Carotid and radial pulse feature analysis with EMFi sensor

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Abstract

The purpose of this work is to show the potential of Electromechanical Film (EMFi) sensor in vascular elasticity studies when pulse wave features from carotid pulse (CP) and radial pulse are studied. ECG, seat ballistocardiogram (BCG) and pulse signals from the limbs and CP were recorded from 48 working aged men in sitting position. Duration and amplitudes of the signal components from the ballistic seat signal, CP and radial pulse according to R wave of the ECG were studied. Several calculated parameters used to obtain vasculature stiffness information were compared with Bland-Altman (BA) plots and with Pearson correlation in order to study, whether CP and radial pulse give consistent information about vascular elasticity.

Results from the BA plots and Pearson correlation show that elastic information obtained from the CP and radial pulse signals clearly differ from each other. The elasticity changes along the arterial tree seen in local pulse signals reflect also to the form of the seat BCG signal.

Keywords: EMFi, BCG, carotid and radial pulse

Introduction

Ballistocardiography (BCG) is a non-invasive method for cardiac and respiratory evaluation and it reflects closely the strength of myocardial contraction revealing the condition of the heart [1]. When the heart pumps blood to the pulmonary arteries and ascending aorta, through aortic arch to the peripheral circulation, recoil of opposite direction is applied to the body and its force and direction is changing according to the cardiac cycle.

The carotid pulse (CP) is a pressure signal recorded from carotid artery when it passes near the surface of the body in the neck. It indicates the variations in arterial blood pressure and volume with each heart beat. As the recording place is located very near the heart, the CP signal resembles the morphology of the pressure signal at the root of aorta [2]. The CP rises abruptly with the ejection of blood from left ventricle to ascending aorta reaching a peak called percussion wave (P). The following secondary wave is called as a tidal wave (T), caused by a reflected pulse returning from the lower body travelling back to the heart. Dicrotic notch (D) is caused by a closure of aortic valve following a brief transient increase in the aortic pressure, the dicrotic wave (DW) [2] (Fig. 1). The carotid pulse supplements the BCG data by giving the onset of the ejection phase and can give information about the coordination of the cardiac activity.

In this paper a Mobile Physiological Signal Measurement Station has been used as a device, which enables the recording of seat BCG and local pulse signals from different locations of the body [3] with EMFi sensors. Pulse wave and contour analysis are used to determine arterial stiffness and vascular distension. The main goal of this study is to show, that EMFi sensor can produce elastic information from the vasculature. Another objective is to study, if consistent elastic information is obtained from a CP and wrist pulse signal measured with EMFi sensor. As arterial properties have an influence on the amplification of the pulse wave, differences in elasticity are expected to found even between CP and wrist pulse signals. As arterial tree have different elasticity values, changes in these have an influence to the BCG signal also.

Methods

The EMFi [4] sensor is basically a thin biaxially oriented plastic film coated with electrically conductive layers which are permanently polarized. Changes in the pressure acting on the film generate a charge on its electrically conductive surfaces and this charge can be measured as a current or a voltage signal. It can convert mechanical energy to electrical and vice versa. Thus the EMFi acts as a sensitive movement sensor suitable for BCG recordings.

Signals from EMFi sensors were recorded with the Mobile Physiological Signal Measurement Station [3] into a notebook computer with a data acquisition card (Daqcard 6036E) and the recordings were made into ASCII format. In the Mobile Physiological Signal Measurement Station an active Butterworth 8. degree low pass filter was used, where the cut-off frequency was 256 Hz. In chair recordings the EMFi sensor (42 cm x 36 cm) was beneath the measured person. Seven EMFi sensor strips (15 cm x 2 cm) were attached to the limbs and on the neck near carotid artery. ECG trace was used as reference in detecting features from the pressure related signals from EMFi sensors.

The form of the pulse wave is defined by the properties of the heart beat, blood pressure (BP) and the properties of the vessel wall. Age and BP affect to the aortic size in adults and also to the form of the pulse wave. The cross-sectional area of the aorta has been shown to double between the ages of 20 to 80 having a considerable effect to the aortic elastic properties in different locations of the aorta [5].

In pulse contour evaluation the carotid pulse obtained from healthy persons and from patients having arterial atherosclerosis show recognizable, marked contour differences being compatible with the clinical condition of the subjects. These contours change along with the clinical signs of the disease and show characteristic abnormal features. Atherosclerosis contributes the mechanical properties of the arterial wall which becomes rigid and loses its elasticity [6]. Elasticity index e (amplitude ratio: a/b; reflecting arterial elasticity), and dicrotic index d (amplitude ratio c/a in %; reflecting the amount of peripheral resistance) [6] are presented in Figure 2.

Measurements

In this study we present pulse feature analysis obtained from CP, radial pulse and seat BCG. The recordings were made from 48 middle aged men (age 41 - 65 years) in a sitting position measured with EMFi sensors. The medical history of the measured persons relating to smoking, hypertension, atherosclerotic disease and diabetes was known (Table 1). All the measurements lasted about 3 min and the used sampling frequency was 500 Hz. Just before the measurements the blood pressure and the pulse were measured with Omron M5-I blood pressure monitor device.

Table 1. Population characteristics with the mean value ± standard deviation and the number of patients.

Variable	All
Number of patients (n)	48
Age (years)	58±5.3
Height (cm)	177.8±6.2
Weight (kg) W0	82.6±12.9
Mean systolic blood pressure (mmHg)[a)] W0	136±17
Mean diastolic blood pressure (mmHg) [a)] W0	86±9
Mean heart rate (bpm)[b)] W0	61±9
Smoking status (present/previous/never) (n)	8/24/16
Hypertension (n)	20
Diabetes mellitus (n)	8
Atherosclerotic disease (CHD, PAD, CVD) (n)	28

W, week; CHD, coronary heart disease; PAD, peripheral artery disease; CVD, cerebrovascular disease. [a)]Values from the Omron M5-I blood pressure monitor device. [b)]Mean values from the ECG's R-R interval (bpm=beats/min).

The BCG recordings were carried out in the morning between 7 and 10.30. Eating and drinking were not allowed 12 hours before the measurement. Informed written consent was obtained from all participants. The study was approved by the ethics committee of Kanta-Häme Hospital district. The measurements were made in Linnan Klinikka, Hämeenlinna, Finland.

Signals were first band pass filtered (0.5 – 30 Hz FIR, 700 taps, time delay corrected), down sampled into 100 Hz and the analysis was done with 0.5s window length. The index of the R point was detected first by differentiating (2 points), squaring and integrating (5 points) and by taking the maximum from the ECG signal. The I slope from the BCG was detected by local minimum method and then the J slope was detected by local maximum using the index of the I point as a starting point. Other slopes in CP and wrist pulse signal were detected at the same way. Matlab software was used in previous calculations.

The R wave of ECG was used as a reference in detecting the slopes from BCG, carotid and radial pulse signals. The P point in the neck CP signal was chosen for the measurement for the reason that the end point of ejection is not seen so clearly as an exact end point in the CP signal, but it is overlapped by a reflected pulse returning from the lower body.

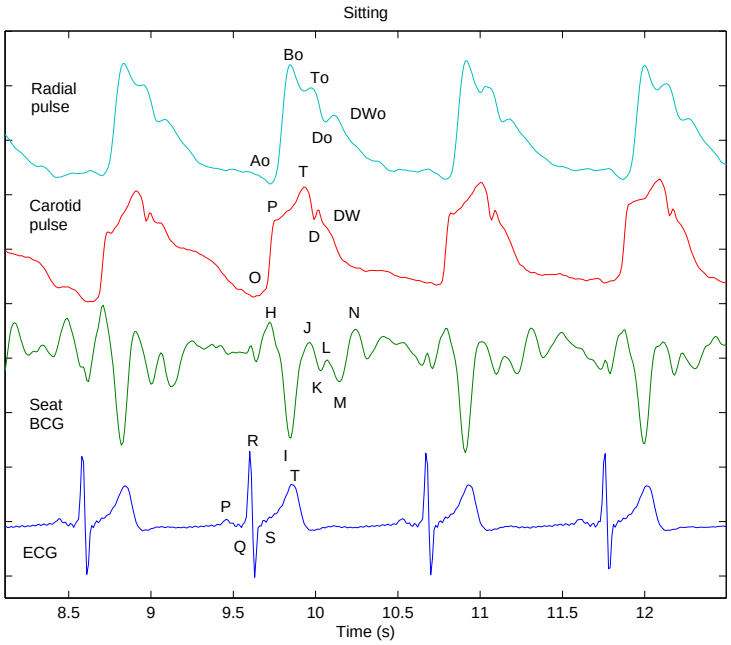

Figure 1. Signals recorded in sitting position (Case 48). Pulse waves from the right side of the neck (CP) and from the right wrist (radial) are labelled as mentioned in this study. As seat BCG signal corresponds to the total recoil of the heart mediated via ejected blood burst from the heart seen as pulse, the labels of the main components of the seat BCG signal are also attached. Four channels of seven recorded ones are presented [3].

In order to study the contraction of the left ventricle, temporal values, like ejection time (TO-D) from the carotid artery signal and (TAo-Do) from the radial pulse signal were extracted (Fig. 1). As the origin of the pulse waves and seat BCG trace is the movement of blood inside large arteries due to the pumping action of the heart seen also as recoil traces in seat BCG signal, the ejection time TH-K from seat BCG signal was included into the study. THI is the time of the rapid ejection phase of the systole. THK is the period of the blood expulsion phase from the ventricles. TRH is the measure of the isometric tension phase of the ventricles. TRK is the duration of the mechanical systole of the heart [1]. Bland-Altman plot (BA) and Pearson correlation coefficient were determined to estimate similarity of the measurements of CP and radial pulse as well as CP and seat BCG. All statistical analyses were performed by using the SPSS 17.0 program (SPSS Inc.).

Results

Detection of the signal components from BCG, CP and radial pulse signals with minimum and maximum method by using a moving detecting window was successful. Calculated elasticity values from CP and radial pulse signal showed distinctive differences judged by the BA plots and very weak correlation between CP and radial pulse (Figs. 3 - 5). No close relation exists between ejection time determined from CP and seat BCG signal (Fig. 6). Quite modest Pearson correlation values indicate differences between signals.

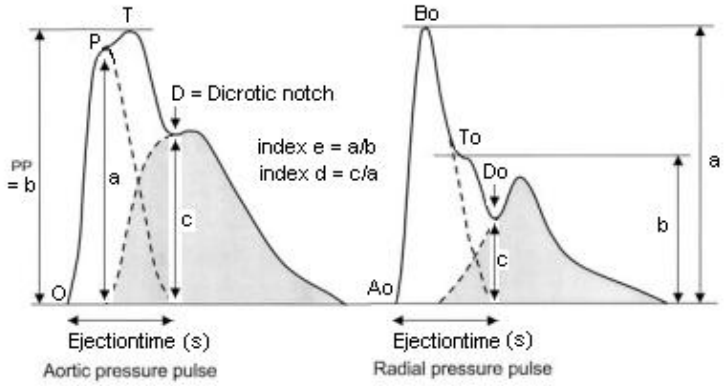

Figure 2. Indexes e and d can be defined from aortic and radial pulse waveforms. They depend on the relative amplitude and reflected (shaded in the picture) pressure waves summing to produce the overall waveform. Re-drawn from [7]; CP and wrist pulse labelled as is in this study.

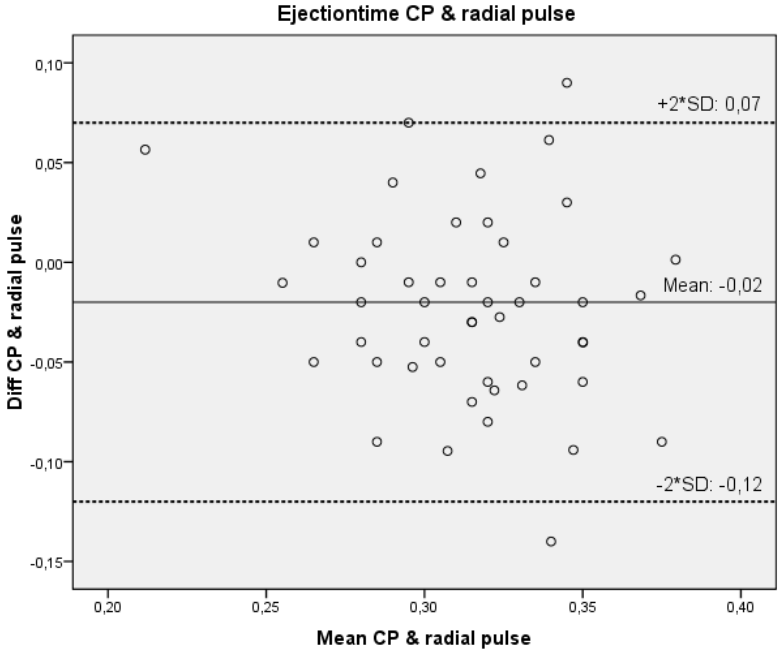

Figure 3. Bland-Altman plot from the ejection time calculated from the CP and radial pulse signal. $T_{O\text{-}D}$ and $T_{Ao\text{-}Do}$ are the corresponding ejection times in seconds (Figs. 1-2). Pearson correlation coefficient 0.312.

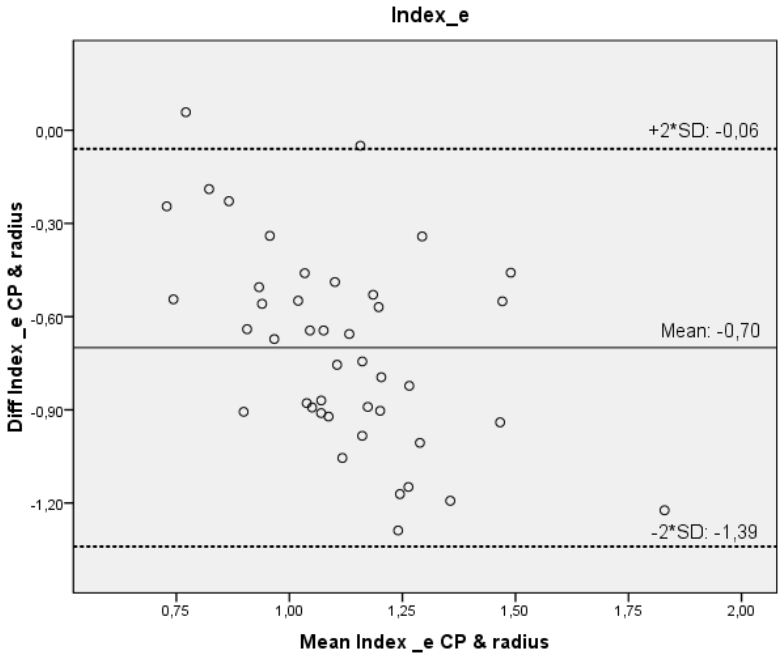

Figure 4. BA plot from the index e (Figs. 1-2) from the CP and correspondingly from the radial pulse (n=43). In [6] the index e value 1.27 was considered as healthy and with value 0.58 having an arterial atherosclerosis. Pearson correlation coefficient 0.329.

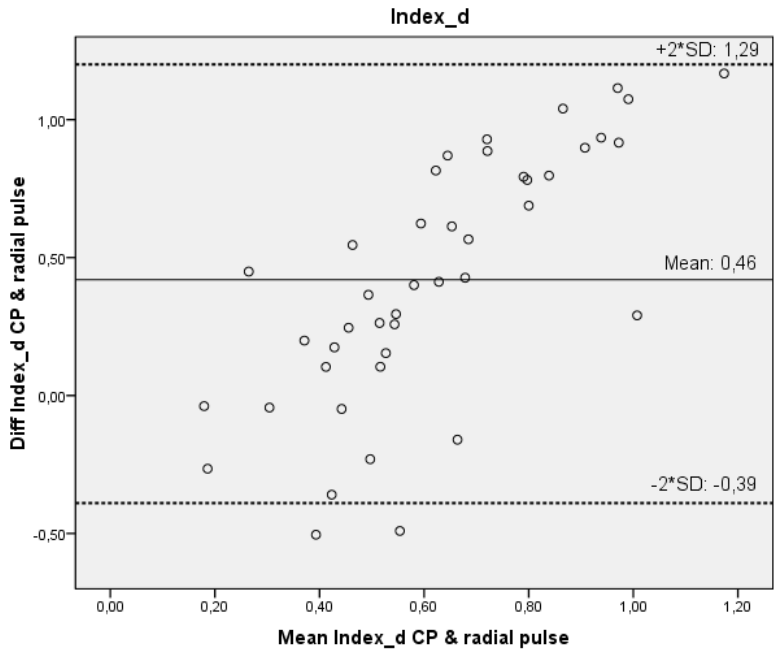

Figure 5. BA plot from the index d from the CP and correspondingly from the radial pulse (n=43). In [6] the index d value 0.59 was considered as healthy and with value 1.23 having an arterial atherosclerosis. Pearson correlation coefficient 0.30.

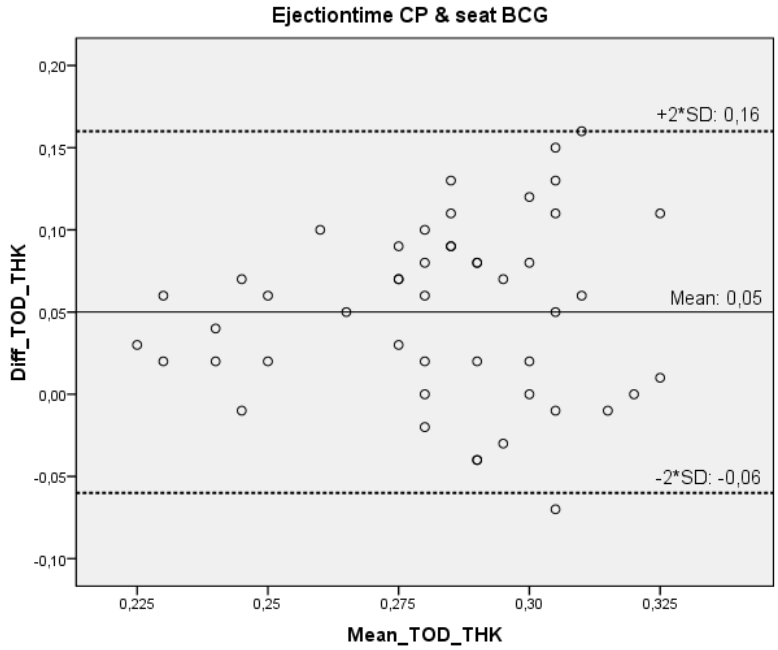

Figure 6. BA plot from the ejection time in seconds between the seat BCG and CP. Pearson correlation coefficient -0,041.

Discussion

Our main result is that carotid pulse features clearly differ from that of radial pulse and seat BCG.

It is known, that the contour of the pulse waveform and systolic BP differ between central and peripheral arteries [7]. When measured from two different locations of the arterial tree, the form of the pulse wave is influenced by the local reflections, BP and measurement position. The local elastic information from radial and carotid pulse differ from each other being also different between different subjects. When measuring local arterial stiffness, it is important to describe measurements as done, because the measurement location in proportion to arterial tree has its own effect to the measurement results. We have earlier shown that signal components of BCG are repeatable in consecutive recordings as well as reproducible in longer time recording intervals [8].

Spreading of the obtained values in BA plots from the CP - radial pulse ejection time and CP between seat BCG may also indicate possible inadequate foot point detection of the pulse wave. In this study, the foot of the pulse wave was detected by local minimum method. Minimum method in foot point detection may fail, as some fluctuation in the signal may happen before the main ejection of the heart placing the detected point before the actual start of ejection. Therefore, the intersecting tangent algorithm would be worth of study. Another source of error may be the inadequate coupling of the EMFi strip sensor to the underlying skin producing small-amplitude signal.

The time domain properties of blood vessels change when blood pressure rises and this has an influence on the ballistocardiographic waveforms and to the elasticity of the veins. Usually, ballistocardiographic amplitude decreases while arterial pressure increases [1]. Some small differences in BCG waveforms between different people can be explained different anatomical causes; as the blood pressure values differ with different people, so does

the contraction ability of the heart and the elasticity of the veins. In Figure 6 the differences in ejection time between CP and seat BCG can be explained differences in the elasticity of the arterial tree seen as a response of the ejection of the heart. Differences in the density of the elastic fibers and thus in the elastic modulus between different parts of the aorta has been discovered: the highest elastic modulus was found from the thoracic section of the aorta having also the highest density of elastin fibers [9].

The augmentation index (AIx) has been used widely in describing arterial and radial elasticity. For carotid pulse it is the amplitude difference between a and b divided by amplitude b. For radial pulse AIx is defined as b/a (Fig. 2). Aortic AIx has been used to evaluate central systolic BP by the means of radial-to aortic transfer function. Central systolic BP differs from brachial BP due to peripheral amplification [7]. As AIx depends on higher frequency information of the pulse wave, but systolic BP not, this approach in the evaluation of central systolic BP has been questioned [7]. AIx is influenced by the arrival time of the pulse wave reflection, thus depending on magnitude and timing of the reflected waves [10,11] and heart rate [12] and it is proposed, that the properties of peripheral muscular arteries and arterioles affect to AIx by changing the amplitude of the reflected wave [10]. Since the validity of AIx as a measurement of arterial elasticity has been questioned [7,10,13,14] and as AIx definition for CP and radial pulse differed, we did not calculate this determination. As Reflection Index (RI) is defined as b/a being inverse with index e (Fig. 2), it was omitted from this study.

This study shows that elastic information is obtainable from both carotid pulse and radial pulse signals with EMFi sensors. However, the information obtained from carotid pulse clearly differs from that from radial pulse and seat BCG. Hence in scientific publications (and even in their titles) the methodology of the measurement of local arterial elasticity should be conclusively described.

Acknowledgments

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