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Study of Electrode Locations for Joint Acquisition of Impedance- and Electro-cardiography Signals

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***Abstract*— ICG (impedance cardiography) and ECG (electrocardiography) provide important indications about functioning of the heart and of overall cardiovascular system. Measuring ICG along with ECG using wearable devices will improve the quality of health monitoring, as ICG points to important hemodynamic parameters (such as time intervals, stroke volume, cardiac output, and their variability). In this work, various electrode locations (12 different setups) have been tested for possible joint ECG & ICG data acquisition (using the same electrodes) and signal quality has been evaluated for every setup. It is shown that, while typically ICG is acquired over the whole thorax, a wrist-based joint acquisition of ECG & ICG signals can achieve acceptable signal quality and therefore can be considered in wearable sensing.**

I. Introduction

Several classical methods exist for monitoring heart rate, which is a crucial body vital sign along with respiratory rate, blood pressure and temperature. The most popular is electrocardiography, which has been available for a long time. Also, developments about impedance cardiography (ICG) have emerged - capable of assessing the status of the cardiovascular system. The electrocardiogram (ECG) presents the electrical activity of the heart, while ICG denotes the mechanical pumping activity of the heart [1], representing the same information in different modalities. Investigations on both methods rely on a classical and predefined placement of electrodes. The co-utilization of ECG and ICG methods allows to determine specific time intervals and characterize the overall operation of the heart, relying on both mechanical and electrical activity of the heart.

ICG is a known method for determining hemodynamical parameters. It has been used since the 1960s [2] to estimate the heart rate (HR) and its variation (HRV), the Cardiac Output (CO), and the Stroke Volume (SV), but also various time-related parameters, such as Left Ventricular Ejection Time (LVET) and Pre-Ejection Period (PEP). Portable solutions have been developed to monitor these hemodynamic parameters [3].

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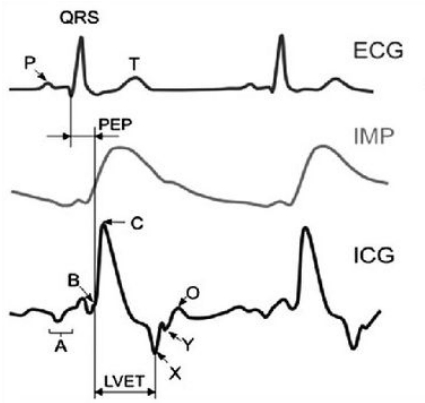
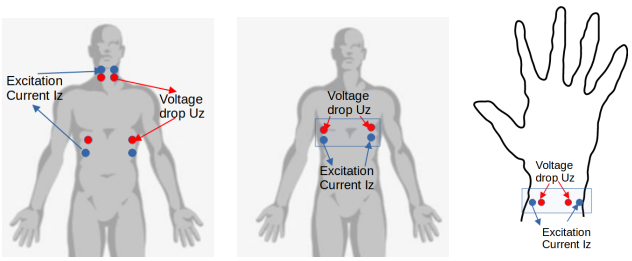


Fig. 1. Typical ECG and ICG waveforms [3]



(a) Classical ICG measurement setup

(b) Wearable belt based ICG measurement setup

(c) Wrist EBI measurement setup

Fig. 2. Various ICG measurement setup configurations

Einthoven's triangle, known for about 120 years, defines the standard lead locations for ECG measurements. The electrode placement strategies are elaborated since then to observe a fully complex and detailed signal. The prerequisite is the location of the heart in the center of the triangle. The recognizable pattern of ECG signal is classically identified by assigning five deflections in the detected signal: P, Q, R, S, and T wave.

Example waveforms of ECG and ICG are given in Fig. 1. As described below and illustrated in Fig. 2a, ICG and ECG signals are traditionally acquired from the thoracic region. However, the human body is a complex entity, providing the option to also acquire the relevant data from the chest (Fig. 2b) or even from the wrist (Fig. 2c).

The simplest way of monitoring hemodynamic parameters is detecting the pulse. This oldest method has been rebuilt in modern devices through different means, like electrical bioimpedance (EBI), bioelectricity (ECG), or optical

(photoplethysmography (PPG)). However, such signals are sophisticated, presenting a variety of key points that represent the operation of the heart.

However, the classical electrode locations for monitoring ICG and ECG are causing the devices to be bulky or very complex. To reduce the size of the device or utilized area on the body surface, new electrode locations need to be chosen – presumably located more densely. This, in turn, is expected to lower the quality of the measured signals, that contain less information or present nonlinearities compared to the actual stroke volume and the measured value of EBI.

Based on its noninvasive means, ICG fits perfectly into the framework of the term: wearability – the incorporation of electrodes and respective electronic circuitry into smart wearables for on-site patient monitoring. For monitoring ICG, electrodes are attached to the skin surface and currents of high frequency and low amplitude are applied onto the thorax. The resulting voltage is recorded. This signal is amplitude-modulated, incorporating the data of pulsatile changes in the impedance of thorax, expectedly caused by cardiorespiratory system [4].

The wrist is often proposed as a location of modern wearable devices. For example, touching the electrode of a smartwatch with a finger of another hand (like the Apple Watch) is a usual control scheme. Also, the applicability of single-arm singe-lead monitoring of ECG is reported in scientific literature [2], [5], capable of replicating all the key components. However, the signal amplitude is significantly reduced with the diminished volume of the body between the electrodes [6], requiring heavy filtering or advanced denoising strategies.

The co-utilization of electrodes for simultaneously monitoring the ICG and ECG has been reported in the literature. For example, in [7], the number of electrodes for wearable autonomous measurement devices has been reduced to four while identifying hemodynamic feature points in both signals. [8] proposes a patented solution for monitoring ICG and ECG with a shared-electrode configuration. In a laboratory environment, such experiments have been reported, incorporating concurrent utilization of a variety of sensors, like in [9], where the ICG and ECG are detected by using the classical Kubicek method (using band electrodes around the thorax).

However, the recognizability of hemodynamic patterns on the signal is expected to deteriorate when relocating the electrodes to novel non-standard positions. Due to that, the determination of feature points in ICG and ECG, gathered by using coinciding electrode location on the arm has rarely been referred to in the relevant literature, constituting a novel research direction. Still, it is expected that hemodynamic patterns on the monitored ICG can be determined, even in the case of non-classical electrode locations. The current paper studies the possibility of co-utilizing the coinciding electrode locations for monitoring ECG and ICG. The paper also explores the detection of hemodynamic patterns in ICG, in parallel with the ECG monitoring. Various electrode configurations are proposed and evaluated.

II. Methods and Measurement Setup

A. Measurement Devices and Properties

The impedance spectroscope HF2IS, accompanied with transimpedance amplifier HF2TA of Zurich Instruments AG (Zurich, Switzerland), was used as a measurement device. HF2IS approves performing simultaneous measurement of impedance at four distinct frequencies up to 50 MHz [10], with two optional auxiliary inputs. One of them is connected to an external ECG monitor for the concurrent acquisition of respective analog signals. The measurement frequency (typical for ICG) is 100 kHz in this study.

A custom 3-electrode ECG monitoring system is used to gather the data of electrical activity of the heart. The ECG monitor was based on a single-lead heart rate monitor front-end of type AD8232ACPZ from Analog Devices Inc. (Wilmington, MA, USA).

For measurements of ICG and ECG, monitoring electrodes of type 2228 of 3M (Maplewood, MN, USA) were used, because of their firm adhesive foam tape backing.

B. Measurement Method

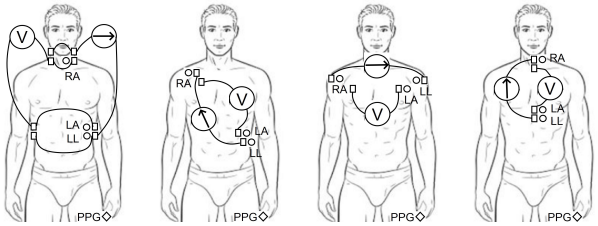
The experimentation with electrode locations for measuring the ICG and ECG was divided into two domains: placed either on the thoracic area (1) or exclusively on the left arm (2). The possibility of utilizing the same electrode locations for determining the ICG and ECG was researched in both cases. Physically separate electrodes were used to pick up ICG and ECG – attached side by side on the skin surface. This approach is explained by the utilization of the single impedance spectroscope without any additional circuitry of signal pick-up – needed for co-usage of the same electrodes. As the electrodes were closely attached, the outcome is comparable and can be considered to imitate the situation when the same electrodes are used.

Implementing the classical Einthoven's triangle necessitates three leads. However, the current research focuses on using a single-lead positive left arm (LA) electrode, right arm negative (RA) electrode approach with the attached third left leg (LL) electrode.

The electrodes for ECG and ICG on the left arm were not located as a pair but at a longer distance in the case of ECG. Specifically, LA electrode was located on the upper arm, while RA and LL were attached to the wrist. The reason for this is the deterioration of the quality of the detected signal in the case of single-arm ECG [5].

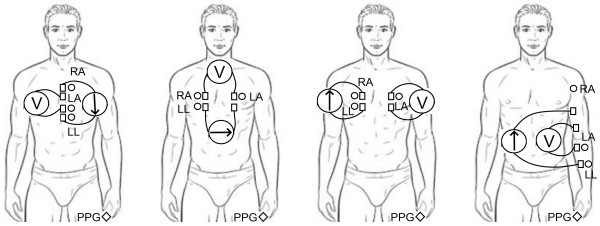
The term ICG is used throughout the whole paper to keep homogeneity and to remark the electrode placement configurations on both cases (thorax and arm): called thoracic electrode placement configurations (TEPC) and arm electrode placement configurations (AEPC), respectively.

The electrodes were attached to the skin surface based on the chosen TEPCs and AEPCs. After 3 minutes, the signal waveforms of ECG and ICG were picked up. The electrodes were attached to the impedance spectroscope through wires as short as possible and crocodile clips.



(a) TEPC-1 (b) TEPC-2 (c) TEPC-3 (d) TEPC-4

Fig. 3. Measurement configuration setups: TEPC-1 to TEPC-4



(a) TEPC-5 (b) TEPC-6 (c) TEPC-7 (d) AEPC-5 (Thorax base)

Fig. 4. Measurement configuration setups: TEPC-5 to TEPC-7 and AEPC-5

The experimental procedures involving humans, described in the current paper, follow the principles outlined in the Helsinki Declaration of 1975, as revised in 2000.

C. Setup for Monitoring ECG and ICG on the Thoracic Area

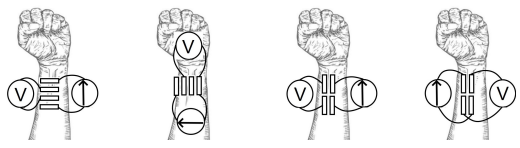
For monitoring ICG on the thoracic area, seven setups were chosen for TEPC. The configurations were either following the classical ICG monitoring electrode locations like TEPC-1 [11] (Fig. 3a); or repeating a literature-based proposal of co-monitoring ICG and ECG like TEPC-2 [7] (Fig. 3b); or intuitive TEPC-3 and TEPC-4 (Fig. 3c-d), where the heart or aorta remains between the electrodes; or presenting new compact approaches that could be suitable for incorporation into a wearable device by forming TEPC-5 to TEPC-7 (Fig. 4a-c).

D. Setup for Monitoring ICG and ECG on the Left Arm

For monitoring ICG on the left arm, five AEPC variants were selected (Fig. 5). Electrodes were either attached distally like AEPC-1; or circularly like AEPC-2; or in mixed configuration respective to the wrist like AEPC-3 and AEPC-4; or covering the whole length of the arm like AEPC-5. In AEPC-1 to AEPC-4, the original size of electrodes was cut to the width of 5 mm to offer a higher electrode density.

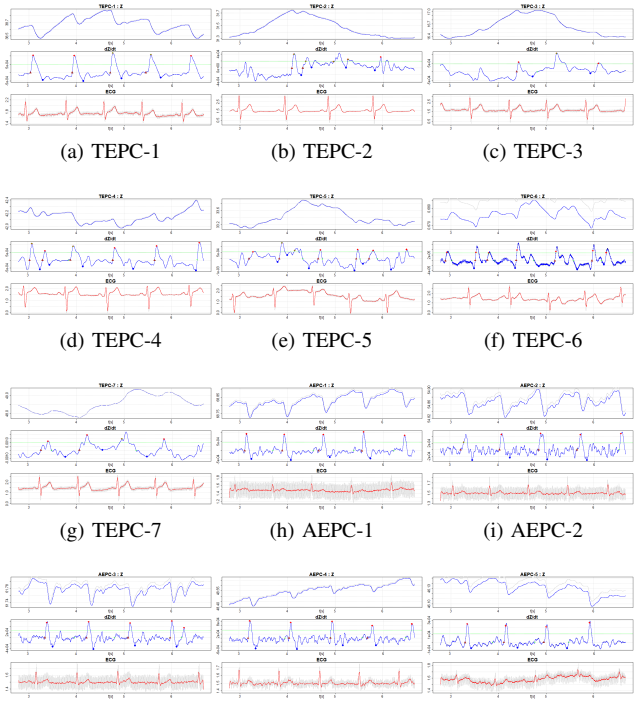
III. Measurement Results and Initial Evaluation

The Impedance (Z) and ECG signals were acquired from a young and healthy male (37 years of age) and saved in the



(a) AEPC1 (b) AEPC2 (c) AEPC3 (d) AEPC4

Fig. 5. Measurement configuration setups: AEPC-1 to AEPC-5



(a) TEPC-1 (b) TEPC-2 (c) TEPC-3

(d) TEPC-4 (e) TEPC-5 (f) TEPC-6

(g) TEPC-7 (h) AEPC-1 (i) AEPC-2

(j) AEPC-3 (k) AEPC-4 (l) AEPC-5

Fig. 6. Measurement results of Z, ICG and ECG for various setups (shown in Ohms for Z and dZ/dt and in Ohms for ECG)

data logs. The single data log was selected for every (of 12) case from series of 3 measurements (after visual comparison of the dZ/dt and ECG graphs, to have more-or-less a similar quality as not all the signals in the sets of three were usable). A Savitzky–Golay low-pass filter was applied on the Z signal (sampling frequency - 1500 Hz, filter order - 5, number of points - 49) before differentiation. The feature points B, C, X (Fig. 1) were determined by a very simple algorithm [12]. Point C is the maximum (extremum over 50% of the peak value threshold), point B is the first zero-crossing to the "left" of C, and point X is the global minimum between two C points.

The Z, dZ/dt, and ECG with estimated B, C, X points of ICG (on dZ/dt plots) are shown in Fig. 6 for all described measurement configurations. In Fig. 6, Z and dZ/dt are shown in Ohms and the ECG in Volts.

The recognizability of these key points largely depends on the electrode placement on the body. The classical electrode placements have been proposed to provide the most sophisticated signal waveforms as possible – like the modified version of the Kubicek method proposed by Sramek [11], based on spot electrodes. In such methods, the electrodes are attached to cover the whole volume of the upper thorax, including the heart and aorta. Tightly set or special EPCs may not cover the whole interesting volume changes in the thorax and the waveforms of ICG may be less informative, need additional processing, or smart analysis. The presence of feature points in the signal of ICG can be used as a base to evaluate the utilized EPCs.

TABLE I

QUALITY ESTIMATION OF THE MEASURED SIGNALS OF ICG: 0,1 - NOT ACCEPTABLE; 2,3 - ACCEPTABLE

No	Conf	Quality	C-C errors	C-X errors	B-C errors	Total periods
1	TEPC-1	**3**	0	0	0	16
2	TEPC-2	1	9	9	8	16
3	TEPC-3	1	2	6	3	9
4	TEPC-4	2	0	0	0	15
5	TEPC-5	1	3	9	1	13
6	TEPC-6	0	11	16	16	27
7	TEPC-7	2	2	12	6	12
8	AEPC-5	2	0	8	2	17
9	AEPC-1	3	0	4	0	17
10	AEPC-2	2	2	7	0	18
11	AEPC-3	2	2	9	0	18
12	AEPC-4	2	0	6	0	17

In the current paper, the focus was on determining the B, C, X points of the ICG needed to estimate the most significant LVET, SV, and CO values of hemodynamics.

IV. DISCUSSION AND QUALITY ESTIMATION OF THE ICG SIGNALS

While the ECG signal is reasonable for all studied cases (see plots in Fig. 6), then the ICG (dZ/dt) signal presents a varying quality. The goodness of ICG signals is estimated in two ways (column "Quality" (1) and columns "C-C errors", "C-X errors", and "B-C errors" (2) in Table I). First, the plots with marked possible B, C, X points are evaluated visually – 0 (*non-recognizable waveform*); 1 (*waveform visible, but not possible to find the feature points*); 2 (*reasonable*); 3 (*strong and clear signal*). These terms were chosen in the frame of the conducted research, where the signals with a quality above 2 (*reasonable*) denote the situation where the algorithm was capable of detecting the feature points.

Secondly, the estimated locations of B, C, X points, the time intervals C-C (cardiac period), B-C, and C-X (forming together the LVET) were estimated and compared against expected values around 900 ms (C-C), 60 ms (B-C) and 200 ms (C-X). Table I reports the count of these erroneous time intervals against the overall number of periods. The proper setups are marked in green (TEPC-1, 4, 7, and AEPC-1 to AEPC-5). As an observation for future work, while the AEPCs can be as good as TEPCs, the C-X interval determination for AEPC presents an error of about 30 to 50 %, probably due to the wrong estimation of X points in some periods.

The AEPC-1 – AEPC-4 configurations have been studied earlier by the TalTech research group to detect the pulse wave through EBI measurements. The effectiveness of selected AEPCs was determined by a FEM model to find the sensitivity distributions and the position of positive and negative regions [13]. The simulation showed the highest sensitivity ratio (and the best result among the four chosen AEPCs in the current study) in the case of AEPC-3 [13]. The results depend on the distribution of sensitivities. The complex and layered structure of the thorax with its vastly varying conductivity largely affects the results. Based on the simulations, it has been claimed that most of the contribution for ICG comes from the skeletal muscle and upper thorax and less than 1% from the aorta [14]. While the representation of the exact sensitivity distribution in the human body is not yet found, the controversy remains – and the gold standard for monitoring the stroke volume is not defined.

V. CONCLUSIONS AND FUTURE WORK

The performed experimentation confirmed that coinciding electrode locations for simultaneous determination of ECG and ICG are highly feasible. Moreover, the variety of electrode locations on the thorax and arm provide waveforms in which the hemodynamic patterns are present. The quality is decent enough to determine the relevant feature points and time intervals. Further research will improve the feature extraction algorithm for X-point. Additionally, to reinforce the presented results, the next step is to acquire complementary statistical data from various persons under different conditions.

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