EMFi sensor usage in ballistocardiographic studies

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Motivation: Cardiovascular risk factors and disorders

- In western countries the most common cause of death are heart-vasculature diseases and the amount of deaths is expected to rise rapidly. Arterial calcification is nowadays the most destructive epidemic being the leading cause of death and bearing the burden of diet, lifestyle and environmental risk factors in modern day society. When followed thru adulthood, differences in risk-factor burden translate into significant differences concerning lifetime risk of cardiovascular disease.

- Life expectancy: No major cardiovascular risk factors: Only 5% of men (6% of women) died before 80 years of age.
- One or more risk factors: 30% of men (21% of women) died before 80 years of age [1].

→ The role of hypertension and elevated cholesterol levels (atherosclerosis) are greater than earlier expected. General health is compromised by decreased vascular elasticity.

→ Heart-vasculature system reveals its own state after manifesting first severe signs of lost health. As the first signs from underlying atherosclerosis appear, the disease has propagated far leading to stenosis and thrombosis.

- In general population clinical coronary events including sudden cardiac death occur in subjects being previously asymptomatic and these events are often unanticipated → Need for risk assessment before the end organ damage or clinical events happen.
- Prevention and therapy: Need for new uninvasive methods and clinically useful tools for risk stratification.
- Ballistic recoil (ballistocardiography) may reveal harmful changes before they became apparent.

Ballistocardiography (BCG)

- BCG: Pre-ejection (FGH), ejection (IJK) and diastolic part (LMN).
- BCG: graphic representation of the ballistic impulses produced inside the body and is set in motion in the heart and great vessels by systole of the atria and ventricles. The direction and the resulting recoil force effects to the body according to cardiac operating cycle.
- By representing mechanical events of the heart it reveals the efficiency and strength of the heart as a pump. Reveals coordination of the myocardial contraction; has been used as a prognostic tool for life expectancy [2].

Electromechanical Film; EMFi

- Thin, biaxially oriented plastic film (polypropylene) coated with electrically conductive layers, which are permanently polarized. Charge, which is proportional to the change in thickness (pressing force), can be measured as a current or voltage signal.
- Inner structure: Several polypropylene layers separated by air voids, which are permanently polarized.
- Reacts to dynamic movements.

$E$ is the internal electric field
Non-invasive estimation of arterial stiffness: past & present time

- Arterial pulse was used to **recognize the changes in pulse features** indicating the presence of a disease.
- Arterial pressure results from an interaction between heart and arterial system reflected into the magnitude and form of the pressure pulse due to changes in peripheral circulation or alterations in cardiac function.

- Marey’s sphymograph in 1876 (revised by Mahomed) was the first clinically useful pulse recorder, which used a stylus to trace a record of the performance of the heart allowing the visual analysis of the heart beat and the force and the volume of the blood’s circulation.

- Riva-Rocci’s cuff sphygmomanometer (1896) made the interpretation easier by providing exact numbers as a form of distal systolic and diastolic pressures about cardiac function.
Problems with cuff devices

• All cuff devices measuring pressure within brachial artery have problems in precision between brachial artery and central aorta and their interpretation of systolic, diastolic, mean and PP → Validity of Riva-Rocci’s method?

• As used and also recommended over a century ago: pulse wave analysis and pulse wave velocity (PWV) provide information about arterial stiffening, early wave reflection and central BP in the case of ageing and isolated systolic hypertension [3].

• Higher wave reflection predicts cardiovascular events independently of conventional risk factors in people with treated hypertension [4].

• Proper medication is needed! Atrovastatin treatment has been associated with less augmentation of the carotid BP waveform and less wave reflection from the body in hypertension [5].


Non-invasive estimation of arterial stiffness: Pulse pressure (PP)

• Central SBP or PP; measured at the site of central arteries and from the common carotid arteries.
• Depends on CO, large artery stiffness and timing of wave reflections. It is associated with age (widened PP with old, with young; increased CO), arterial stiffness being also a risk factor for cardiovascular disease.
• Framingham study: different age groups have different PP and BP. Brachial PP: risk factor for the development of coronary and carotid events.
• →BP at the brachial artery does not reflect the BP at the ascending aorta (pressure seen by the heart and the major organs are exposed to the pressure prevalent in the central arteries) →central aortic BP predicts better cardiovascular outcome than peripheral pressure measured conventionally from the brachial artery.
Non-invasive estimation of arterial stiffness: PWV

- Carotid-femoral **PWV** is a ‘golden standard’ and a direct measure for arterial stiffness and an integrated measure of the effect of cardiovascular risk factors on the arterial wall:
  - usually measured from foot-to-foot velocity method
  - inversely related to the response to antihypertensive therapy; depends on pressure, vessel size and the elastic properties of the arterial wall; provides elastic information from the local vessel

- Commercial devices for PWV determination: Complior & Sphygmocor → Differences in TT due to different sensors and algorithms → PWV values between these devices are not interchangeable.

- Timing of wave reflection affects to the degree of pressure amplification. With young people wave reflection does not affect to PP value both in aorta and the brachial artery due to wave reflection, which returns at late systole or early diastole (smaller amplification in radial and aorta). With older people wave reflection returns during early systole augmenting the aortic PP & BP [Sola J, etc. Ambulatory Monitoring of the Cardiovascular System: the Role of Pulse Wave Velocity. InTech, 2010:pp. 391–424].

- Aorta stiffens more with people having CV risk factors (hypertension, diabetes). Correlation between aortic stiffness and carotid stiffness weakens → aortic stiffness and carotid stiffness cannot be used as interchangeable predictors concerning high-risk patients → Carotid feature analysis & BCG study with EMFi sensor?
Pulse contour analysis and indexes derived from that

- In pulse contour evaluation the carotid pulse obtained from healthy persons and from patients having arterial atherosclerosis show easily 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 [6].

- Despite the fact, that increased local and regional stiffness parameters have correlated significantly with the impaired arterial function with CAD patients, stiffness parameters are not capable to provide any information about the arterial damage in coronary vessels. As arterial stiffness describes the function of the inner lining of the endothelium, its correlation with the severity and extent of the coronary heart disease is incomplete [7].


Carotid & radial pulse feature analysis with EMFi sensor

• 48 men (age 41-65 years); measured in sitting position. Stiffness parameters from carotid pulse (CP) and radial pulse were studied with Bland-Altman (BA) plots and with Pearson correlation.

• Do CP and radial pulse give consistent information about vascular elasticity?

• Ejection time: Carotid pulse \(T_{O-D}\) & radial pulse \(T_{Ao-Do}\).

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

BA plot from the ejection time in seconds between the seat BCG and CP. Pearson correlation coefficient -0.041. \(\rightarrow\) Distal recording site & tissues cause delays to BCG’s systolic time.
Carotid & radial pulse feature analysis with EMFi sensor

- Stiffness parameters from carotid pulse (CP) and radial pulse were studied with Bland-Altman (BA) plots and with Pearson correlation. Indexes e and d.
- Spreading of values in BA plots & modest Pearson correlation value → Carotid pulse features clearly differ from that of radial pulse and seat BCG.

BA plot from the index e from the CP and correspondingly from the radial pulse (n=43). Pearson correlation coefficient 0.329.

BA plot from the index d from the CP and correspondingly from the radial pulse (n=43). Pearson correlation coefficient 0.30.


Comparison of local pulse wave velocity values acquired with EMFi sensor

- Duration of the signal components (median pulse transit time; PTT) from the foot point and from the peak of the ankle and radial pulse signals according to R wave of the ECG were studied.
- PWV parameters between left and right wrist and respectively between left and right ankle were compared with Bland-Altman (BA) plots and with Pearson correlation in order to study, whether foot point (min. value) or peak point (max. value) from the ankle and radial pulse give consistent information about vascular elasticity in the form of PWV.
Comparison of local PWV values acquired with EMFi sensor

Ranne foot kohta pulssiaallosta (minimi):

BA plot from the PWV calculated from the foot point of the left and right radial pulse signals (in m/s). Pearson correlation coefficient 0.593.

Ranne huippukohta pulssiaallosta:

BA plot from the PWV calculated from the peak point of the left and right radial pulse signals (in m/s). Pearson correlation coefficient 0.681.

Nilkka foot kohta pulssiaallosta (minimi):

BA plot from the PWV calculated from the foot point of the left and right ankle pulse signals (in m/s). Pearson correlation coefficient 0.880.

Nilkka huippukohta pulssiaallosta:

BA plot from the PWV calculated from the peak point of the left and right ankle pulse signals (in m/s). Pearson correlation coefficient 0.810.

➔Pearsonin korrelaatiot ovat suurempia nilkan signaaleista ➔ PWV mittauksen luotettavuus paranee etäisyyden kasvaessa.

➔Kaulasta-nilkkään mitattu PWV on saanut ‘kultaisen’ standardin aseman. Elastista tietoa on saatavissa sekä ranteen että nilkan pulssiaallosta EMFi anturilla!
Aortic Characteristic Impedance (Zc)

- Being commonly used measure of arterial stiffness, aortic characteristic impedance Zc is determinable from pressure and flow waves recorded simultaneously from the ascending aorta.
- Ratio of pressure harmonics to flow harmonics and depends on the dimensions and viscoelasticity of the involved artery, blood’s physical properties as well as on reflected waves from more distal parts of the arterial tree.
- Zc provides information about the physical state of the arteries, evaluating the level of external ‘afterload’ for the left ventricle.

- Arterial input impedance describes comprehensively and completely an arterial system. In order to specify aortic input impedance, pressure and flow waveforms are transformed into frequency domain (derived to their respective sinusoidal components) by computing Fourier transform of the waveforms to solve the frequency dependence of the aortic impedance.
Aortic Characteristic Impedance (Zc)

Input impedance (Zc) expressed as a function of frequency of the human systemic arterial tree. Modulus and phase angle of the impedance are obtained from the amplitude ratio and phase difference from the sine waves of the aortic pressure and flow.


Changes in the arterial system presented by means of ascending aortic input impedance (Zc) between normal condition (in blue) and hypertension (in red).

Aortic Characteristic Impedance (Zc)

- Two spectrum figures from a tilt test obtained from a larger EMFi sensor beneath studied persons. Change in orientation made minor changes into the BP values (left: age 26 years and apparently healthy). Right: frequencies of the main systolic complexes are clustered around the 6 Hz frequency area and the 0.2 Hz spike is minor when compared to other cases in the study (age 50 years) [9].

Night BCG tracing recorded from a sleeping four month old baby boy with an EMFi sensor below the baby [10]. Amplitude spectrum from the same recording taken from three peaceful sleeping sections between movement artefacts presenting an impedance spectrum from an arterial system having no hardening elements due to adolescence.

[9] Alametsä J, Viik J, Palomäki A. Ballistocardiographic spectrum studies with a tilt table. 11th World Congress on Medical Physics and Biomedical Engineering. September 7-12, 2009 Munich, Germany.
Seven years follow-up of ballistocardiography: Time domain results: Years 2006 - 2012

- Visually signal traces appear to be very stable.

- BCG trace from healthy people has been characterized by a ‘considerable distinctness of the waves and a constancy of all the time intervals’ [11]. This seems to be valid also in this study.

Seven years follow-up of ballistocardiography: Changes in spectral domain: Seat BCG 2006 - 2012

- The highest spikes in seat BCG differ from CP both in amplitude and in frequency.
Seven years follow-up of ballistocardiography: Changes in spectral domain: Carotid pulse 2006 - 2012

Cumulated and normalized amplitude spectrum; 0 – 20 Hz area from CP

The shifting of the frequency spikes to the right towards higher frequencies due to increase in heart rate is seen especially with elevated heart rates (p.75) in 060209 and (p.70) 130111.

The constancy of the spectral components in longer time interval is apparent.
Changes in temporal, amplitude, BP&PWV&HR values

<table>
<thead>
<tr>
<th>Time R-H (±SD)</th>
<th>Time R-I (±SD)</th>
<th>Time R-J (±SD)</th>
<th>Time R-K (±SD)</th>
<th>Amp H-I (±SD)</th>
<th>Amp I-J (±SD)</th>
</tr>
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<tbody>
<tr>
<td>0,10 ± 0,01</td>
<td>0,23 ± 0,02</td>
<td>0,31 ± 0,02</td>
<td>0,39 ± 0,01</td>
<td>1,14 ± 0,26</td>
<td>1,08 ± 0,29</td>
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<tr>
<th>Amp J-K (±SD)</th>
<th>Time R-P (±SD)</th>
<th>Time P-D (±SD)</th>
<th>Amp E-P (±SD)</th>
<th>Amp E-D (±SD)</th>
<th>Amp E-T (±SD)</th>
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<tr>
<td>0,53 ± 0,11</td>
<td>0,16 ± 0,02</td>
<td>0,22 ± 0,01</td>
<td>0,08 ± 0,03</td>
<td>0,02 ± 0,01</td>
<td>0,08 ± 0,03</td>
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<tr>
<th>BP systole (±SD)</th>
<th>BP diastole (±SD)</th>
<th>PWV foot (m/s ± SD)</th>
<th>PWV_max (m/s ± SD)</th>
<th>HR_Omron (±SD)</th>
<th>HR_calc RR (±SD)</th>
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<tr>
<td>147 ± 11,7</td>
<td>91,7 ± 5,3</td>
<td>6,4 ± 1,3</td>
<td>3,7 ± 0,2</td>
<td>63,7 ± 7,00</td>
<td>64,2 ± 6,78</td>
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-Conclusion: Time domain and spectral properties of the seat BCG and carotid artery signals remained relatively stable between the same person. We have earlier shown that signal components of BCG are repeatable in consecutive recordings as well as reproducible in longer time recording intervals [12].

-Variability in BP values had their own influence to arterial elasticity values seen in calculated PWV values.