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Cardiac contractility assessment from arm impedance plethysmography (IPG)

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Abstract. Impedance plethysmography (IPG) is a non-invasive technique for measuring total electrical conductivity of a specific body section and its changes along time. It permits several haemodynamic parameters to be derived including stroke volume, heart rate and cardiac output. The upper arm IPG and control thorax IPG data from 8 cases within the research team was recorded using a commercial IPG & ECG integrated recording system for comparative analysis between the two methods of electrodes placement (arm versus thorax). Three IPG waveform parameters were assessed in the signal averaged IPG (SAIPG), for establishing the signal parametric relation between the conventional thorax-IPG and upper arm-IPG. ECG R-wave event to IPG peak time difference (ms): the average [Arm-IPG timing] - [Thorax IPG timing], was of 37.3ms (±9.5ms SD). Thus, a delay was identified in the 8 cases. The IPG pulse peak amplitude (Ω) in the arm-IPG is about 18.3% (±10.4% SD) of the amplitude of thorax-IPG. Metrics of the mid-amplitude IPG pulse-waveform time width (ms), revealed that the arm-IPG pulse-waveform width is an average of 26.3ms (±10.6ms SD) narrower than thorax-IPG. This initial study shows the feasibility of obtaining a long-term clinical profile of the cardiac contractibility or heart pumping activity from an accessible part of the body, as is the upper arm, by means of a rolling SAIPG signal denoising method.

Keywords: Impedance Plethysmograghy, Arm-IPG, Signal Averaged IPG, SAECG, SAIPG, Cardiac output, Brachial artery, Long-term ICG monitoring, Ambulatory heart contractility method.

Introduction

In the UK one person dies every three minutes from heart and circulatory diseases. This amounts to a quarter of all deaths in the UK. According to the British Heart Foundation there are over 100,000 hospital admissions each year due to heart attacks [1]. Hemodynamic parameters such are cardiac output (CO), and Stroke Volume (SV) are often used to assess the mechanical activity of the heart which can further assess

suspected cardiovascular diseases and congestive heart failure. However, options for obtaining CO and SV include Thermodilution Pulmonary Artery Catheter, Doppler echocardiography as well as others [2]. These Techniques are expensive and require skilled professionals to carry out the procedures. As well as this they cannot be used for real time monitoring as they are discontinuous [3].

Impedance plethysmography (IPG) is a technique for determining and measuring the changes in tissue volumes within the body by measuring the electrical impedance on the body's surface [4]. It works by placing two current and two voltage sensing electrodes on a local or regional position on a limb [5]. When current passes through the tissue it produces a voltage difference between the electrodes, this voltage difference can then be used to calculate the tissues electrical resistance. Changes in the electrical resistance show changes to the blood volume in the area of tissue [6].

The brachial artery is the major artery of the upper extremity. Starting at the teres major muscle (shoulder) and branching off into the ulnar and radial arteries when it reaches the cubital fossa (forearm). The brachial artery supplies blood to the bicep, triceps and coracobrachialis muscle [7]. It is often used for non-invasive blood pressure monitoring, obtaining brachial pulse and providing an access point for radiology procedures [8]. A diagram showing the anatomical localization of the brachial artery in the left arm [17] is depicted in Figure 1.

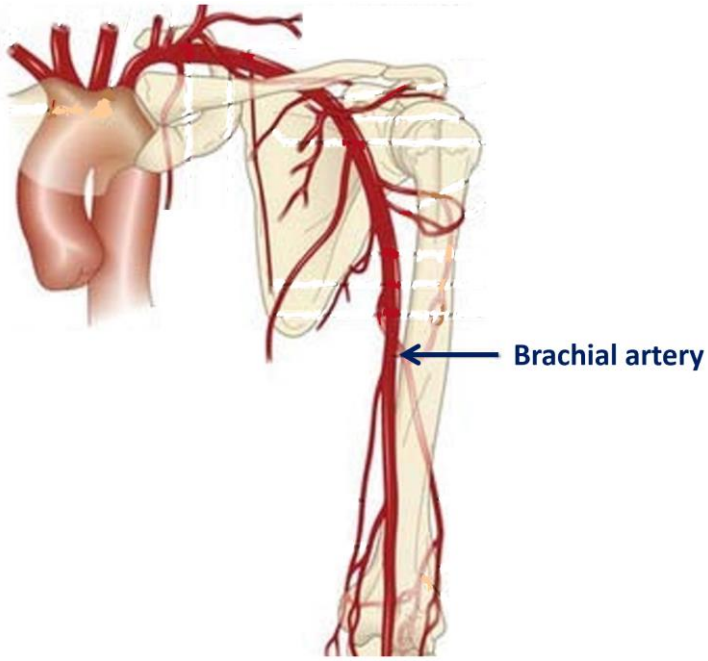


Figure 1. Anatomical localization of the brachial artery in the upper-arm.

Acquiring IPG signals from the upper-arm offers several advantages over Thorax derived IPG signals including fewer signal sources, when taken from the upper arm it is likely the only source of the signal is the brachial artery [9]. Furthermore, taking IPG signals from the upper arm will not be affected by parameters such as extravascular lung water which affects thoracic derived IPG signals [9].
During the recording stage, IPG signals are affected by many types of artefacts, including those caused by respiration, movement, and poor electrode contact. This means that the analysis of these IPG signals can be difficult to see and lead to inaccuracies. This is a problem that could lead to improper diagnosis of cardiac diseases. Furthermore, artefacts affecting the signal can lead to baseline drift, that will cause issues in identifying the characteristic points in the IPG which are used as an estimation of the hemodynamic parameters [10-12].
In this study IPG waveform parameters were assessed by signal averaging the IPG signals. Signal averaged IPG (SAIPG) can be achieved by the singular fiducial point alignment technique (SFP) [13-14]. SAIPG allowed for a comparison of two electrode placements (Thorax Vs Upper arm) to determine the feasibility of obtaining long term cardiac activity from the upper arm.

Methods and Materials

2.1 Recordings of ECG & IPG

The subjects were healthy volunteers from the in-house cardiovascular research team at NIBEC Ulster University. The subjects age ranged between 22-65 years, the average age was 39 years and 62.5% were male. Recordings were carried out on different days using the same room environment and recording equipment and the subjects being recorded sat at rest with their left arm resting on a table. A database of 8 subject cases (N=8) recordings from the left arm was acquired using AcqKnowledge 5.0, by BioPac Inc. (Goleta, California, USA) and processed using Mathworks Matlab (9.9 R2020b) programming environment. Recording duration was 480 seconds at a sample rate of 2000Hz.

2.2 Arm IPG recording electrodes location

The electrode placement has been chosen to be on the upper left arm near maxilla point axially. Since it is proven to be the point where the brachial artery passes.[15] and greater current can be withdrawn through this point. We have deployed 4 electrodes (Ch-12 to Ch-15) on the upper arm at the anterior side. As it is can be seen from Figure 2. ECG electrodes for Lead 1 are placed simultaneously, to record ECG alongside the two study protocols i.e., Thorax IPG & Upper-Arm IPG along the arm. (Ch-1, Ch-2 and Ch-3) are ECG electrodes and (Ch-4 to Ch-11) are Thorax IPG electrodes; Where (Ch-4, Ch-5 and Ch-10, Ch-11) makes the outer ring for Current injection point and termination point and (Ch-6, Ch-7 and Ch-8, Ch-9) makes the inner ring for voltage measurement start point and voltage measurement end point. (Ch-12 to Ch-15) are

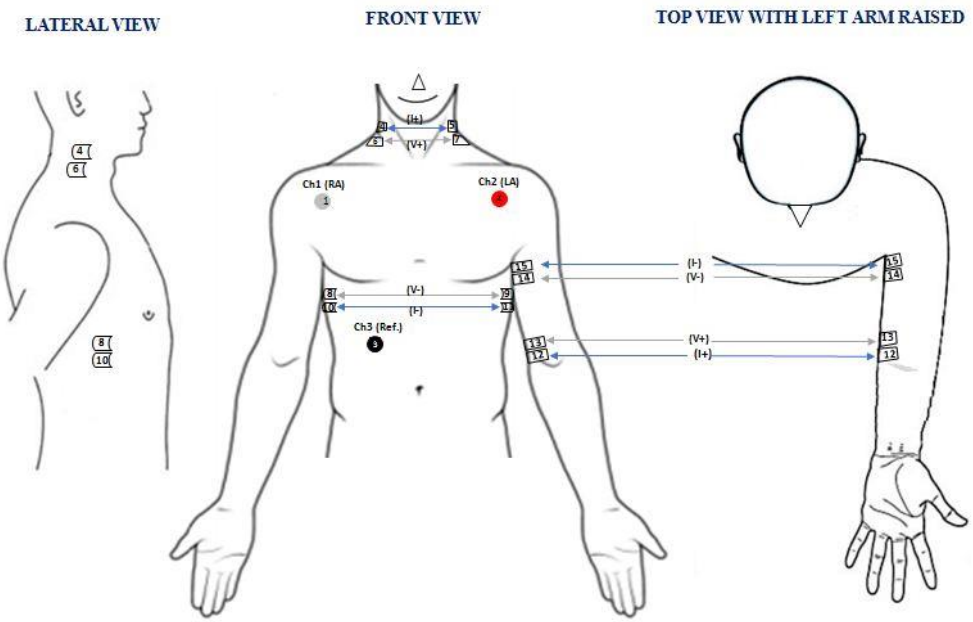


Figure 2. Electrodes placement ECG standard Lead I, IPG-Thorax and IPG-Arm (upper-arm).

Table 1: IPG Electrodes polarity with terminals at BN-NICO-T (BioPac)

IPG-Thorax		
Electrodes	Polarity	Terminals
Ch-4 & Ch-5	+I	I out
Ch-6 & Ch-7	+V	V in
Ch-8 & Ch-9	-V	V in
Ch-10 & Ch-11	-I	I out
IPG-Arm (upper-arm)		
Electrodes	Polarity	Terminals
Ch-12	+I	I out
Ch-13	+V	V in
Ch-14	-V	V in
Ch-15	-I	I out

placed on the anterior side of the upper-arm near cubital fossa and axilla making the point of current injection at Ch-12 and termination at Ch-15 and voltage measurement starts at Ch-13 and end at Ch-14. As it is illustrated in Figure 2, the electrodes are placed in such a manner that it would dissect the thorax in IPG-Thorax recordings, and the

brachial artery for IPG-Arm (upper-arm) recordings; with the flow of current (I) and measure the voltage (V) change in impedance across the thorax and upper-arm brachial artery. The Table 1 above, shows the description for the polarity of the placed electrodes. A constant current of 1mA at 100 kHz is being introduced by the BioPac bioimpedance system instrumentation at the current injection points in both of the cases (thorax and arm). The change in the body bioimpedance is projected by the receiver BN-NICO-R device (BioPac) at a sampling frequency of 2 kHz. To AcqKnowledge 5.0 software which is then displayed in the real-time.

2.3 Simultaneous ECG and IPG Recordings

It is necessary to have an ECG signal alongside IPG so the changes in stoke volume can give a clear indication that the patient is experiencing the systolic or diastolic pressure. For this purpose, ECG was recorded using the standard Lead I electrodes position, hence the three electrodes were placed on the chest with the orientation as follows, Vin- on the right armor clavicle, Vin+ on the left armor clavicle and the Ground/Reference electrode on the right lower rib. Figure 2. The signals were transmitted through (BN-RSPEC-T device, BioPac) at 2 kHz of sampling rate to MP-160 Receiver and the recorded data was observed via the AcqKnowledge 5.0 visualisation software.

2.4 ECG Electrodes Placement

In our research approach we have selected the standard ECG Lead I electrodes and placed the electrodes on the chest to facilitate ECG processing for signal averaging of the IPG (SAIPG of arm and thorax) and the ECG (SAECG) simultaneously, particularly for enhancing the Arm-IPG noisy signal, and to enable some comparative metrics IPG-Thorax *vs* Arm-IPG analysis, described later in the Section 3. We can use the wearable ECG device and place the electrodes on the upper arm as previously reported [16].

2.5 IPG electrodes placement

To study the placement of IPG electrodes on the upper-arm is our main research objective, since there has been little agreement on the electrodes positioning for arm-IPG recording for long-term monitoring of cardiac contractility. The conventional IPG electrodes placement for presenting impedance cardiography parameters such as the heart stroke volume and cardiac output, is done by placing electrodes around the neck and waist. Where the current is entered through the thorax and ends at the diaphragm. Figure 2 (front view) illustrates the conventional IPG thorax electrodes placements.

The distance *L* between the V+ and the V- electrodes is greater for the thorax which is significant for the current to pass through the thorax and the impedance is derived from potential differences variations. The noticeable point is that the current enters at the outer top electrode at (I+) and ends at the outer bottom electrode at (I-). The voltage difference is measured between the V+ electrodes, near the I+ electrodes, and the V-, near the I- electrode.

In the case of upper arm IPG recording, we have mimicked the same placement as it is done around the thorax, but with longitudinal placement of electrodes along the upper-arm and collaterally with the brachial artery (refer to Fig.1); to make sure the current enters through the brachial artery volume changes resulting in bioimpedance variations (ΔZ) along time which can be recorded.

Figure 3 provides a clear representation of actual experiment, where the electrodes placed on the upper arm on the same plane, current (I+) runs through the arm intersecting the brachial artery and ends on the same side of the arm at (I-). The electrical potential difference, as indicated in the sketch, is between the V+ and the V- in the same inner side of the arm, as the arm axilla anatomical reference point. The placement of electrodes on the same side of the arm intuitively would provide a larger Arm-IPG signal recording. Furthermore, the I- and V- electrodes should be placed up close to the axilla point where the greater blood pressure builds up.

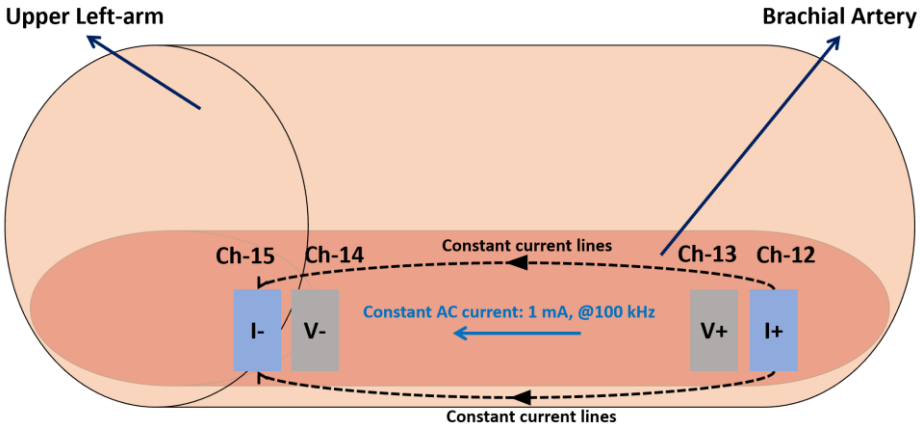


Figure 3: Upper left-arm IPG electrodes placed longitudinal, nearby the brachial artery.

2.6 Hardware description

In this research we have used hardware devices from BioPac Systems Inc. based in California, USA. The transmitter BN-NICO-T for IPG signals and the Transmitter BN-RSPEC-T for ECG signal both transmitters connect to their respective receivers NICO-R and RSPEC-R. Since the arrangement is completely wireless the common-mode rejection ratio is extremely high as compared to wired configurations. The receivers are attached to MP-160 central data acquisition system adjacently, which connects through Ethernet cable to the computer (see Figure 4).

Data acquisition software AcqKnowledge 5.0 is provided by BioPac Systems Inc. which allows us to carry out different pre-processing analysis. Results and Signal processing carried out on MATLAB by Mathworks® (Ver. 9.9 R2020b) on Windows operating system. The electrodes used for this project are medical grade, pre-gelled disposable ECG surface electrodes.

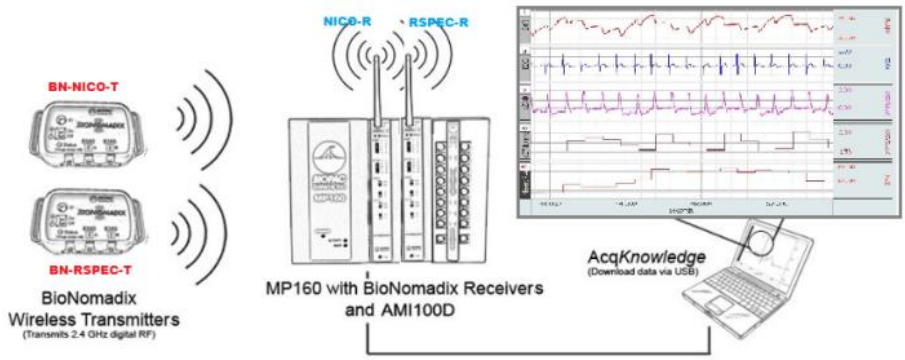


Figure 4. Hardware system block diagram.

2.7 Pre-filtering

The IPG signal in both the cases (Thorax & Upper-arm) was conditioned by a pre-filtering process to effectively eliminate noise artefacts without significantly deteriorating the main spectral content of the IPG signals. First an 8^{th} order lowpass butterworth filter was applied at 8Hz cut-off frequency, and subsequently, a high pass 4^{th} order butterworth filter at 0.5Hz cut-off frequency was applied to the signal. The ECG signal was just subjected to a notch filter of 50Hz for mains noise interference elimination.

2.8 Signal averaging of IPG (SAIPG) and ECG (SAECG)

Signal averaged (SA) window frames for the simultaneous acquired IPG (arm or thorax) and respective ECG (Lead I) were generated by applying the Single Fiducial Point (SFP) beat alignment technique [13, 14, 16] on the reference chest ECG Lead I. For the SA process, the algorithm uses the SFP time reference for the ensembled averaging ECG and IPG signal frames of 1400 sample (700ms) centred around the detected SFP time reference; which corresponds to 0.22s in the signal averaged window illustrated in Figure 5, The detected SFT alignment point in every valid heart beat is highly time deterministic to the ventricular depolarisation event in the ECG [16]. Figure 5 shows the 0.7s segment of ECG (blue) and IPG (brown) processed using the SFP technique, after averaging 681 detected valid beats in the ECG (Lead I). The IPG signal averaging is applied after its particular bandpass prefiltering process (5-8Hz). More precisely, the SFP point is always at the 440 sample point (0.22s) in the averaging frame (here, the sampling interval is 0.5ms = 1/2000 Hz), and the frame ends at 959 samples after the SFP position in the averaging frame. Henceforth, the SA algorithm divides by N the accumulated ensembled data points in the frame for N incoming validated beats.

2.9 Software architecture

Acqknowledge 5.0 is providedby BioPac Systems Inc. Data acquisition software installed on PC (windows or iOS versions available), the data can be recorded, and plotting options, grids and zoom in/out, selecting various analyses, on the signals are also available. The data could be saved in various different forms including (.xlsx & .mat) format. The recorded data in the form of (.mat) is then processed into MATLAB for conveniently executing the required signal processing in this study.

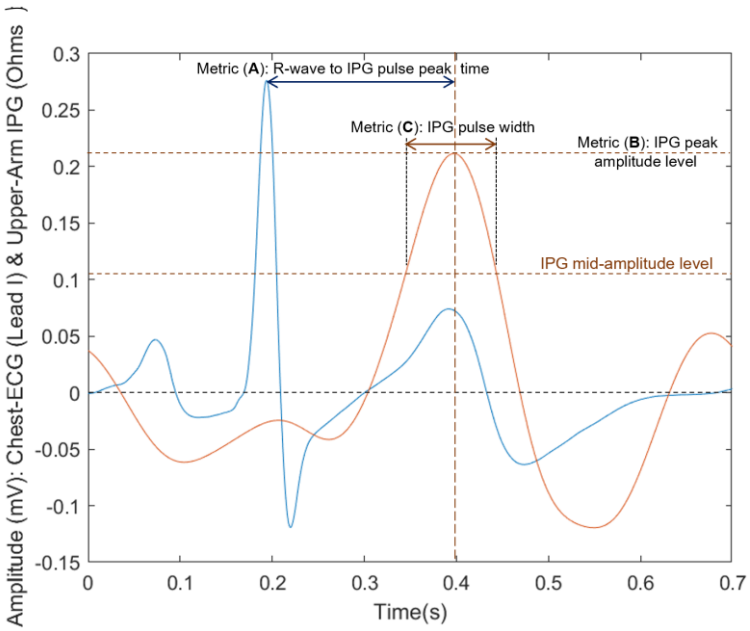


Figure 5. Upper-arm SAIPG (brown trace) in the 700ms (or 1400 samples) frame for N=681.

2.10 SAIPG waveform metrics

Six basic waveform metrics will be used to characterise the signal averaged IPG (SAIPG) waveform and establish intuitive comparative assessment for validating the usefulness SAIPG as a tool for establishing signal characteristics of the Arm-IPG in relation to conventional Thorax-IPG. These six metrics are labelled from as A to F and defined as follows (Figure 5 depicts the first three IPG waveform metrics):

(**A**): For measuring the relative time delay (ms) of the IPG pulse peak with respect the ECG R-wave event peak in a particular subject.

(**B**): Is the IPG pulse peak amplitude (Ω),

(**C**): Is the IPG pulse-waveform time width (ms) at mid-amplitude level, measured on the signal averaged Thorax-IPG (SAIPG-thorax) and Arm-IPG (SAIPG-arm), and comparative metrics.

(**D**): Is the comparative metric of amplitude **B** values ratio (%) of Arm(**B**)/Thorax(**B**).

(**E**): Is the IPG pulse width time metrics difference (ms) of [Thorax(**C**) - Arm(**C**)].

(**F**): Is the time metrics difference (ms) of [Arm(**A**) - Thorax(**A**)].

These six parameters will be determined for the 8 subject cases (N=8) in this study, as part of the analysis results.

Results and Discussion

Eight minutes of simultaneous IPG and ECG signals recording were acquired separately for the arm and for thorax on each subject case (total 16 minutes of data recording per case), using the BioPac systems, and then exported and processed with MATLAB: IPG signals pre-filtering (bandpass at 0.5-8 Hz), followed by further denoising processing by signal averaging of the IPG signals with respective simultaneously recorded ECG (Lead I) signal. Figure 6 (for a conventional Thorax-IPG) and Figure 7 (for an upper Arm-IPG) show two example cases of the raw ECG trace (blue) recorded simultaneously with respective bandpass prefiltered IPG trace (brown).

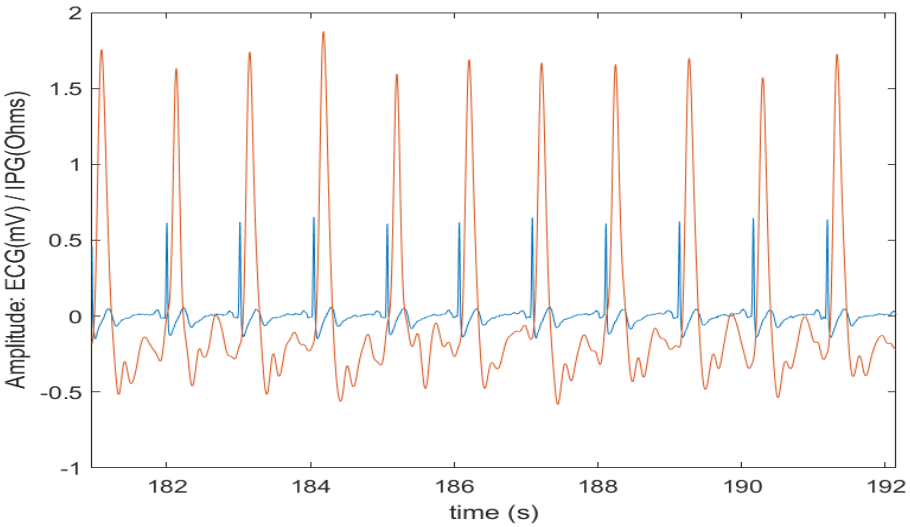


Figure 6. Case-8 ECG & pre-filtered IPG Thorax trace.

After applying the particular pre-filtering process on IPG signals (not applied to the respective simultaneously recorded ECG Lead I), the signal averaging process was applied after determining all valid heart beats in the ECG (Lead I), in a particular subject case, and determining the associated detected beats time reference SFP array.

Thus, for every subject case, two SA 700ms frames were generated: for the arm-SAIPG & respective SAECG, see Figure 8, and for the thorax-SAIPG & respective SAECG, see illustration in Figure 9). Then, the generated pair of SA signal enhanced (denoised) Arm-IPG/ECG and Thorax-IPG/ECG for each of the 8 subject cases, enabled the determination of the six IPG parameters defined in Section 2.10, for characterising the IPG pulse waveform (brown waveform) relatively located between the R- wave and the T-wave of the SAECG (blue waveform), and to provide a

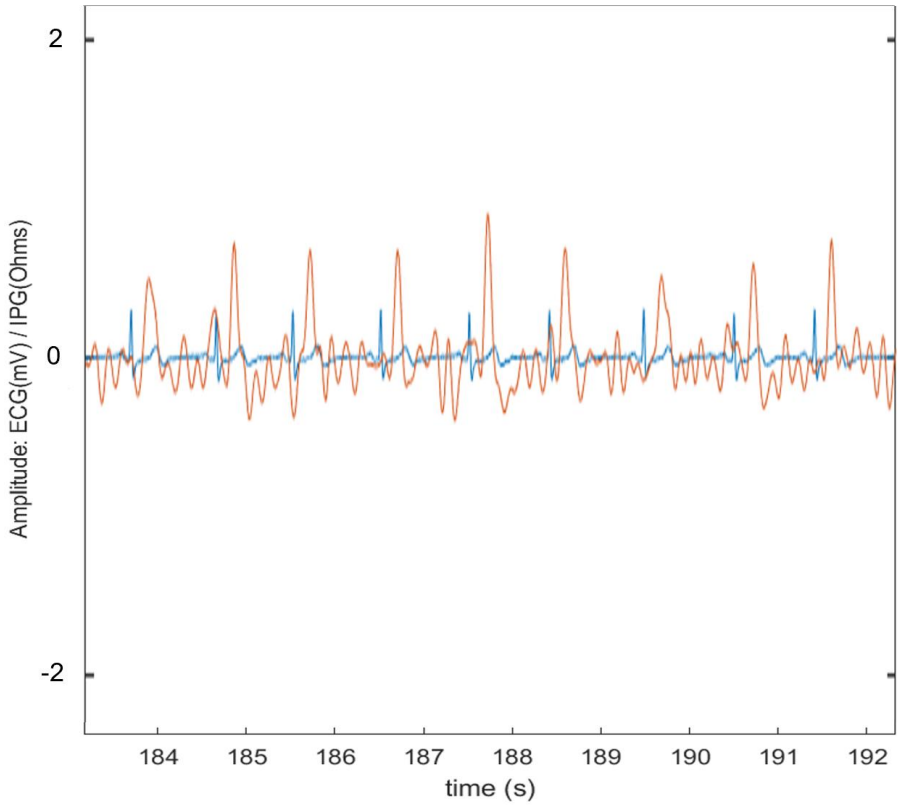
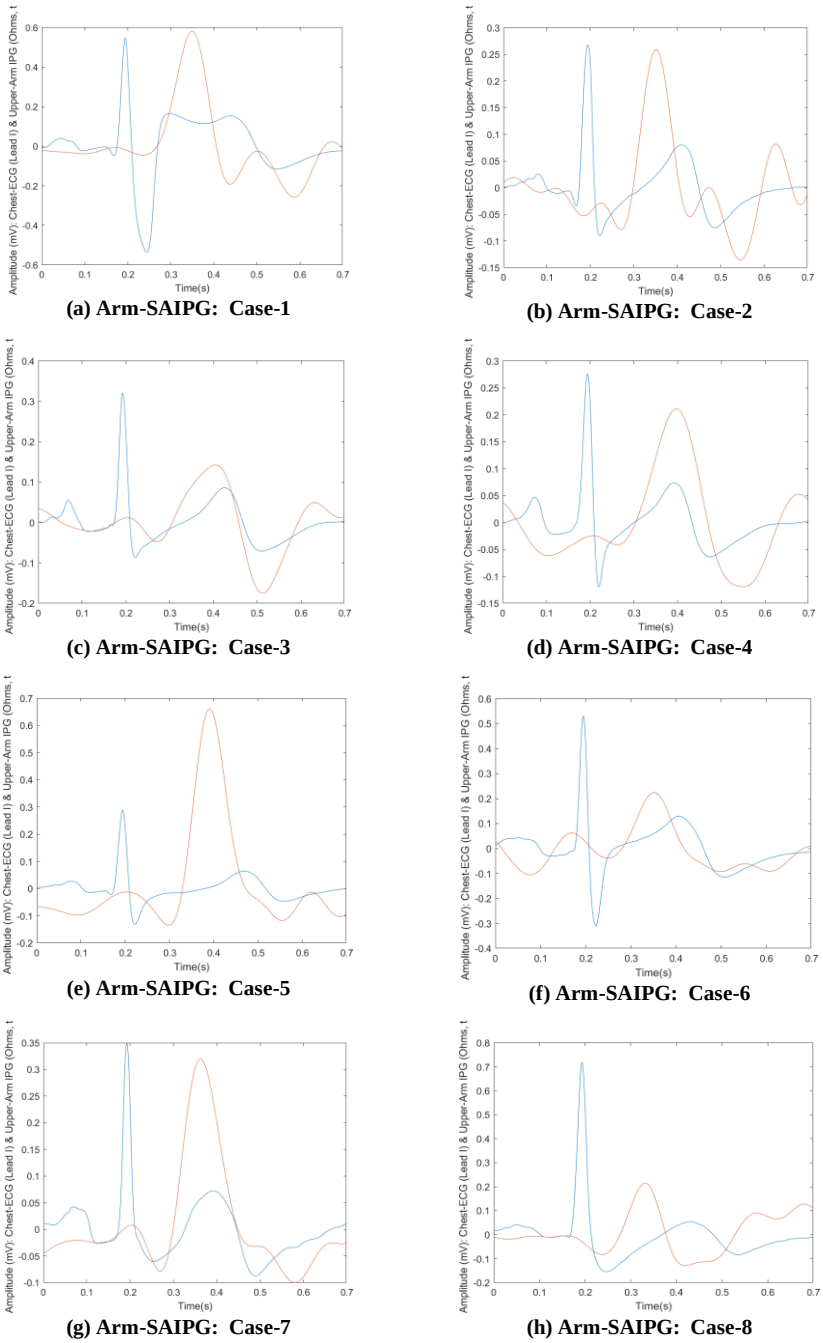


Figure 7. Case-5 ECG & pre-filtered IPG upper-arm trace.

comparative assessment between the arm and the thorax IPGs in each subject case, and for summarising the study with some basic descriptive statistical mean value, standard deviation (SD), the median value and interquartile range (IQR) for this small but significant pilot study (N=8), as compiled and presented in Table 2.

The graphical illustration of the results for each of the cases arm SAIPG/SAECG is presented in Figure 8 (a-h). On the other hand, the thorax SAIPG/SAECG for 4 selected cases were processed with MATLAB and the results of which are presented in Figure 9 (a-d).

More specifically, for establishing signal parametric relationship between conventional thorax-IPG and upper arm-IPG, we measured on the SA 700ms frames the following IPG waveform features: (A) the R-wave peak to IPG peak time (ms), (B) the amplitude of IPG signals (Ω) and (C) the mid-amplitude IPG pulse-waveform time width (ms). These 3 basic waveform metrics enabled the determination of 3 other comparative metrics: (D) IPG Amplitude ratio (%) between arm and thorax IPG in same



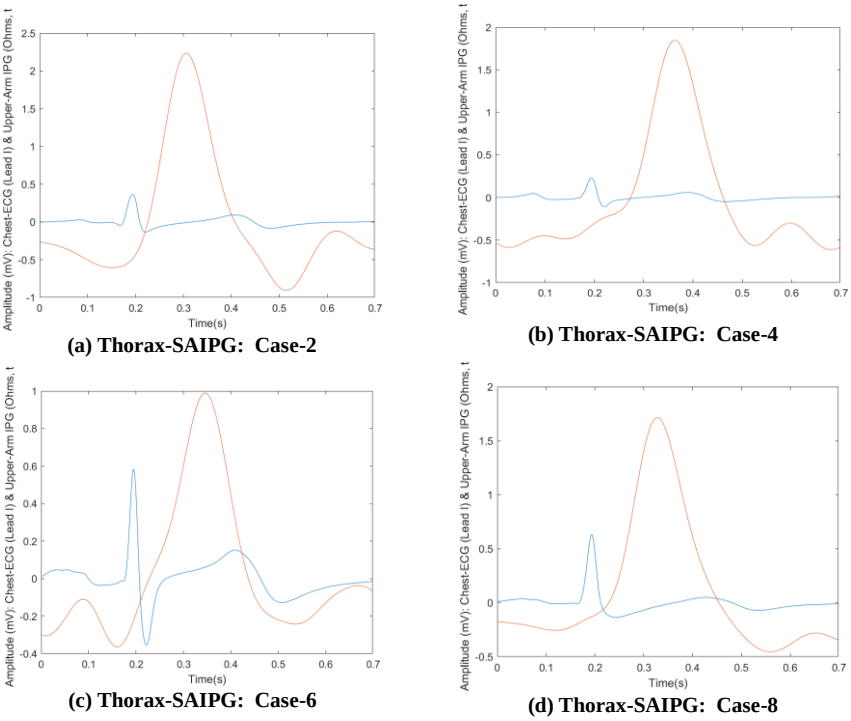
(a) Arm-SAIPG: Case-1 **(b) Arm-SAIPG: Case-2**

(c) Arm-SAIPG: Case-3 **(d) Arm-SAIPG: Case-4**

(e) Arm-SAIPG: Case-5 **(f) Arm-SAIPG: Case-6**

(g) Arm-SAIPG: Case-7 **(h) Arm-SAIPG: Case-8**

Figure 8. Arm-IPG (brown) and standard Lead I ECG (blue) 700ms signal averaged IPG (SAIPG) and ECG (SAECG) frames for the 8 subject cases in this study.



(a) Thorax-SAIPG: Case-2

(b) Thorax-SAIPG: Case-4

(c) Thorax-SAIPG: Case-6

(d) Thorax-SAIPG: Case-8

Figure 9. Thorax-IPG (brown) and standard Lead I ECG (blue) 700ms signal averaged IPG (SAIPG) and ECG (SAECG) frames for selected subject cases 2, 4, 6 and 8 in this study.

subject case, which indicated the percentage amplitude of the arm-IPG to the thorax - IPG, (E) the IPG pulse-width time difference (ms) between thorax C metric and the arm C metric, revealing the tendency of the arm-IPG pulse being narrower than the thorax-IPG pulse, and (F) the time difference (ms) between the arm A metric and the thorax A metric, which quantifies the expected relative time delay difference of the IPG pulse position with respect the ECG r-wave. The results of these six parameters measurement and calculation are presented in Table 2.

Table 2. Summary of IPG waveform metrics (six: A, B, C, D, E and F) on the SAIPG 700ms frames as defined in Section 2.10, determined for the 8 subject cases (N=8).

Metrics →	**A** (ms)	**B** (Ω)	**C** (ms)	(**D**) %	(**E**) ms	(**F**) ms
Case 1 (Thorax-IPG)	122.0	1.45	99	39.95	22.25	32.75
Case 1 (Arm-IPG)	154.8	0.58	76.75			
Case 2 (Thorax-IPG)	113.0	2.23	98.5	11.60	32	44.5
Case 2 (Arm-IPG))	157.5	0.26	66.50			
Case 3 (Thorax-IPG)	168.5	2.06	95.25	6.94	Outlier value	42.75
Case 3 (Arm-IPG)	211.3	0.14	100.8			
Case 4 (Thorax-IPG)	169.0	1.84	102.0	11.44	16.25	34.25
Case 4 (Arm-IPG)	203.3	0.21	85.75			
Case 5 (Thorax-IPG)	148.8	3.22	100.3	20.48	26.25	47.5
Case 5 (Arm-IPG)	196.3	0.66	74.00			
Case 6 (Thorax-IPG)	150.0	0.98	104.5	22.70	27.3	Outlier value
Case 6 (Arm-IPG)	157.0	0.22	77.25			
Case 7 (Thorax-IPG)	147.75	1.53	101.0	20.78	14.5	22
Case 7 (Arm-IPG)	169.75	0.31	86.5			
Case 8 (Thorax-IPG)	134.0	1.71	108.0	12.55	45.75	Outlier value
Case 8 (Arm-IPG)	138.25	0.21	62.25			
Mean (SD)	N/A	Thorax: 1.88 (0.67) Arm: 0.33 (0.19)	Thorax: 101.06 (3.89) Arm: 78.72 (12.21)	18.31 (10.37)	26.32 (10.55)	37.29 (9.48)
Median (IQR)	N/A	Thorax: 1.78 (0.59) Arm: 0.24 (0.17)	Thorax: 100.63 (3.75) Arm: 77.0 (13.81)	16.52 (9.70)	26.25 (12.06)	38.50 (10.94)

Conclusions

Impedance plethysmography (IPG) is a non-invasive, low-cost technique that enables for continuous monitoring of cardiac contractility parameters. Obtaining the IPG data from the upper arm can also allow for long-term cardiac profiles to be obtained from an accessible and convenient part of the body, i.e., the upper left-arm. By implementing a rolling signal averaging denoising process on the arm-IPG. The results highlight the feasibility of this technique which is exposed in Table 2. There, can be extracted the following main observation: the average [Arm-SAIPG timing] - [Thorax-SAIPG timing], was of 37.3ms (±9.5ms) SD, meaning that a delay was identified in the 8 cases. The SAIPG pulse peak amplitude (Ω) in the arm-IPG was found to be about 18.3% (±10.4%) SD of the amplitude of thorax-SAIPG. The metrics of the mid-amplitude SAIPG pulse-waveform time width (ms), revealed that the arm-SAIPG pulse-waveform width is an average of 26.3ms (±10.6ms) SD narrower than thorax-SAIPG.

The results of this study show some interesting similarity and dependency between the conventional way of acquiring the IPG signal from the thorax and the investigated approach of acquiring the signal averaged IPG from the upper-arm. Which encourages us to further develop the enabling techniques for reliable upper-arm IPG recordings during extended time in the ambulatory setting as a diagnosis tool for detecting cardiac related disorders. A possible system implementation which integrates arm-ECG recording [16] could complement the arm-IPG techniques investigated in this study.

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