were found using palpation. After several investigations how to attach PCG sensors, microphones were fixed on the chest using thin double-sided tape (Fig. 1 left), with a hole so as the sensor is in contact with the skin. Pressure was then applied to the microphones thanks to Tegaderm (3M) transparent medical dressing. Each measurement took 2 minutes. For each subject, 12 successive measurements were carried out.

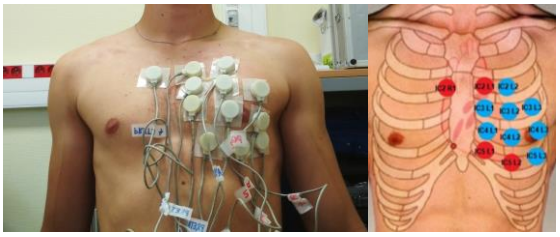

Figure 1. Heart auscultation sites for PCG recordings. ICi is the number of intercostal space. Rj or Lj indicates the right or left parasternal area and j is the distance from the sternal bone. Red points correpond to 4 reference (standardized) heart sound measurement areas (from left to right and top to bottom: aortic, pulmonray, mitral and tricuspid valves).

B. *Signal processing*

S1 and S2 occur in all healthy individuals, and most of studies on PCG analysis deal with the detection of these sounds. A wide amount of methods uses the signal envelope detection for analyzing heart sounds [3,5-7]. Other methods are based on Short Time Fourier or Wavelet transformation in order to investigate the exact features of the heart sound [8]. More sophisticated methods also include probabilistic models such as Hidden Markov Models for segmentation of heart sounds [9,10] or neural networks [11,12]. For a most accurate reliability of the detector, the multimodality aspect of the acquisition has been exploited; synchronous ECG and PCG capture enables the use of the ECG signal as a time reference to improve detection of heart sounds on PCG signal.

PCG signals were analyzed according to a signal envelope detection method using the Normalized Averaged Shannon Energy, classification and more accurate detection based on synchronization with the R and T waves of ECG. This method allows by simple set of different parameters to analyze very variable PCG signals measured on standardized but also non-standardized locations. All processing steps were carried out using Matlab®.

1) Heart sounds envelope signal estimation from PCG

PCG signals were first band-pass filtered between 15 and 150Hz and normalized to the maximum absolute value of the signal. The extraction of the heart sound envelope (Fig. 2) is then implemented, according to [16], by calculating the normalized average three-order Shannon energy, in continuous 20-sample segments throughout the normalized signal with 10-sample segment overlapping using the following formula. It has been shown that the average Shannon energy can attenuate the effect of low value noise.

$$E_S = -\frac{1}{N} \cdot \sum_{i=1}^{N} |x(i)|^3 \cdot log|x(i)|^3$$

where x is the normalized signal and N the samples number.

The normalized average Shannon Energy was standardized by the following relationship, where μ is the average value of energy E_S of the signal and σ the standard deviation of E_S. $E_N$was then low-pass filtered (cut-off frequency = 20Hz) and used as the envelope of heart sound signal.

$$E_N = \frac{E_S - \mu}{\sigma}$$

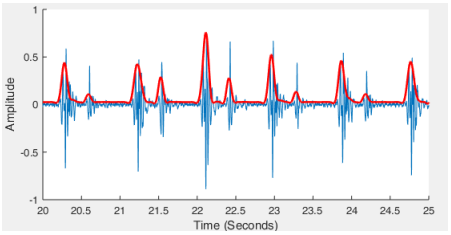

Figure 2. PCG signal and envelogram of heart sounds signals..

2) Detection of R and T waves on ECG signals

The classical algorithm of Pan-Tomkins was applied on each ECG to detect R-waves. ECG were then processed through FIR Butterworth band-pass filter [0.5 - 10 Hz]. Then the signal was divided into individual RR segments, obtained by previous R peak detection. In order to make T wave dominant feature in RR segments the QRS complex were removed (as 50 ms at the start and at the end of RR segment). Then local maxima were found in each segment, with respect to minimum amplitude and minimum peak width for T wave based on literature.

3) Detection of S1 and S2 sounds

PCG envelope is divided into segments bounded by R peak. According to clinical knowledge, S1 occurs always after R peak and S2 occurs with the end of T wave for healthy heart conditions. It is difficult to determine the exact time of the S1 or S2 sounds, but it is possible to get wider time blocks, in which S1 and S2 are likely to be found. The time intervals for these blocks of interest were determined on the basis of [17]. The block of interest for S1 was determined as 0.05 RR - 0.2 RR and the one for S2 as 1.2 RT - 0.65 RR, where RR interval is the time between adjacent R peaks and RT interval is the time between R peak and the following T wave. Local maximum of PCG envelope was then detected inside each block of interest and annotated S1 or S2 depending the block. In case of no local

maximum or many local maxima, the most significant peak in block of interest was selected.

4) Parameters estimation

With determined S1 and S2 on PCG signals and R and T waves on ECG signals, different parameters for temporal analysis were calculated, as illustrated on Fig. 3. It includes RR, RT, RS1, RS2, S1S1, S1S2, where XY corresponds to the interval between X event and the following Y event.

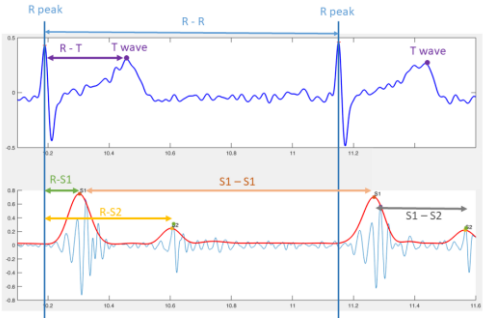

Figure 3. Parameters considered for analysis. Starting form R peaks and T waves of the ECG (top) and S1 and S2 sounds of one simulatenous normalized PCG (amonf the 12 chest positions), several temporal delays are computed all along the various recordings .

C. Statistical analysis

Statistical methods were considered to analyze the differences between PCG signals measured at different positions. First, statistical hypothesis tests were realized to evaluate if the various intervals were statistically different depending on PCG localization. Before each test, normal distribution of data was tested. If the assumption of normality was met, the paired Student's t-test was performed with 5% significance level. Then, for purpose of getting information about statistical relationship, correlations between data samples were measured.

III. Results

A. Comparison between S1S1 and RR intervals

The relationship between S1S1 and RR intervals was evaluated within one PCG channel (one position) and ECG channel for each recording. For each subjects, S1S1 and RR intervals were compared to each other so as to verify the functionality of the detection algorithm. The test of mean between S1S1 and RR interval durations was performed for all PCG positions and the mean difference S1S1 and RR was always 0 ($p<0.05$). And the correlation coefficient between S1S1 and RR was greater than 0.8 for all PCG measurements. RR intervals plotted against S1S1 intervals for one recording and for the 12 PCG channels is shown on Fig. 4 with computed linear regression. As expected, the heart rate computed from ECG is the same as the heart rate calculated from S1 sounds from PCG, regardless of the position of the sensors. This demonstrates the heart sounds detection algorithm's efficiency.

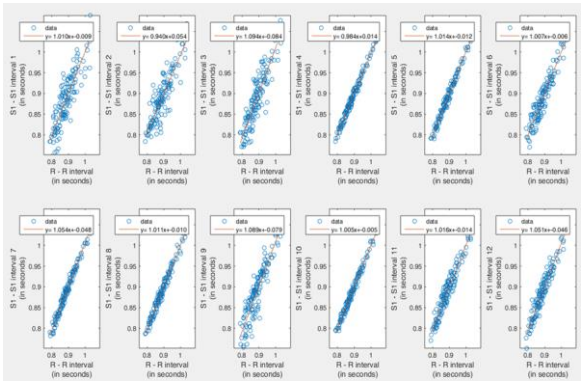

Figure 4. Correlation between S1S1 and RR intervals for 12 microphones positions on the chest . The relationship is linear (regression line y=x) and correlation coefficient greater than 0.8 for each graph.

B. Are RS1 and RS2 the same all over the chest?

The statistical relationship between RS1 (respectively RS2) intervals calculated from the different positions within a single measurement was tested. Test of mean was performed between each sensor location and the 11 remaining positions.

After testing normal distribution, the paired Student's t-test was performed with following hypothesis. $H_0: \mu_d = 0\ s$, $H_A: \mu_d \neq 0\ s$. For a great majority of measurements, considering RS1 intervals (resp. RS2), H_0 was rejected at the 5% significance level, which means there is a significant difference between the duration of the RS1 (resp. RS2) interval for different positions on the chest. This is illustrated for one measurement of one subject on Fig. 5 with the boxplots of RS1 and RS2 intervals for the 12 PCG positions.

Moreover, when considering RS1 intervals for all measurements, only 12% of the paired comparisons between 2 PCG positions could bring the conclusion that RS1 samples from one position have the same mean duration than the RS1 samples from the other position. Therefore, in 88% remaining comparisons, the mean RS1 duration was not the same between 2 PCG localizations. It is also important to note that among the 12% of situations with no significant difference on RS1 delays between 2 PCG positions, the 2 concerned positions were rarely the same. Obviously, none specific pair of sensors seems to stand out.

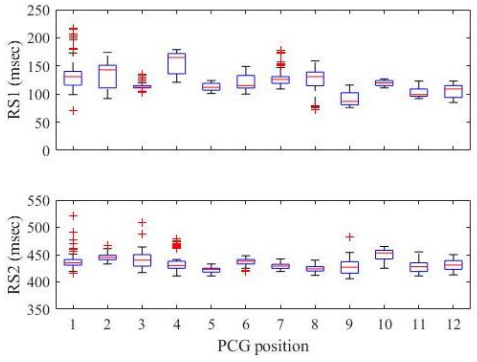

Figure 5. RS1 and RS2 distributions for the 12 PCG poisitions on the chest for one measurement of one subject. The line inside the box corresponds to the median value, the boxlimits represent the first and the third quartiles and whiskers highlight extreme values.

Similarly, for each sensor location, the correlation coefficient between RS1 (resp. RS2) from the considered position and RS1 (resp. RS2) from the 11 remaining positions was computed and was smaller than 0.8 for almost all measurements. As for an example, for one subject, among the 792 computed correlations on RS1 samples (corresponding to 66 paired comparisons on 12 measurements), only 13 correlation coefficients were higher than 0.8 and among the 12 measurements, it was never the same pair of PCG locations that provides this coefficient. Figure 6 shows for one measurement, RS1 intervals from aortic area position (position 1) against RS1 intervals from the other PCG localizations, highlighting the absence of linear relation between RS1 intervals computed from various PCG positions.

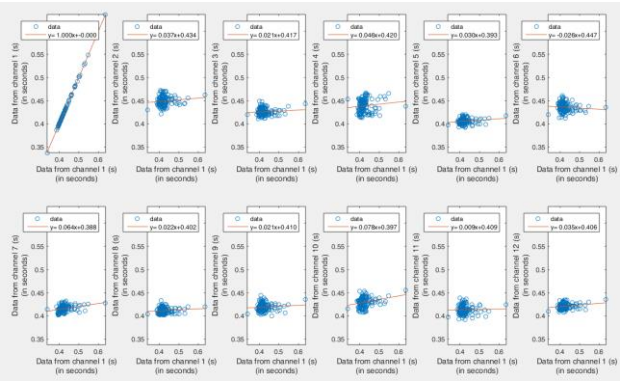

Figure 6. RS1 from aortic area (position 1) plotted against the 11 other position on the chest

The differences between RS1 (resp. RS2) intervals obtained from different PCG positions on the chest are then statistically significant, delays are variable and show that the heart sounds are propagated through the chest area.

IV. Conclusion

Nearly one hour of multi-channel PCG and ECG recording was measured and analyzed. For heart sound analysis, S1 and S2 detectors have been developed using PCG synchronization with R and T waves of ECG for a more reliable detection.

Due to lack of information in previous research, the spread of the heart sounds on the chest surface has been investigated. The aim of the work was to prove whether at the same time, the same or at least similar signals could be measured at different positions on the chest. For this purpose, the intervals RS1 and RS2 were examined across the various chest localizations, by means of correlation and difference of mean values. The results show that with the chosen method of heart sound detection, there are significant differences in time domain for different areas of sensor placement. For next research and future works on PCG, studies dealing with the analysis of heart sounds or those proposing new heart sounds detection algorithms should therefore take into consideration the location of the sensors. Indeed, many studies that consider mean delays between ECG and PCG may fail when applied from one subject to another, if the microphone is not placed at the same position.

Moreover, many tests also demonstrated the importance of the way of attaching PCG sensors to the patient, with various tested ways of attachment. The greatest differences were in the level of noise and magnitude of heart sound amplitudes.

As a conclusion, telling what is the optimal localization of the PCG sensor is very difficult. Evaluation depends on many parameters (investigated parameters, considered signal processing methods, ways of attachment of sensors...). The assessment of their optimality depends on what applications and for what purpose the data obtained will be used.

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