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# Beat-to-Beat Estimation of LVET and QS2 Indices of Cardiac Mechanics from Wearable Seismocardiography in Ambulant Subjects

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*Abstract*— **Seismocardiogram (SCG) is the measure of the minute vibrations produced by the beating heart. We previously demonstrated that SCG, ECG and respiration could be recorded over the 24h during spontaneous behavior by a smart garment, the MagIC-SCG system. In the present case study we explored the feasibility of a beat-to-beat estimation of two indices of heart contractility, the Left Ventricular Ejection Time (LVET) and the electromechanical systole (QS2) from SCG and ECG recordings obtained by the MagIC-SCG device in one subject. We considered data collected during outdoor spontaneous behavior (while sitting in the metro and in the office) and in a laboratory setting (in supine and sitting posture, and during recovery after 100W and 140W cycling). LVET was estimated from SCG as the time interval between the opening and closure of the aortic valve, QS2 as the time interval between the Q wave of the ECG and the closure of the aortic valve.**

**In every condition, LVET and QS2 could be estimated on a beat-to-beat basis from the SCG collected by the smart garment. LVET and QS2 are characterized by important beat-to-beat fluctuations, with standard deviations in the same order of magnitude of RR Interval. In all settings, spectral profiles are different for LVET, QS2 and RR Interval. This suggests that the biological mechanisms impinging on the heart exert a differentiated influence on the variability of each of these three indices.**

## I. Introduction

Seismocardiogram (SCG) is the measure of the minute vibrations produced by the beating heart. SCG can be assessed by an accelerometer usually placed on the sternum, and provides information on cardiac mechanics, including the timing of 1) opening and closure of heart valves, 2) filling and contraction of heart chambers and 3) blood flow ejection [1]. SCG has a magnitude of few milli-gs, and can thus be estimated whenever the subject stays relatively still, because major body accelerations induced by walking or physical activity would completely mask the limited amplitude of heart vibrations.

In 2012 we demonstrated that SCG, together with ECG and respiration, can be recorded over the 24h during spontaneous behavior by using a smart garment, the MagIC-SCG system.

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Figure 1 - The MagIC-SCG system. Left panel: the vest and the pocket containing the electronic board; mid panel: the electronic board; right panel: particular of the textile electrodes for ECG recording.

In the present case study we explored the feasibility of a beat-to-beat estimation of two indices of heart contractility, the Left Ventricular Ejection Time (LVET) and the electromechanical systole (QS2) from SCG and ECG recordings obtained by the MagIC-SCG device. This was done by collecting data during outdoor spontaneous behavior and in the laboratory setting.

## II. Methods

### A. The MagIC-SCG smart garment

MagIC-SCG system is composed of a cotton vest that embeds textile sensors for the ECG and respiratory assessment, and an electronic module. The module, located in a pocket of the vest that guarantees its contact with the sternum (fig. 1), includes a three axis accelerometer for movement and SCG assessment, a memory card for data storage and a Bluetooth connection for data transfer to an external device. All data are sampled at 200Hz on 12 bits. SCG was estimated from the sagittal (dorso-ventral) component of the accelerometer. Further details on this device and SCG assessment can be found in [2, 3].

### B. The experimental protocol

Two different data sets were recorded in one healthy subject (age: 26 years) to explore the feasibility of the beat-to-beat extraction of LVET and QS2 from the SCG signal: 1) during spontaneous behavior in daily life (DL), and 2) in the laboratory environment (LAB) during postural changes and early recovery after physical exercise. Specifically:

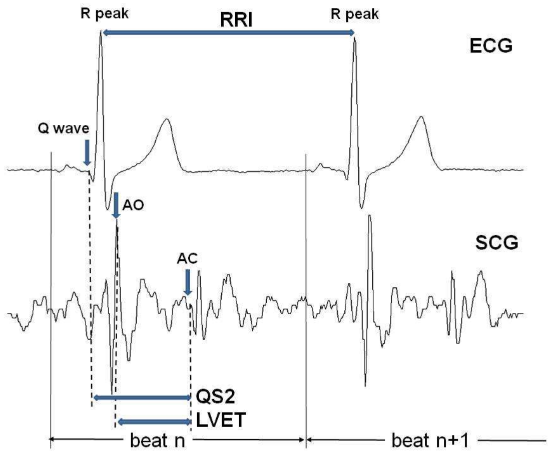

Figure 2 - Example of collected signals and indication of fiducial points considered for the RRI, QS2 and LVET extraction. AO= Aortic valve opening, AC= Aortic valve closure (according to Crow et al. [1])

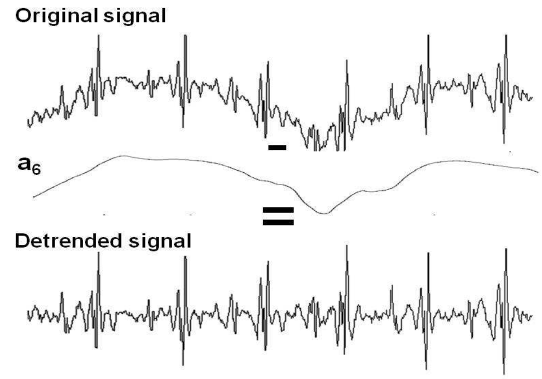

Figure 3 - Schematization of the wavelet-based procedure for the removal of the baseline wandering from the SCG signal. The original series was decomposed by using the db4 mother wavelet, then the level 6 approximation component ($a_6$) was subtracted from the original signal.

DL - The recruited subject previously performed a 24h recording by the MagIC-SCG device during a standard working day [2]. The recording started at 8 a.m. In the present study we considered two paradigmatic data segments excerpted from the file: 1) while the subject was sitting in the metro on his way to the office (**DL-Metro**, 46 beats), and 2) while he was working at the computer in the office (**DL-Office**, 187 beats).

LAB - In our laboratory, data were collected in the same subject by the smart garment in supine (**LAB-sup**, 292 beats) and in sitting (**LAB-sit**, 158 beats) posture. Subsequently, the subject sat on a recumbent cycle ergometer and, after having pedaled at 100W for 1.5 minutes, a recording was made for 2 min during recovery (**LAB-rec100**, 148 beats); then he pedaled again at 140 W for 1.5 minutes, and an additional recording was made during the second recovery (**LAB-rec140**, 126 beats).

*C. Data analysis*

In all data segments, the quality of ECG and SCG signals was good and suitable for a beat-to-beat analysis without requiring any data averaging to reduce noise (see an example in fig. 2). Sometimes, respiration produced a slow wandering of the SCG baseline. In this case the respiratory component was removed from SCG by a wavelet-based filtering procedure previously described [2] and here schematized in fig. 3. Then, the detrended data segments were split into individual heart beats, each starting 200 ms before the ECG R peak; for each beat, RR Interval, RRI, was estimated as the interval between two consecutive R peaks, LVET and QS2 were estimated as follows:

LVET was measured as the time interval between the SCG peaks associated with the opening and closure of the aortic valve, AO and AC, respectively, according to the nomenclature proposed by Crow et al. [1] and illustrated in fig.2.

QS2 was measured as the time interval between the beginning of the Q wave in the ECG and the closure of the aortic valve, AC (in the past estimated by the second heart sound, S2) (fig. 2).

In biological terms, both LVET and QS2 are indices of heart contractility and are influenced by the autonomic nervous system. In short, LVET is the time duration of the aortic valve opening, while QS2 is the summation of LVET and pre-ejection period, PEP. The latter includes a) the time interval from the start of the electrical stimulation of the ventricle (corresponding to the onset of ECG Q wave) to the start of the mechanical ventricle contraction, and b) the time length of the ventricle contraction preceding the opening of the aortic valve. It has been suggested that abnormal values of the ratio between the QT interval in the ECG and QS2 could be a major marker of myocardial failure [4]. Also an excessive lengthening of QS2 with respect to the diastolic time, i.e. the ventricle relaxation time, measured as (RRI - QS2) was reported to be another marker of ventricular dysfunction [5].

The above indices, together with RRI have been estimated through a semi-automatic procedure based on a software package specifically developed in our lab. The computer program, after an initial learning phase, automatically localized the relevant fiducial points in the ECG (Q and R waves) and the SCG (AC and AO) from each heart beat. An operator supervised the analysis, and manually modified the few erroneous identifications. On this basis, separate beat-to-beat series were obtained for RRI, LVET and QS2. Mean value, standard deviation (SD), coefficient of variation (CV, i.e. SD/mean) and power spectral density (PSD) as obtained by the Fast Fourier Transform were estimated from each series. PSD was then integrated in the Low Frequency (0.04-0.15 Hz) and High Frequency (0.15-0.4 Hz) bands, traditionally considered for the assessment of the cardiac autonomic control by the analysis of heart rate variability [6]. The power in the HF band, influenced by respiratory activity, and the LF/HF power ratio are respectively assumed to reflect the level of parasympathetic and sympathetic drive to the heart [6].

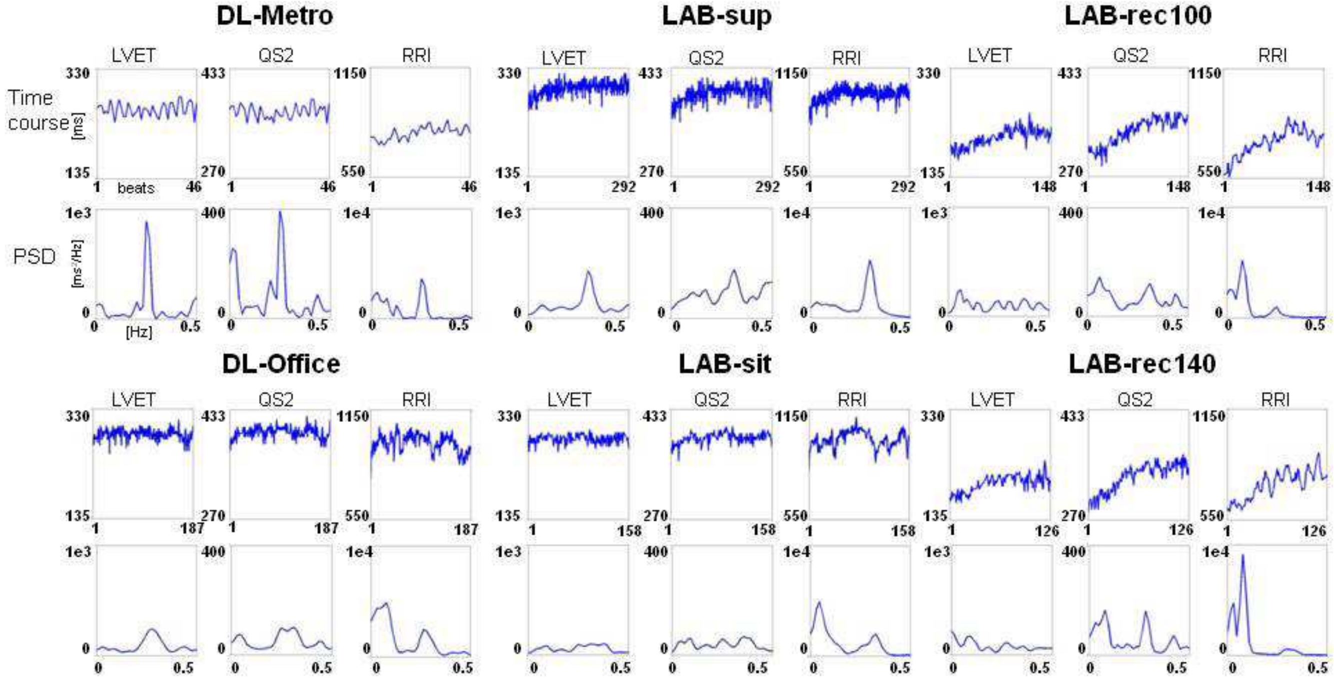


Figure 4 - LVET, QS2 and RRI measured in each behavioral condition. In each inset, the upper panel represents the time course of the index and the lower panel illustrates the respective power spectral density.

Additionally, to evaluate the linear interaction between RRI, LVET and QS2 dynamics, we estimated the coefficients of determination, $r^2$, resulting from the RRI vs. LVET, and RRI vs. QS2 regression analyses.

## III. Results

In every behavioral condition LVET and QS2 could be estimated on a beat-to-beat basis from the SCG collected by the smart garment. Time profiles and spectra of LVET, QS2 and RRI are illustrated in fig. 4. The respective variability parameters are reported in Table I.

### *A. Magnitude of LVET and QS2 beat-to-beat variability*

LVET and QS2 displayed important beat-to-beat fluctuations over time. Indeed, the CV values indicate that, when normalized by the respective means, SD of RRI, LVET and QS2 are in the same order of magnitude, with QS2 displaying CV values slightly reduced with respect to LVET.

### *B. Spectral characteristics*

Graphs in fig. 4 show that in each behavioral condition LVET, QS2 and RRI spectra are different each other in terms of power magnitude and power distribution along the frequency axis (see quantitative values in Table I), even if some common feature can also be observed. In particular, in most spectra there is a clear influence of respiration (resulting in a power peak in the HF band), although the relative contribution of this component with respect to the other spectral components is different for LVET, QS2 and RRI. The second common feature of spectra refers to the increase in the LF/HF power ratio observed in all the three indices on shifting from the sitting posture (condition characterized by a reduced sympathetic drive to the heart) to the post-exercise recovery (condition where the sympathetic

TABLE I - Parameters of Variability for LVET, QS2 and RRI in the Different Behavioral Conditions as Obtained by the SCG

| | **DL-Metro** | **DL-Office** | **LAB sup** | **LAB sit** | **LAB rec100** | **LAB rec140** |
|---|---|---|---|---|---|---|
| **LVET** | | | | | | |
| *mean* | 258 | 284 | 292 | 278 | 205 | 197 |
| *SD* | 11.9 | 10.2 | 13.0 | 8.2 | 16.0 | 17.1 |
| *CV* | 0.05 | 0.04 | 0.04 | 0.03 | 0.08 | 0.09 |
| *LF* | 2.2 | 4.8 | 8.4 | 5.6 | 13.3 | 9.8 |
| *HF* | 44.5 | 27.9 | 37.1 | 17.7 | 17.8 | 8.2 |
| *LF/HF* | 0.05 | 0.2 | 0.2 | 0.3 | 0.7 | 1.2 |
| $r^2$ | 0.001 | 0.060 | 0.176 | 0.007 | 0.574 | 0.300 |
| **QS2** | | | | | | |
| *mean* | 367 | 396 | 392 | 388 | 336 | 331 |
| *SD* | 9.5 | 8.7 | 12.3 | 8.0 | 19.9 | 20.5 |
| *CV* | 0.03 | 0.02 | 0.03 | 0.02 | 0.06 | 0.06 |
| *LF* | 3.0 | 3.6 | 7.5 | 4.0 | 11.7 | 12.6 |
| *HF* | 25.3 | 14.3 | 22.3 | 10.5 | 9.2 | 9.4 |
| *LF/HF* | 0.1 | 0.3 | 0.3 | 0.4 | 1.3 | 1.4 |
| $r^2$ | 0.003 | 0.058 | 0.159 | 0.056 | 0.709 | 0.700 |
| **RRI** | | | | | | |
| *mean* | 791 | 968 | 1004 | 986 | 742 | 740 |
| *SD* | 33.7 | 50.6 | 43.3 | 47.2 | 75.1 | 76.4 |
| *CV* | 0.043 | 0.052 | 0.043 | 0.048 | 0.101 | 0.103 |
| *LF* | 99.3 | 310.6 | 108.4 | 220.8 | 343.8 | 503.8 |
| *HF* | 201.5 | 232.9 | 370.0 | 205.0 | 71.9 | 35.7 |
| *LF/HF* | 0.5 | 1.3 | 0.3 | 1.1 | 4.8 | 14.1 |

SD = standard deviation; CV= coefficient of variation; LF=Power in the Low Frequency band (see text); HF= Power in the High Frequency band (see text); r2= coefficient of determination of the linear regression between the given variable and RRI. Mean and SD are expressed in ms, LF and HF in $ms^2$

drive is significantly increased). The LF/HF increment during physical activity is expected in RRI, because this finding has been repeatedly reported in literature, but it has never been described for LVET and QS2. This result is in line with the reported sympathetic influence on LVET and QS2. Parenthetically, LF/HF was unexpectedly lower while the subject was sitting in the metro than when he was in the office or in the lab. This might indicate that in this subject train traveling is less stressful than computer programming (in the office) or being engaged in experimental activities (in the laboratory).

### *C. Interaction with RR interval*

On the shift from one condition to the other, the *mean values* of LVET and QS2 change in the same direction of the RRI mean value. Conversely, if we consider the *beat-to-beat values,* the $r^2$ parameter obtained from the linear regression analysis among indices, indicates that in sitting posture (DL-Metro, DL-Office, and LAB-sit) less than 6% of the LVET and QS2 variability is explained by a linear correlation with RRI (see Table I). This correlation increases to about 15% in supine position and dramatically augments in the early recovery after exercise (up to 70%).

## IV. Discussion and Conclusion

Results of this case study provides a first confirmation on the feasibility of a beat-to-beat estimation of LVET and QS2 through the SCG assessment by the MagIC-SCG smart garment. Such an assessment was possible both in controlled conditions and, more importantly, in daily life during spontaneous behavior.

Beat-to-beat variability of LVET and QS2 has been poorly addressed so far. Thus, notwithstanding our data have been collected in one subject, some features of LVET and QS2 variability appeared in our study and not yet reported in literature deserve to be mentioned:

1) LVET and QS2 displayed important beat to beat fluctuations, with dynamics having a magnitude comparable with the RRI variability (when the SDs were normalized by the respective mean values).

2) Similarly to RRI, also LVET and QS2 appear to be influenced by respiration as demonstrated by the presence of a power peak at the respiratory frequency in most spectra. Moreover, the LH/HF power ratio of LVET and QS2 parallel the behavior of the LF/HF index in RRI, and importantly increased on the shift from the quiet sitting position to the acute recovery post exercise. This finding provides evidence of the reported sympathetic influence on LVET and QS2.

3) Apart from the similarities reported above, in all settings the spectral profiles and values of the LF/HF power ratio are different for LVET, QS2 and RRI. This suggests that the three indices are not under the same degree of influence of the biological mechanisms impinging on the heart. Rather, each of them might contain specific biological information on the cardiac function that can be exploited to obtain a more comprehensive picture of the cardiovascular function.

4) Since LVET and QS2 reflect events occurring within a single heart cycle, a certain correlation with the RRI can be expected. The observed similar trends in the *mean values* of LVET, QS2 and RRI on shifting from one condition to the other is in line with the hypothesis of a strong correlation among these indices on a *long time scale*. Conversely, the analysis of the *beat-to-beat values* indicates that the strength of the *short term correlation*, as quantified by $r^2$, between RRI vs. LVET and between RRI vs. QS2 may be relatively weak in quiet behavioral conditions, and becomes important under physical activity.

Two limitations of the study are acknowledged. First, as already mentioned, data have been collected in one subject. This choice was due to the pilot nature of the study, and the preliminary findings we obtained should be confirmed on a larger population. The second limitation regards the sampling frequency of the signals (200Hz). We cannot exclude that the current 5 ms temporal resolution might mask possible subtler aspects of LVET and QS2 variability. We are currently tuning our system and in a short time we should be able to increase the temporal resolution of the measurements and explore also finer beat-to-beat changes of cardiac mechanics indices.

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