Non-invasive method for the aortic blood pressure waveform estimation using the measured radial EBI

Andrei Krivoshei\textsuperscript{1,2}, Jürgen Lamp\textsuperscript{2,3}, Mart Min\textsuperscript{1}, Tiina Uuetoa\textsuperscript{2,4}, Hasso Uuetoa\textsuperscript{1,5} and Paul Annus\textsuperscript{1,2}

\textsuperscript{1} Tallinn University of Technology, Estonia
\textsuperscript{2} ELIKO Competence Center, Estonia
\textsuperscript{3} JR Medical OY, Estonia
\textsuperscript{4} East-Tallinn Central Hospital, Estonia
\textsuperscript{5} Sahlgrenska University Hospital, Sweden

E-mail: andrei.krivoshei@gmail.com

Abstract. The paper presents a method for the Central Aortic Pressure (CAP) waveform estimation from the measured radial Electrical Bio-Impedance (EBI). The method proposed here is a non-invasive and health-safe approach to estimate the cardiovascular system parameters, such as the Augmentation Index (AI). Reconstruction of the CAP curve from the EBI data is provided by spectral domain transfer functions (TF), found on the bases of data analysis. Clinical experiments were carried out on 30 patients in the Center of Cardiology of East-Tallinn Central Hospital during coronary angiography on patients in age of 43 to 80 years. The quality and reliability of the method was tested by comparing the evaluated augmentation indices obtained from the invasively measured CAP data and from the reconstructed curve. The correlation coefficient \( r = 0.89 \) was calculated in the range of \( AI_{\text{CAP}} \) values from 5 to 28. Comparing to the traditional tonometry based method, the developed one is more convenient to use and it allows long-term monitoring of the AI, what is not possible with tonometry probes.

1. Introduction

Increasing mortality in developed countries, caused by cardiovascular disease, and mainly by atherosclerosis and/or hypertension, is a major concern in modern medicine nowadays. Thereupon, the situation requires developing of novel, non-invasive and reliable monitoring and diagnosing tools capable to recognize a heart disease on its early progress stages.

Along with other parameters, the Central Aortic Pressure (CAP) and the Augmentation Index (AI) have been indicated in several studies as important cardiovascular risk markers \cite{1, 2}. It is well known, that the CAP curve is formed from the sum of the direct aortic pressure wave, just pumped out from the heart, and from the traveling wave reflected from peripheral arteries. A quickly arrived reflected wave will produce an increase in the CAP, and significant rise of which can be recognized as a risk marker. Thus estimating the contribution of a reflected wave to the CAP gives important information about condition of arteries and patient health risk.

Non-invasive estimation of the AI and the CAP is usually done by a well-known applanation tonometry, when a peripheral blood pressure is measured on a radial artery and then calibrated by the pressure values obtained using the brachial cuff. After that both, the CAP and the AI values, are estimated from the measured radial pressure and generalized transfer function \cite{3 - 6}.
In our research we show that AI can be estimated from a radial electrical bio-impedance (EBI) as well as from radial blood pressure curve. Comparing to the traditional tonometry based method, presented one is more convenient to use and it allows long-term monitoring of the AI, what is not possible with tonometry probes.

2. Method

Clinical experiments were carried out on 30 patients during coronary angiography in the Center of Cardiology of East-Tallinn Central Hospital. After that, the found out spectral domain transfer function TF was used to estimate the CAP waveform from the noninvasively measured radial EBI. All patients in age of 43 to 80 years were informed about the purpose and threats of an investigation and they all have signed consents. The investigation was carried in according to the decision of the Ethics Committee of the National Institute for Health Development.

The EBI was measured using the bracelet-type holder and specially designed tetra-polar sensor (figure 1), placed on a wrist directly onto a radial artery in close region to a scaphoid bone. The electrodes were made of non-toxic and non-irritable silver compound. The distance between measuring electrodes of 5 mm was used to limit the volume of the tissue under the measurement and thus to avoid any possible influence from surrounding veins and arteries. The distance of 14 mm was used between the current injecting electrodes, which were placed on the both sides from the voltage measuring electrodes. The frequency of the injecting current was 125 kHz and the amplitude 0.2 mA.

The measuring procedure, on the whole, was carried out using the JR Medical’s CE-certified wireless multichannel impedance cardiograph – circulation monitor “Circmon BT101” (figure 2), which allows simultaneous measurement of 6 impedance channels and one ECG channel in its default configuration. For the proposed investigation, two channels of the cardiograph were used for the EBI and for the ECG signal measurement, and another one was adapted to simultaneous acquiring of invasive CAP data using the PVB’s XTRANS sensor.

The block diagram of the BT101 is shown in the figure 3 and presented in more details in [7]. The major advantage of the BT101 is the significant increase in the precision of the EBI measurements, which has been achieved by using the carrier compensation technique [7] provided by the DDS2, the compensation signal which is subtracted from the modulated carrier in the summing element in figure 3. Both, the amplitude and phase of the compensating signal are estimated before the main EBI

![Figure 1 Experimental EBI sensor.](image1)

![Figure 2 View of the impedance cardiograph – circulation monitor “Circmon BT101”.](image2)

![Figure 3 A simplified block diagram of the impedance measurement device BT101.](image3)
detection procedure. As a result, the large basal impedance signal (carrier) is compensated and the base band EBI signal begins from the DC component without any distortions usually caused by the low pass filtering in traditional impedance cardiographs.

The data with 5 ms sampling intervals were transmitted via Bluetooth™ link to a personal computer in which the CircMon™ program runs for performing the initial data processing.

3. Transfer function (TF) estimation technique

To estimate the wanted transfer function TF, the initial cardiac periods of EBI and CAP were taken between the beginnings of two systolic intervals. The periods have zero mean value and are normalized by theirs standard deviations. To normalize the relative time positions, the periods are aligned in time domain by shifting the fronts of EBI and CAP waveforms of the systolic interval to the middle position of signal periods. The circular shifting of signal arrays was used for this purpose.

The transfer functions TF between the EBI and CAP spectra (1) are estimated by dividing (2) the complex spectra of CAP by the EBI spectra for each patient’s data individually.

\[
S_{EBI}(j\omega) = \text{DFT}\{EBI(t)\} \\
S_{CAP}(j\omega) = \text{DFT}\{CAP(t)\} \\
\text{TF}(j\omega) = \frac{S_{CAP}(j\omega)}{S_{EBI}(j\omega)} 
\]

Further, the estimated transfer functions (TF) are scaled (stretched or squeezed) in spectral domain by corresponding heart rate (HR) values. And, after ensemble averaging of all the found individual transfer functions the generic TF was found.

4. Results

The on-line operating algorithm for the CAP waveform reconstruction and AI value estimation from the measured radial EBI waveform is implemented as a DLL function, programmed in the NI LabVIEW environment.

During experimentation, the EBI signal periods are sent individually into the DLL, where the generic TF, found on the analysis stage, is scaled back (squeezed or stretched) by corresponding HR value and multiplied by the harmonic spectrum of the received EBI signal period. The reconstructed CAP signal spectrum is transformed back into time domain and returned from the DLL into the main CircMon™ program together with the estimated AI value (3) for displaying and further diagnosing (see figure 6).

The AI values for original CAP (AI_{CAP}) and for reconstructed one (AI_{EBI}) are calculated as

\[
AI_{\{\text{CAP/EBI}\}} = \frac{(CAP_B(t) - CAP_C(t))}{(CAP_B(t) - CAP_A(t))} \times 100\% ,
\]

where \( CAP_n(t) \), \( n = \{A, B, C\} \) are pressure values of the CAP curves at points \( A, B, C \) in figure 6.

The quality and reliability of the method were tested by comparing two AI values, AI_{CAP} and AI_{EBI}
– those based on the invasively measured CAP data (channel RA in figure 6) and those obtained from the reconstructed CAP curve (channel AO in figure 6). A correlation coefficient for all 30 patients is $r = 0.89$ in the range of 5 to 28 of the $AI_{CAP}$ values (see figure 4 and figure 5).

5. Discussions and conclusions
As shown above, the EBI measurement at radial artery can give a new non-invasive and easy-to-use reliable and operator independent method for estimating the beat-by-beat CAP curve continuously. This is helpful for cardiovascular disease risk assessment in clinical practice. Moreover, further development of the method can open new frontiers for dynamic CAP analysis, e.g., during exercising or mental stress testing of patients.

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References
[1] Avolio A P, Butlin M and Walsh A 2010 Arterial blood pressure measurement and pulse wave analysis – their role in enhancing cardiovascular assessment Physiol. Meas. 31 R1–R47
[2] Nürnberg J, Keflioglu-Scheiber A et al 2002 Augmentation index is associated with cardiovascular risk J. Hypertens. 20 2407-14
[3] Karamanoglu M, O’Rourke M F, Avolio AP, Kelly RP 1993 An analysis of the relationship between central aortic and peripheral upper limb pressure waves in man European Heart J. 1993 14 160-7
[4] O’Rourke M F 1993 Method for ascertaining the pressure pulse and related parameters in the ascending aorta from the contour of the pressure pulse in the peripheral arteries. US Patent 5,265,011
[5] O’Rourke M F 2000 Non-invasive determination of aortic flow velocity waveforms US Patent 6,010,457
[6] Hahn J-O, Reinsner A T and Asada H H 2010 Estimating aortic blood pressure from non-invasive extremity blood pressure. US Patent Application 2010/0016736 A1
[7] Annus P, Lamp J, Min M and Paavle T 2005 Design of a Bioimpedance Measurement System Using Direct Carrier Compensation Proc. of the European Conference on Circuit Theory and Design Aug.29-Sept.02 2005 Cork Ireland vol III pp 23 – 6