Morphological and Temporal Variations of Seismocardiograms across the Chest: A Guide for Single Channel Sensor Placement

Deboleena Sadhukhan, Christian Dorme, Mathias Fink, Ros Kiri Ing

Institut Langevin, Université de Paris / CNRS UMR 7587 / ESPCI, Paris, France

Abstract

Context: *Accuracy of single channel Seismocardiogram (SCG) for cardiac monitoring relies on sensor placement, owing to the signal attenuation and delay caused by propagation effects on the chest.* ***Aims:*** *This work comprehensively evaluates the morphological and time delay variation in SCG data across the chest in comparison with the conventionally used xiphoid channel SCG (xSCG).* ***Methods:*** *Multichannel SCG (mSCG) on the chest were recorded with a high-fidelity air-borne ultrasound based Surface Motion Camera from 15 healthy volunteers. Cross-correlation and Dynamic Time Warping (DTW) based distance analysis were performed between the mSCG and xSCG to quantify the similarity, delay and morphological dissimilarity as well.* ***Results:*** *Although the correlation similarity is preserved (>0.7) over all channels localized over the heart, the morphological dissimilarity increases while moving away from the xiphoid with the DTW distance increasing to 50% near the aortic and pulmonary auscultation points. Channels near the apex of the heart shows a time advancement of 8 ± 7 ms compared to xSCG.* ***Conclusions:*** *These findings can aid in the sensor placement problem to ensure better accuracy and robustness for single channel SCG based cardiac monitoring applications.*

1. Introduction

Seismocardiogram (SCG) is the non-invasive recording of the cardiac induced chest surface vibrations and has currently emerged as a promising technique for cardiac monitoring and diagnosis [1].

Unlike the Electrocardiogram (ECG), which reflects the electrical activity of the heart, the SCG signal provides useful information about the cardio-mechanics which traditionally was obtained from Echocardiograph. The signal morphology has been proven to represent the vital cardio-mechanical events as the opening and closing of the valves, maximum contraction and relaxation of the cardiac muscles [2]. Researches have proposed the use of these signature patterns in the SCG signal for monitoring the vital Cardiac Time Intervals, as an easier and robust alternative to the Echocardiographic based measurements [3]. Moreover, several studies have established the utility of the SCG signal analysis for diagnosis of various cardiac diseases including heart valve disorders, ischemia and heart failure [1, 4].

The standard definitions of the fiducial events in the signal and most of the applications are based on single channel SCG recorded from the Xiphoid point (middle sternum) [2]. However, it has been shown that this single channel measurement only captures the composite of all cardio-mechanical activities. Changes in the sensors location cause signification variations in the acquired signal owing to the signal attenuation and time delay caused by propagation effects on the chest [5, 6]. These morphological variations in SCG waveform can significantly affect the extraction of reliable features for cardiac diagnosis. Hence, utility and accuracy of single channel SCG data largely relies on the sensor placement.

There is no consensus available till date to guide the sensor placement problem for different SCG applications. Few studies have aimed at quantifying the temporal variations in the signals only at specific locations on the sternum [5, 6]. However, no researches have focussed on studying the continuous variation of both the signal morphology and time delay on the chest surface.

This work takes the advantage of non-contact multichannel SCG monitoring (mSCG) using the airborne ultrasound based Surface Motion Camera (SMC) as proposed in [7] to evaluate the morphological and time delay variation in SCG data across the chest in comparison with the conventionally used xiphoid channel SCG (xSCG). Cross-correlation analysis is used to quantify the correlation similarity and time delay. Dynamic Time Warping (DTW) based distance measure is computed to quantify the morphological dissimilarity. The delay and similarity metrics are mapped on the chest surface to visualize the spatial variations. Such results can aid the sensor placement problem based on specific applications and need.

2. Material and Methods

2.1. Multichannel SCG data acquisition

SCG data across the chest surface are recorded using the airborne ultrasound based SMC device described in [7] that allows high fidelity vibration recording from multiple channels in a non-contact way. The device comprises of multi-channel ultrasonic transmitter-receiver systems working in echo-graphic mode at an operating frequency of 40 kHz. Measurement zone covers 40×30 cm^2 area on the chest with a spatial resolution of 1 cm. The acceleration in the perpendicular (z) direction of the chest is recorded at a sampling frequency of 500 Hz. Fig. 1a and b display the SMC device panel and the data acquisition set up respectively. Fig 1c shows the measurement channels on the chest for a representative subject, along with reference xiphoid marking and ECG lead connection points.

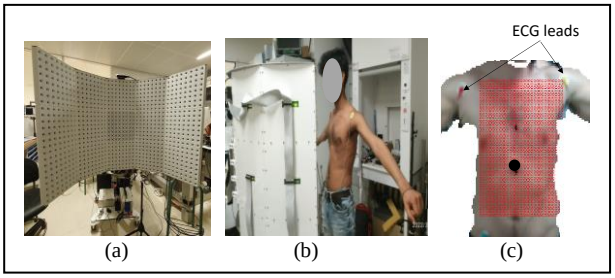

Figure 1. (a) SMC device panel with multi-channel transmitter-receiver system; (b) Data acquisition set up; (c) Measurement points on the chest with reference Xiphoid point marked

Multichannel SCG data is recorded from 15 healthy male volunteers (Age: 28±7 years, Body Mass Index: 21-4.5 kg/m^2) with no known cardiac abnormalities, in the upright standing position for a duration of 5 s. The subjects were restricted from breathing during the data acquisition to avoid artefacts due to respiration effect. A single ECG in lead I configuration is also recorded simultaneously by placing three ECG electrodes on the left and right shoulder and the right lower abdomen. The ECG data, specifically the R peaks, serve as a reference for segmenting the cardiac cycles from the SCG data.

2.2. Data processing and analysis

The SCG data from the channels are pre-processed by filtering using 6^{th} order Butterworth filter with cut-off frequencies at 0.5 Hz and 100 Hz. The channels covering the area of the chest over the heart (i.e. 12 cm on top and 3 cm on the bottom from the xiphoid reference point, and from 5 cm to the right of the sternum) are only considered for the analysis to represent signals corresponding to the cardiac activity. The selected zone of interest is shown in fig 2 b. This selection allows to vary the measurement area with the chest dimension of the subjects to account for the subject variability. The 5 s data from each of these channels are segmented into individual cardiac cycles by considering the ECG QRS complex as the reference start point. The Q points from the ECG data are detected using the method proposed in [8]. Fig. 2 c shows the processed SCG data from the common auscultation points used for heart sound analysis for a single cardiac cycle.

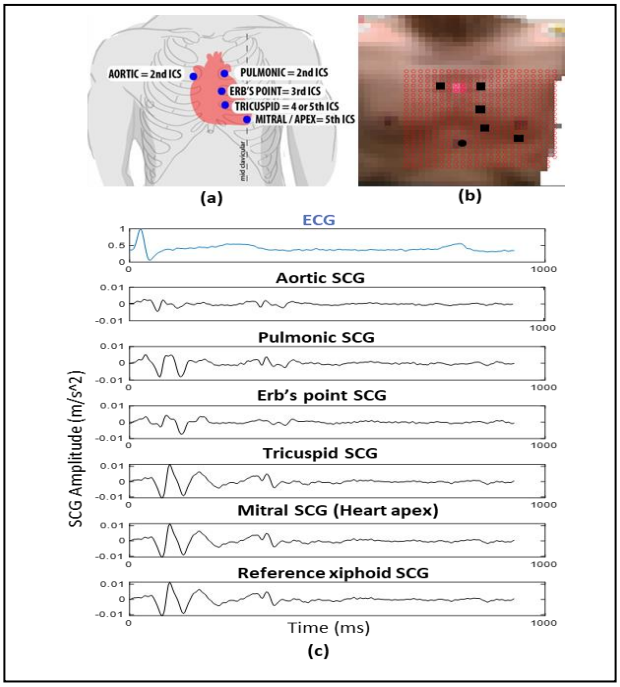

Figure 2. (a) Reference auscultation points; (b) Selected channels of interest with the auscultation points and reference xiphoid point marked with black; (c) SCG signals from the selected channels for one cardiac cycle along with the reference ECG data

Fig 2 c shows the morphological variation and the time delay introduced in different channels. To quantify the similarity and delay, cross correlation analysis is performed between the reference xSCG and the individual channels (mSCG) on the chest. The correlation similarity (CS) is the maximum correlation coefficient for normalised correlation and quantifies the linear similarity between the signals. The delay (D) with respect to the xSCG is computed from the lag at the point of maximum correlation using eq. 3.

$$C_{xm}(\tau) = \sum_{\tau=0}^{N-1} xSCG(n).mSCG(n+\tau) \quad (1)$$

$$CS = max_{\tau}\left(\frac{1}{\sqrt{C_{xx}(0)C_{mm}(0)}}\, C_{xm}(\tau)\right) \quad (2)$$

$$D = [N - arg_{\tau}\, max\left(C_{xm}(\tau)\right)]/F_s \quad (3)$$

N is the number of samples in the cardiac cycle and F_s is the sampling frequency. $C_{xx}(0)$ and $C_{mm}(0)$ represent the auto-correlation coefficient at zero lag for the xSCG and individual mSCG signals respectively.

To quantify the morphological dissimilarities irrespective of the time delays, Dynamic Time Warping based similarity measure is also computed between the xSCG and each of the mSCG channels. This technique computes the optimal distance between two time series that vary in phase [9]. Greater the DTW distance, lesser is the morphological similarity.

The similarity measures and the delays of the individual channels are then mapped on to the corresponding locations on the chest to allow for visualisation of the variations on the chest surface.

3. Results

It is observed in fig. 2c that the SCG data from different channels differ significantly with respect to both the waveform morphology and time of occurrence of events. The signal at the xiphoid channel clearly shows a delay with respect to the tricuspid and mitral position.

Fig 3 shows the similarity maps and the delays maps for SCG variations for a representative subject. From the correlation similarity map in Fig 3a it is seen that the linear similarity between SCG waveforms and xSCG remains high (>0.7) for the channels corresponding to the zone of the heart location on the chest. The correlation drops below 0.4 while moving away from this zone, which indicates that the cardiac activity induced vibrations are not prominent from areas away from the heart.

Fig 3b shows the morphological similarity in terms of the DTW based distance measure, the higher scales representing greater dissimilarity.

In spite of the retained correlation similarity, the actual morphological similarity drops rapidly while moving away from the xiphoid point. Even at the point of auscultation for the aortic and pulmonic valve, the similarity drops to below 50%. This is in accordance with the morphological dissimilarity as observable in Fig 2c. This might be indicative of the location specific variations in the waveform features.

Fig. 3c displays the time delay variations of the SCG signals with respect to the xSCG. The negative values indicate time advancement while the positive scales indicate the delay. The delay values for correlations above 0.5 are only shown to avoid irrelevancy of the delay computations due to signal mismatch. In addition, Table 1 tabulates the average time variations at the common auscultation points for all the subjects.

Table 1. Time delay variations of SCG at common auscultation points w.r.t. Xiphoid point

Auscultation point	Delay w.r.t. xSCG (ms)
Aortic point	4.38 ± 2.2
Pulmonic point	3.04 ± 2.4
Erb's point	2.68 ± 2.8
Tricuspid point	- 2.08 ± 2.6
Mitral point	- 6.80 ± 2.1
Heart Apex	- 8.00 ± 7.2

It is observed that moving up or down from the xiphoid channel usually incorporates a delay in the signal. However, it is interesting to note that for all the subjects the points near the apex of the heart including the mitral point, the SCG signal is advanced in time. This might indicate the greater contribution of the apical heart muscle contractions to create the vibrations on the chest leading to the signature SCG waveform.

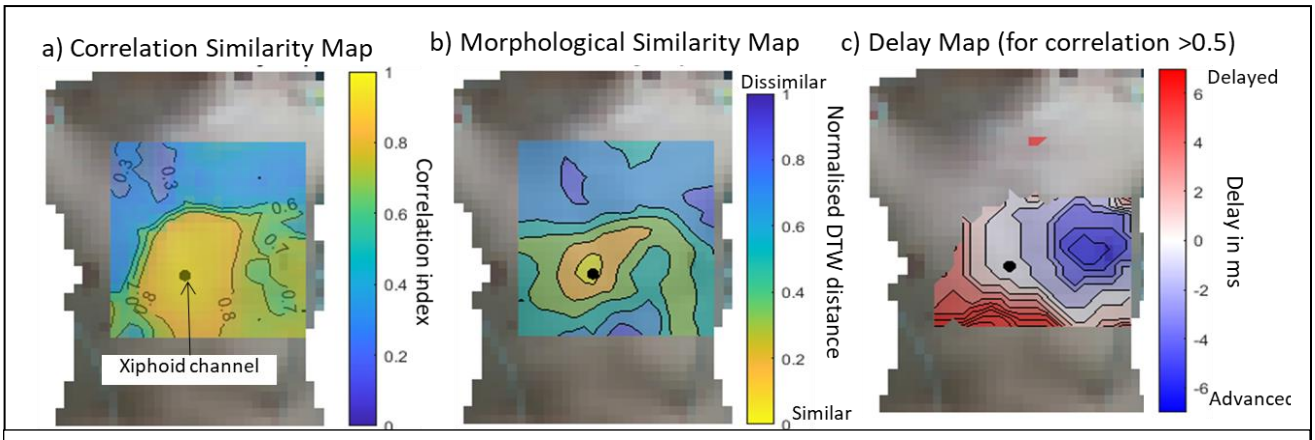

Figure 3. Correlation, morphological similarity and delay map for variation of SCG data w.r.t. xiphoid SCG on the chest surface of a representative subject

4. Discussion

The variations in the sensor placement position on the chest largely affect the SCG signal morphology. In fact, there is also delay induced due to propagation effect on the chest surface. These variations must be considered for optimizing the sensor placement for the SCG based cardiac diagnosis applications.

For all the subjects, the signals near the heart apex are advanced in time by 8 ± 7 ms. These results suggest that for monitoring cardiac time intervals, sensor position near the apex of the heart might ensure better accuracy by avoiding the propagation delays.

The large variation in the signal morphology at the different auscultation points might be indicative of the vibrations caused by localized events, like opening and closing of particular valves and blow flow through specific chambers. Further investigation into these is necessary to define such location specific fiducial cardiac events observed from the SCG signals. This finding also indicates to the superiority of multichannel SCG monitoring for more comprehensive analysis of the cardiac mechanics. Algorithms following the conventional definition of the signal morphology [2] require the sensor placement close to the xiphoid process.

The variations follow a similar trend for all the 15 subjects with mostly normal BMI. However, the morphological signal variations are also affected by the muscle mass and tissue properties of the thorax. Hence, for subjects with significant variation of the body mass the trends may vary. It is therefore necessary to establish more consistent research to study these variations over a greater population with large variance in their body composition.

5. Conclusion

SCG is gaining significant research attention for monitoring the cardio-mechanical activities due to its easy and low-cost acquisitions. However, the accuracy of signal interpretation is largely dependent on the sensor positioning on the chest. This study provides a quantitative analysis of both the morphological variations and the delay caused due to variation in sensor positions in SCG recordings on the chest. The findings highlight the importance of carefully selecting the location of SCG sensors when monitoring cardio-mechanical functions. Our future researches are focussed on comparing these findings with the gold standard echocardiographic results to provide a comprehensive methodological framework for sensor placement in detecting various cardiac events which in turn can improve the accuracy of SCG-based cardiovascular disease diagnosis algorithms.

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Address for correspondence:

Deboleena Sadhukhan.
Institut Langevin, 1 Rue Jussieu - 75005 Paris, France.
deboleena.rainbow@gmail.com