Can multi-source phonocardiography enable inexperienced users to record heart sounds for telemonitoring applications? A comparative analysis

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Abstract

The use of heart sounds in telemonitoring is extremely appealing due to portability, low cost, non-invasiveness. Nevertheless, the positioning of the electronic stethoscope is critical and prevents the use of phonocardiography (PCG) by inexperienced users. Multi-source PCG may provide a solution: by recording multiple signals from different points on the chest at high spatial resolution the problem of finding the best auscultation point is moved from the recording phase to the processing phase. In this study, we compare the quality of PCG signals recorded by inexperienced users through multi-source PCG against the quality of PCG signals recorded by an expert through a traditional single-source system. We enrolled 42 inexperienced volunteers and asked them to record signals on each other using a multi-sensor array that we designed for this purpose. An expert user also recorded signals from each volunteer from the four typical auscultation areas. Experimental results show that the multi-source system enabled inexperienced users to record signals of equal or better quality. We believe that our results lay the foundations to apply multi-source PCG in homecare.

1. Introduction

Phonocardiography (PCG) is the digital recording of heart sounds. After suffering a decrease of popularity during the end of the last century due to the spread echocardiography, PCG is now again object of wide research. In fact, PCG has multiple characteristics that make it appealing for telemonitoring: portability, low cost, non-invasiveness [1]. Combined with electrocardiography (ECG), it provides an interesting insight in the electromechanical behaviour of the heart, difficult to monitor otherwise. For example, Cardiac Time Intervals extracted from simultaneous recordings of ECG and PCG in a homecare setting could enable the non-invasive monitoring of patients affected by heart failure [2], [3].

The main issue limiting the applicability of PCG in homecare resides in the positioning of the electronic stethoscope. Traditionally, auscultation areas were defined for each cardiac valve according to decades of clinical experience [4]. Nevertheless, the auscultation areas must be identified using fiducial marks such as the intercostal spaces: an inexperienced user (such as the patient or a caregiver) cannot be trusted on reliably finding the correct point. Therefore, the applicability of PCG in telemedicine is subjected to the availability of a system which enables inexperienced users to reliably record the signal of interest.

Multi-source PCG is expected to provide a solution to this problem. In fact, by recording multiple signals on different positions of the chest with a high spatial resolution, the problem of finding the exact auscultation point is shifted from the recording phase to the processing phase. The patient can simply position the device over the left hemithorax: then the algorithm chooses the most appropriate microphone.

In this work, we compare the quality of the PCG signals obtained through a single-source approach by an expert user on the four auscultation areas against the PCG signals obtained through a multi-source approach by inexperienced users. The goal of the study is to demonstrate that multi-source PCG enables inexperienced users to record signals of equal or superior quality to what obtained by an expert user with a traditional method.

2. Materials and methods

2.1. Multi-source PCG recording system

We performed the multi-source PCG recordings using a multi-sensor array that we developed for this purpose. The array is a flexible pad to be placed on the patient's chest. Figure 1 presents pictures of the array with the sensors highlighted. It is based on a flexible printed circuit board (PCB) mounting:

- 48 microphones for PCG recording
- 3 electrodes for ECG recording

To achieve a sufficiently high spatial resolution,

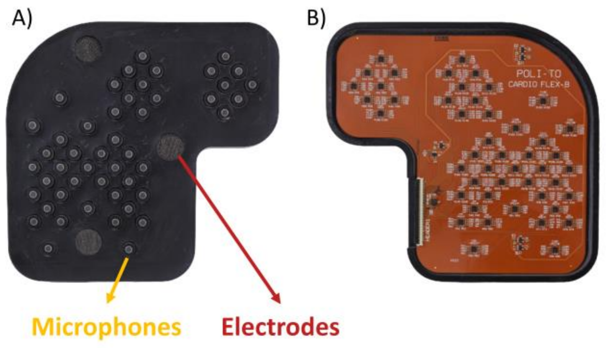

Figure 1. Pictures of the multi-sensor array in respectively A) the chest side with the sensors highlighted, B) the top side.

condenser microphones with a diameter of 4 mm were used. These microphones allow for a good trade-off between miniaturization and performances on low frequencies (higher than 20 Hz, as required for heart sounds). The microphones are located over a non-uniform grid where the closest neighbours are distanced by 12 mm. Microphones are more densely concentrated over the traditional auscultation areas, but they are present also elsewhere, over a total 150 mm-by-140 mm L-shaped area. This is meant to allow for rough positioning, feasible for an inexperienced user. The signal output by the microphones is amplified by 50 dB and highpass filtered at 2 Hz to remove baseline wandering.

The electrodes are meant to record a simultaneous ECG signal. Three dry electrodes were realized using 16-mm stainless steel disks. They are located to create a nonstandard precordial lead, since no morphological analysis of the ECG signal is required. A typical ECG front-end is realized, based on an instrumentation amplifier. The reference is created by means of the well-known Right Leg Drive circuit.

The PCB was inserted in a 3D-printed case that we realized using a biocompatible flexible elastomeric resin not to lose flexibility. The signals were simultaneously sampled at 1 kHz multiplexed and acquired by means of the DAQ USB 6210 card by National Instrument™, which includes a 16-bit Analog-Digital Converter (ADC).

2.2. Single-source PCG recording system

The single-source recordings were performed by means of a commercial system for the acquisition of biomedical signals (ReMotus™ by IT-MeD). The system provides 4 analogue input channels, equipped with a 24-bit ADC. All channels were sampled with a 1 kHz frequency, and the system ensures a 3-dB bandwidth from DC to 262 Hz.

For this study, the first channel was equipped with an active probe with three disposable Ag/AgCl electrodes for the recording of an ECG signal. The second and third channels are used for PCG recording and equipped with custom-designed microphone probes for the specific purpose. Each probe is shaped as a stethoscope head and based on an electret condenser microphone. Further details about this system are presented in [5].

2.3. Experimental protocol

Inexperienced volunteers, i.e., subjects with no technical nor clinical knowledge about auscultation, were enrolled in couples. In each couple, a volunteer was first assigned the role of the patient and the other was assigned the role of the caregiver. For each volunteer-patient couple, the experimental protocol involved three phases.

Phase 1. Multi-source recording. The volunteer-patient was asked to lay on an examination table with bare thorax. In the meanwhile, the volunteer-caregiver was given a simple set of written instructions on how to use the multi-sensor array. When he/she was ready, the volunteer-caregiver was asked to locate the device on the chest of the volunteer-patient and to fix it with an elastic band. A 5-minute recording was then carried out.

Phase 2. Single-source recording optimized for the left heart valves. A member of the research group, acting the role of the expert user, positioned the electrodes as to recreate a first standard lead. Then, the expert user located the two microphone probes respectively over the:

- **Mitral area**: fifth left intercostal space, along the mid-clavicular line
- **Aortic area**: second right intercostal space, next to the border of the sternum

A 5-minute recording was performed.

Phase 3. Single-source recording optimized for the right heart valves. The expert user kept the position of the electrodes but changed the position of the two microphone probes, placing them respectively over the:

- **Tricuspid area**: fourth left intercostal space, next to the border of the sternum
- **Pulmonary area**: second left intercostal space, next to the border of the sternum

A 5-minute recording was performed again.

Figure 2 shows the positioning of the sensors respectively in the multi-source and in the single-source recording. Once the experimental test was completed on the first volunteer, the roles were reversed. In the end, for each subject, a 48-channel recording performed by an inexperienced user and a single-source recording for each cardiac valve performed by an expert user were available.

We applied our experimental protocol to a population of 42 healthy volunteers. None of the subjects had previous experience nor theoretical knowledge in terms of auscultation. The subjects were different in terms of biological sex (50% females), Body Mass Index (17.2 kg/m^2 to 32.1 kg/m^2) and thoracic circumference (59 cm to 116 cm).

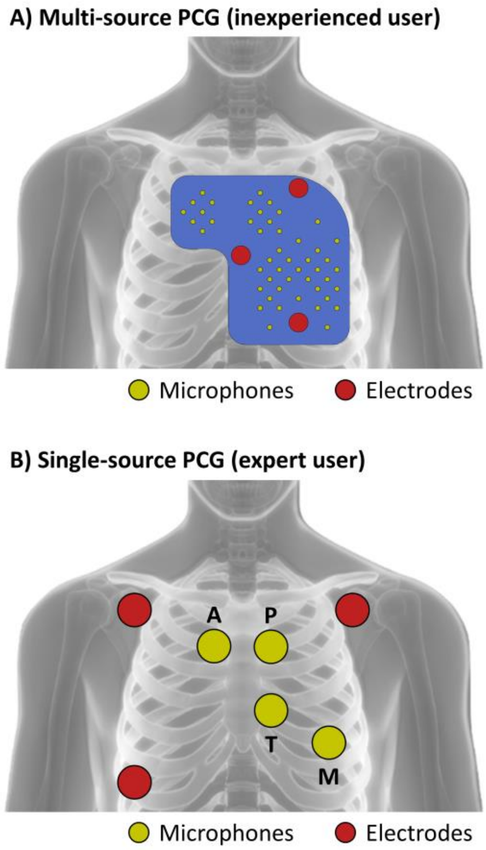

Figure 2. Positioning of the sensors in A) multi-source PCG, and B) single-source PCG.

The experimental protocol was approved by the Research Ethics Committee of Politecnico di Torino (protocol number 16863/2021).

2.4. Quality assessment and comparison

Each PCG signal was first subjected to digital filtering (IIR Chebyshev I digital filter between 20 Hz and and 100 Hz, as suitable for heart sounds [6]). Each signal was segmented into heartbeats using the R-wave peak in the simultaneous ECG as reference, identified using a modified version of the well-known Pan-Tompkins algorithm. The SNR of each heart sound was estimated heartbeat-by-heartbeat, as a metric of the quality of the signal, using the method described in [7]. The two main heart sounds (first heart sound – S1 – and second heart sound – S2) are treated independently.

In the analysis phase, the distribution of the SNR of the signals over the chest was evaluated to determine if the quality of the heart sounds depended on the area of the chest, as expected from the theory. We achieved this by computing, channel by channel, the percentage of recordings where the SNR of S1 was higher than the SNR of S2, and the other way round.

In the end, we divided the microphones of the array in four areas, according to the theoretical auscultation areas. From each area, we selected the microphone with the highest SNR. We statistically compared, for each cardiac valve, the SNR of the single-source signal against the SNR of the selected microphone in the multi-source recording using a paired Student t test ($\alpha = 0.05$).

3. Results and discussion

Figure 3 shows the channel-by-channel maps of the percentage of recordings with respectively the SNR of S1 higher than the SNR of S2, and the other way round. The maps show that the SNR of S1 is the most relevant over the mitral and tricuspid areas, as expected from the theory. Similarly, the SNR of S2 is the most relevant over the aortic and pulmonary area. This demonstrates that the positioning of the multi-sensor array over the chest was coherent with what forecasted.

Grounding on this, we compared the SNR of the signals recorded by inexperienced users with the multi-sensor array (best channel for each auscultation area) and the SNR of the signals recorded by an expert user with the single-source system. Figure 4 presents the boxplots of the values for each auscultation area. Table 1 proposes a comparison of the average SNR value obtained by the single-source against multi-source signals for each auscultation area. The table also reports the p-value of the Student t test applied to each comparison.

Table 1. Comparison on the average SNR of the signals recorded at each auscultation area with the two systems. The * highlights the comparisons which produced a statistically different result.

Cardiac valve	Single-source SNR (dB)	Multi-source SNR (dB)	p-value t test
Mitral	21.4	21.8	0.59
Tricuspid	21.0	22.9	**0.008 ***
Aortic	17.1	18.1	0.19
Pulmonary	18.9	22.4	**< 0.001 ***

The presented results highlight that there is no statistically significant difference in the comparison on the auscultation area corresponding to the valves of the left side of the heart. On the contrary, the quality of the signals obtained for the right heart valves is statistically different. In this case, we compared the average values and concluded that the multi-source system, even if used by inexperienced users, allows for obtaining signals with statistically a higher SNR than the single-source system.

We can conclude that the multi-sensor array enables inexperienced users to record signals of equal or higher quality than the ones obtained by expert users using the traditional single-source system. This holds for all four auscultation areas.

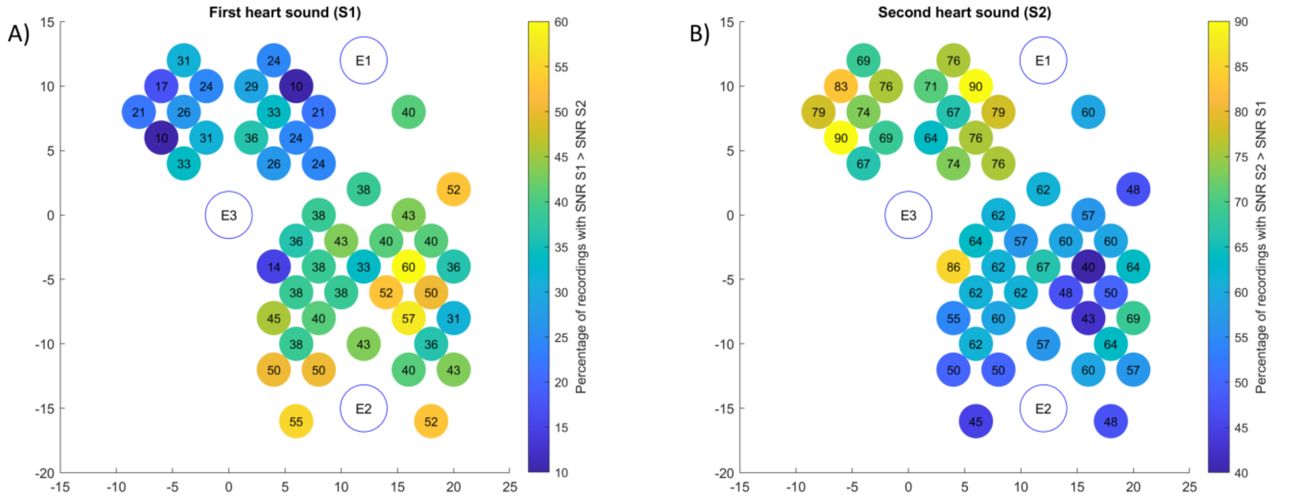

Figure 3. Maps of the percentage of recordings with respectively A) the SNR of S1 higher than the SNR of S2 and B) the SNR of S2 higher than the SNR of S1. Each circle represents a microphone.

4. Conclusions

In this study, we compared the quality of signals recorded by inexperienced users using a custom device that we developed to perform multi-source PCG against the signals obtained by an expert user with the traditional single-source system positioned over the four auscultation areas. We demonstrated that the multi-source approach enables inexperienced users to record signals of equal or better quality than those acquired following the single microphone approach. We believe that the reported results lay the foundations for exploring the use of multi-source PCG in telemonitoring applications. This may lead, in the near future, to novel possibilities for the home monitoring of chronic patients.

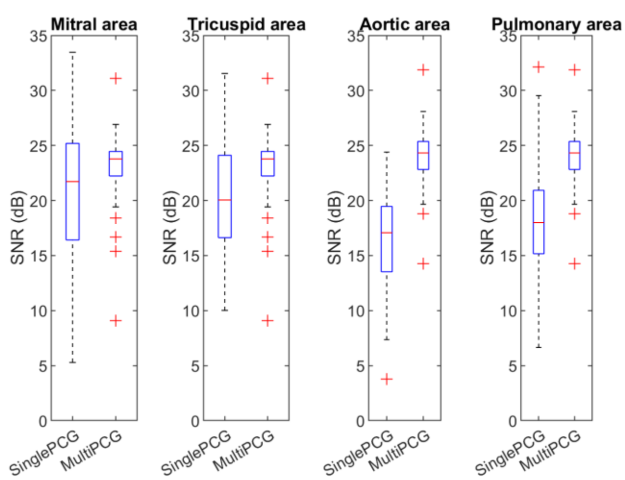

Figure 4. Boxplots of the SNR of the single-source PCG and the multi-source PCG for each cardiac valve.

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