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Empirical Mode Decomposition of Respiratory Inductive Plethysmographic signals for stroke volume variations monitoring: respiratory protocol and comparison with impedance cardiography

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***Abstract*— We investigate Respiratory Inductive Plethysmography (RIP) to estimate cardiac activity from thoracic volume variations and study cardio-respiratory interactions. The objective of the present study is to evaluate the ability of RIP to monitor stroke volume (SV) variations, with reference to impedance cardiography (IMP). Five healthy volunteers in seated and supine positions were asked to blow into a manometer in order to induce significant SV decreases. Time-scale analysis was applied on calibrated RIP signals to extract cardiac volume signals. Averaged SV values, in quasi-stationary states at rest and during the respiratory maneuvers, were then estimated from these cardiac signals and from IMP signals simultaneously acquired. SV variations between rest and maneuvers were finally evaluated for both techniques. We show that SV values as well as SV variations are correlated between RIP and IMP estimations, suggesting that RIP could be used for SV variations monitoring.**

I. Introduction

Continuous monitoring of vital signs is an emerging concept of healthcare and implies to use non-invasive techniques. Progress in sensor and communication technologies, as well as in data processing, have helped the development of monitoring and diagnostic devices [1]. These devices, often implemented in electronic textiles, allow an easier practice of personalized health care. Most of proposed systems are dedicated to one specific type of physiological sign, cardiac or respiratory [2], mainly for technologic simplification concerns. Respiratory Inductive Plethysmography (RIP) has already been tested for respiratory rate monitoring [1, 3] and used for ventilatory function assessment [4-6]. Our challenge here is to investigate RIP for cardio-respiratory function tests and to propose an integrated physiological tool for the study of cardio-respiratory interactions, which are both of physiological and clinical interest [7-9]. The peripheral nature of RIP measurements generates a complexity in the signal due to multiple physiological interactions. Our aim is to extract new information from these physiological interferences, and in particular to estimate cardiac stroke volumes (SV), so as to jointly monitor cardiac and respiratory volumes.

Time-scale analysis is considered for this extraction and more precisely Empirical Mode Decomposition (EMD). EMD is a nonlinear local signal processing technique for adaptively representing signals as sums of zero-mean AM-FM components [10]. It allows to extract all the oscillatory modes embedded in a signal without any requirement of stationarity or linearity of the data. Studies of the literature [11-14] have already demonstrated the interest of EMD or its variants [15-16] in the cardio-respiratory context. In particular, [13] showed that Ensemble Empirical Mode Decomposition (EEMD) was a promising nonlinear method for efficient cardiogenic oscillations extraction in simulated CR signals. In [14], Complementary Ensemble Empirical Mode Decomposition provided satisfactory results for the extraction of cardiac volumes from RIP signals.

In this preliminary study [14], for 4 subjects asked for calm respiration, SV estimations from RIP were compared with estimations obtained from impedance cardiography (IMP) measurements, a non-invasive SV measurement method validated against invasive gold-standard techniques [17-19]. In [14], we showed satisfactory correlation between RIP and IMP and limits of agreement between the 2 types of measurements satisfying the required criterion for the acceptance of a new cardiac technique [20]. However, we observed systematic under-estimation of SV values estimated with RIP. This suggested that RIP technology should rather be used for SV variations monitoring.

In the present study, we propose a specific respiratory protocol assumed to induce significant variations of SV and we pursue the comparison of RIP estimations with IMP. [21] showed that the Valsalva maneuver (VM) performed in the supine and seated postures induced a significant SV decrease. Indeed, the VM produces transient but dramatic alterations in venous return, SV, and arterial pressure, due to an increase of the intrathoracic and intra-abdominal pressure [22]. In order to make manipulations easy to performed, reproducible, and quantifiable, we chose an adapted VM for our study. Subjects were asked to blow into a manometer in order to maintain a specific pressure.

II. Material and Methods

A. Subjects and experimental protocol

Five healthy volunteers (1 female and 4 males, aged from 23 to 27) participated in the study. They provided informed consent and the study was approved by the relevant ethics committee (CHU Grenoble). Subjects, first in seated position then in supine position, were asked to alternate spontaneous calm respiration during 2-3 minutes (noted as rest) and respiratory maneuvers. The maneuvers consisted in blowing

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in a U-bend manometer while holding a pressure higher than 30 cmH_2O, one maneuver lasting around 30 seconds. Each couple rest/maneuver was repeated 5 times. Participants were asked not to move during recording in order to avoid any motion artifacts on signals.

B. Recorded signals

Thorax and abdomen cross sectional area changes were recorded with a computer-assisted RIP vest (Visuresp®, RBI, Meylan, France). During a few minutes at the beginning of the recordings both in seated and supine positions, breathing was also simultaneously recorded with a flowmeter (Fleish head no.1) and a differential transducer (163PC01D36, Micro Switch) placed on a face mask. Electrocardiogram (ECG) was also recorded during the whole recordings.

Simultaneous measurements were made with a thoracic electrical bioimpedance monitor (PhysioFlow™, Manatec Biomedical, Paris, France). This device is based on analysis of instant impedance variations using 6 electrodes for ECG measurement and thoracic impedance cardiograph. The electrodes were taped to the skin under the RIP vest. The beat-to-beat stroke volumes values ($\mathbf{SV_{IMP}}$) were continuously estimated from the impedance signal by the PhysioFlow system.

The synchronous acquisition of all signals, sampled at 100 Hz, was realized using a PowerLab data acquisition system and Chart software (ADinstruments).

C. Methods

For each position (seated or supine), starting from the thorax and abdomen cross sectional area changes and the airflow, the method used in [6] was applied to obtain a calibrated respiratory inductance plethysmographic volume signal (V_{RIP}).

Empirical Mode Decomposition (EMD) was then applied on sequences of V_{RIP} signals. We applied a variant of EMD algorithm, named Complementary Ensemble Empirical Mode Decomposition (CEEMD) [16]. EMD is an iterative fully data-driven processing method to decompose a signal into its oscillatory components named Intrinsic Modes Functions (IMF) from the highest embedded frequency to the lowest one. CEEMD is based on the addition of white noise to the original signal x before performing EMD to make the scales uniformly distributed. For CEEMD, each white noise sample is used twice: for a collection $(n_i)_{1\leq i\leq N}$ of N white noises, EMD is applied to each $x+n_i$ and each $x-n_i$. For a given scale, the N resulted IMFs are then averaged to converge towards the true IMF. CEEMD was applied on sequences of V_{RIP} signals, with N=100 white noise segments and a signal-to-noise ratio of 0.6. For each maneuver repetition, we considered a 20-second stationary sequence at rest just before the maneuver, denoted as a rest sequence, and a 20-second sequence including the respiratory maneuver, denoted as a maneuver sequence.

Fig.1 shows the result of CEEMD application to one rest sequence of one V_{RIP} signal. We considered that IMF_1 and IMF_2 were likely composed of noise, the cardiac signal was spread over IMF_3, IMF_4, and IMF_5, and the remaining IMFs concerned respiration and other body movements. This physiological attribution of IMFs was confirmed, by visual inspection, for all sequences (rest and maneuver) of each subject in both positions. The robustness of this attribution will be analyzed in a further study.

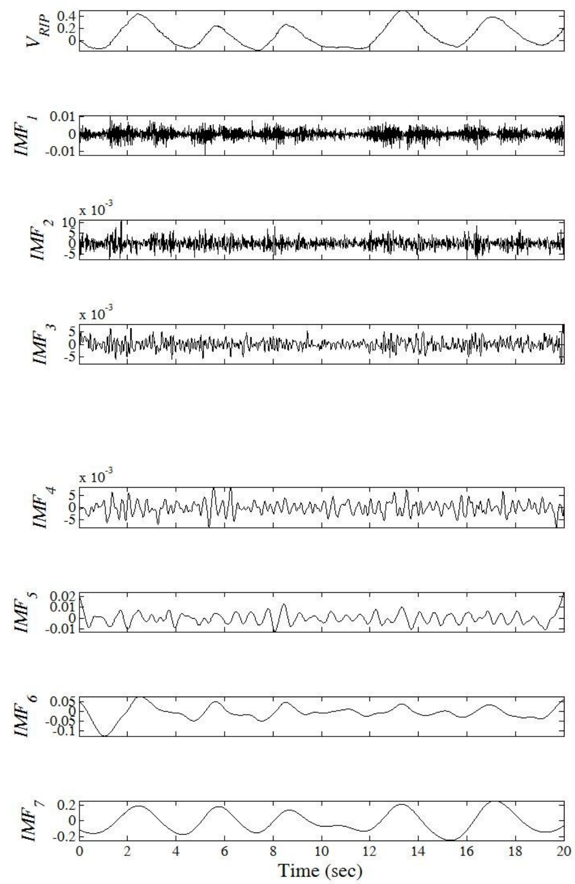

Figure 1. IMF_{1-7} obtained after CEEMD applied on one rest sequence of one V_{RIP} signal. Further IMF are not shown.All units are in liters.

Therefore we defined the extracted cardiac signal, noted V_h, as the sum of the cardiac IMFs (3 to 5). For the rest sequence processed in Fig.1, the V_h signal can be observed in Fig.2. From the extracted cardiac signals, we estimated beat-to-beat stroke volumes, noted $\mathbf{SV_{RIP}}$, as the difference between maximum and minimum of each cardiogenic oscillation [23], detected by the R waves of the ECG. This provided a continuous estimation of beat-to-beat $\mathbf{SV_{RIP}}$ values, in parallel with that determined by impedance cardiography ($\mathbf{SV_{IMP}}$). For both $\mathbf{SV_{RIP}}$ and $\mathbf{SV_{IMP}}$, an average over 12 consecutive cardiac cycles, in quasi-stationary state (Fig. 2), was then realized for each 20-second sequence.

It is noteworthy that each SV value obtained for a maneuver sequence could be associated to the SV value of the preceding rest sequence. Since the investigated protocol aimed at inducing diminution of SV between rest and maneuver and since impedance measurement was considered as the reference in this article, we eliminated from the study a few rest/maneuver couples where no SV diminution was observed on impedance. This was mainly due to a bad realization of the maneuver. The number of averaged values of $\mathbf{SV_{RIP}}$ and $\mathbf{SV_{IMP}}$ was finally N=92. Moreover, for each couple rest/maneuver all subjects included and for each technique of measurement, a relative variation $\mathbf{vSV_{RIP}}$ (resp. $\mathbf{vSV_{IMP}}$) was computed for RIP measurement (resp. for impedance measurement).

$$\mathbf{vSV_x}(i) = \frac{SV_x(\text{rest}_i) - SV_x(\text{maneuver}_i)}{SV_x(\text{maneuver}_i)}$$

where x=*RIP* or *IMP* and i=1:N.

Finally, a comparative study was carried out on the averaged values of $\mathbf{SV_{RIP}}$ and $\mathbf{SV_{IMP}}$, as well as on the variations $\mathbf{vSV_{RIP}}$ and $\mathbf{vSV_{IMP}}$.

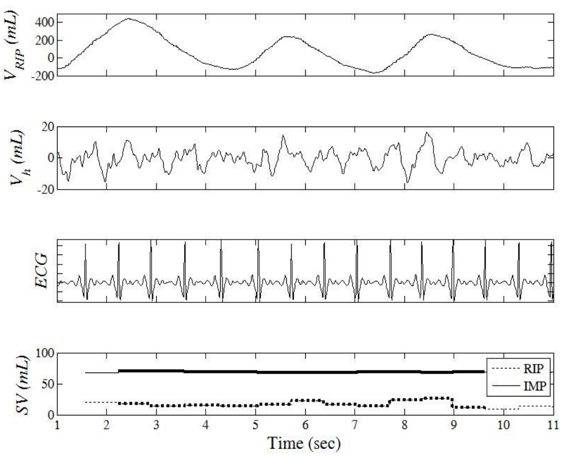

Figure 2. Cardiac signal V_h extracted from the previous rest V_{RIP} signal, as the sum of IMFs 3 to 5, considered as cardiac. For better legibility of the figure, we limit to 10 seconds. Simultaneous ECG signal indicates each cardiac cycle. Beat-to-beat $\mathbf{SV_{RIP}}$ and $\mathbf{SV_{IMP}}$ estimated for this sequence and the 12 cardiac cycles (in bold) considered for the SV average.

III. RESULTS

All sequences and subjects taken together, a positive correlation is found between $\mathbf{SV_{RIP}}$ and $\mathbf{SV_{IMP}}$ (r=0.8, N=92, $p < 0.001$, Fig. 3). This coefficient is satisfactory compared to other values reported in the literature [24] and similar to the one of our previous study (r=0.76 in [14]). We also observe a systematic under-estimation of $\mathbf{SV_{RIP}}$ compared to $\mathbf{SV_{IMP}}$ (Fig. 3 and lower graph of Fig. 2). All these results are comparable to [14] extending them to the wider range of SV values induced by the proposed experimental protocol.

The respiratory maneuvers consisting in blowing in a U-bend manometer had effects similar to the standard VM ones. They induced some falls of SV between rest and maneuvers; these diminutions are clearly observed both for impedance and RIP estimations. SV values are separated in 2 correlation plots in Fig. 4 depending on the position of the subjects; rest and maneuvers values are also differentiated. For both seated and supine positions, we observe correlated variations of $\mathbf{SV_{RIP}}$ and $\mathbf{SV_{IMP}}$. SV values can be discriminated in 2 groups according to the condition (rest or maneuver). The groups are positioned along the correlation lines, indicating a decrease of SV value for both techniques. However, the analysis of SV relative variations (Table I) shows higher values for $\mathbf{vSV_{RIP}}$ than for $\mathbf{vSV_{IMP}}$.

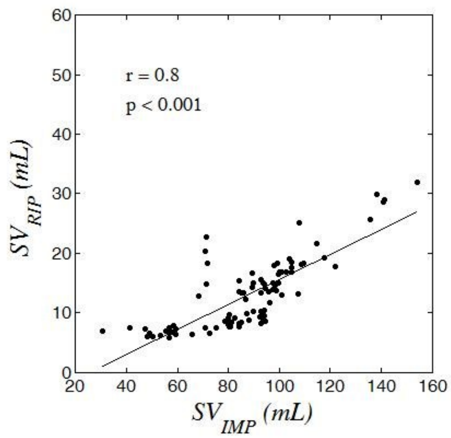

Figure 3. Correlation plot between averaged values of $\mathbf{SV_{RIP}}$ and $\mathbf{SV_{IMP}}$ for all subjects in seated and supine positions at rest and during maneuvers (N=92).

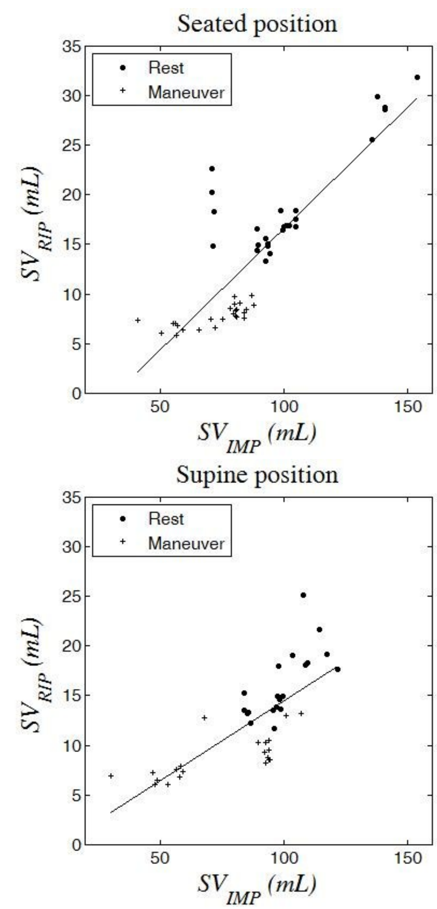

Figure 4. Correlation plot between $\mathbf{SV_{RIP}}$ and $\mathbf{SV_{IMP}}$ for all subjects. Rest and maneuver SV values are differentiated for both seated (top) and supine (bottom) positions.

TABLE I. AVERAGED VALUES OF SV RELATIVE VARIATIONS ON ALL SUBJECTS DEPENDING ON POSITIONS AND MEASUREMENT TECHNIQUES

	vSV_{RIP}	vSV_{IMP}
Seated position	56 %	25 %
Supine position	43 %	24 %

IV. DISCUSSION

In accordance with our preliminary study [14], the results demonstrate that SV values can be estimated from cardiac activity present on Respiratory Inductive Plethysmography signals and are correlated with impedance technique, considered as reference. The bias between $\mathbf{SV_{RIP}}$ and $\mathbf{SV_{IMP}}$ indicates an under-estimation of the RIP estimations, for which several explanations can be proposed. First, during the RIP measurements, the location of the thoracic and abdominal measures is not optimal to capture the cardiac thoracic movements [23]. Second, part of the cardiac contraction is converted into airflow instead of thoracic movements [25]. Finally, one explanation can come from the signal processing applied on V_{RIP}. After CEEMD on V_{RIP}, the reconstruction of the cardiac volume signal implies to add up cardiac IMFs. We have chosen to sum IMFs 3 to 5, but it appears that IMF_6 could be not only respiratory but may contain cardiac information which has not correctly been decomposed by CEEMD. Improvement of the algorithm is therefore currently under process.

Nevertheless, when considering the variations of SV, this question of under-estimation is laid aside. In the present study, with a specific respiratory protocol inducing significant diminutions of SV values, we show that RIP is able to follow SV variations as IMP does. However, it seems that both technologies do not have the same sensibility to this maneuver. This motivates the possible extension of the study to test other maneuvers and physiological conditions.

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