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Estimating the Transfer Function between the CAP and Radial EBI Cardiac Periods: Use of PCA for Dominating Spectral Features Analysis

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Abstract. The paper presents an estimating algorithm of the transfer function (TF) between the Central Aortic Pressure (CAP) and the Electrical Bioimpedance (EBI) cardiac periods. The Principal Component Analysis (PCA) algorithm is applied to harmonic spectra of the EBI and CAP periods and used to emphasize the dominating spectral features in the resulting estimated TFs by suppressing less interesting and disturbing features. The research work is in active development stage. The proposed algorithm is implemented in LabView programming environment as a software tools. Some promising qualitative results are obtained already, however more detailed analysis is needed.

Keywords: Central Aortic Pressure; Electrical Bioimpedance; Blood Pressure; Non invasive blood pressure; Transfer function

1. Introduction

According to [Avolio et al., 2010] and [Nürnberger et al., 2002], along with other parameters, the high blood pressure is well recognized as the risk factor for cardiovascular, cerebrovascular, renovascular and some other diseases.

In clinical practice, arterial pressure is mostly measured from the brachial artery using a sphygmomanometer. Due to arterial elasticity/stiffness, different vessel diameters and pulse wave reflections, blood pressure varies in different arteries. It is known that blood pressure in brachial artery (BaBP) is not always directly correlated with the central aortic pressure (CAP). It has been recognized that CAP has a better predictive value as a risk marker when compared to the BaBP. Besides, it has been pointed that some treatment can reduce the BaBP, while the CAP remains largely unchanged [B. Williams et al., 2006]. Accordingly, cardiovascular and other risks may remain high despite the decreased or even normalized BaBP. As a result, a better understanding of the curvature shape of CAP values and Augmentation Index (AI) could prospectively be valuable indices for guiding antihypertensive therapy and predicting the risk of cardiovascular mortality [Chirinos et al., 2005] and [Mitchell et al., 2010].

The CAP can be measured directly only by expensive and time consuming invasive methods. Possible limitations of the invasive approach are that this can be carried out only under stationary conditions and, therefore, in a limited number of patients. Due to this restriction, possible application of personalized diagnostics with subsequent therapy and relevant rehabilitation to broader population cannot be attained.

Nowadays, the CAP can be measured and calculated non-invasively using different methods. Most commonly it can be done from radial artery pressure waveform analysis. For that purpose, the Sphygmocor device is widely used [Karamanoglu et al., 1993], [O'Rourke, 1993], [O'Rourke, 2000] and [Hahn J-O. et al., 2010]. Still, this approach has some limitations like estimation of the CAP curve is available in subjects under resting conditions, in lying or sitting position. Also, significant intra- and inter-operator variability can lead to poor reproducibility of measurements.

The current situation stimulated us to develop the present non-invasive continuously operating monitoring and diagnostic tool. The proposed study serves a part of an ongoing research project described by [Krivoshei et al., 2013].

Comparing to tonometry, the present method is more convenient and reliable to use and allows long-term continuous monitoring of the AI and CAP.

2. Data Acquisition

The data acquisition system and measurement procedure were described in detail in [Krivoshei et al., 2015]. For the proposed paper the same measured data are used. Therefore, we describe the measurement procedures used for data recordings shortly.

All clinical experiments were carried out in the Heart Centre of the East-Tallinn Central Hospital, Tallinn, Estonia. The investigation was approved by the Ethics Committee of the National Institute for Health Development.

Electrical Bioimpedance (EBI) measurements and direct invasive blood pressure recordings from contra-lateral radial artery and from aortic root were registered from about 60 voluntary patients aged from 43 to 80, admitted to the Heart Centre of the East-Tallinn Central Hospital for elective coronary angiography.

The EBI measurement was carried out using a wireless multichannel impedance cardiograph and circulation monitor Circmon^{TM} BT101 from JR Medical (Tallinn, Estonia) with a bracelet-type tetra-polar sensor. The sensor was placed on the left wrist directly above a radial artery close to the scaphoid bone.

The electrodes of the EBI sensor were made of non-toxic and non-irritable silver compound. The distance between voltage measuring electrodes was 5 mm. The distance between the current injecting electrodes was 14 mm. The current injecting electrodes were placed on both sides of the voltage measuring electrodes. The frequency of injected current was 125 kHz and the amplitude had a RMS level of 0.2 mA.

The invasive pressure measurements were carried out with catheters dedicated for percutaneous coronary angiography (Optitorque Sarah Radial, Double braided 5F Terumo Interventional Systems; or Infiniti Diagnostic Catheters, Braided, 6F, JL4 Cordis Corporation). Catheter was inserted through the femoral or radial artery during the standard coronary angiography procedure. For that after the local skin anesthesia, the radial or femoral artery was punctured by needle and short guidewire was inserted to arterial lumen. Over the guidewire the special cannula (6F Ultimum TM Hemostatic introducer, St.Jude Medical, USA) was introduced and flushed with heparine solution. That set up access to the arterial blood stream. Through the cannula the long guidewire passed up under fluoroscopy control to the aorta, then over that guidewire the coronary angiography catheter guided to the aortic root. For the measurement of central aortic blood pressure (CAP), the catheter tip was placed under X-ray control in a center of aortic root. Proximal connector of the catheter was connected with pressure sensor (DPT-9000/Xtrans; CODAN PVB Medical GmbH (Germany)) for invasive aortic pressure curve registration and recording.

The frequency of sampling of the EBI and CAP signals was 200 Hz and the resolution of used A/D converter in Circmon BT101 device was 16 bits [Annus et al., 2005].

All patients were informed about the situation and procedures, they signed consent forms before recruitment. Patients were clinically stable and did not have indication for any further coronary interventions.

3. Use of PCA for Dominating Spectral Features Analysis

In the paper we propose an approach to extract the most significant features in the transfer function between the CAP and radial EBI signals.

The main point in the proposed idea is next: looking for some relations (i.e. the transfer function or frequency response) between time domain signals, like the EBI and CAP, we automatically assume that the signals have some common information, which they are share.

In our study we assume, that the radial EBI and the CAP signals have some significant common features in their waveforms and also have some differences as well.

On the basis of the assumption made above, we propose the transfer function estimation algorithm using the PCA [Migueí A Carreira-Perpiñán, 1997] to filter out the signals differences, which are less interesting for the transfer function under estimation and, therefore, to emphasize common peculiarities.

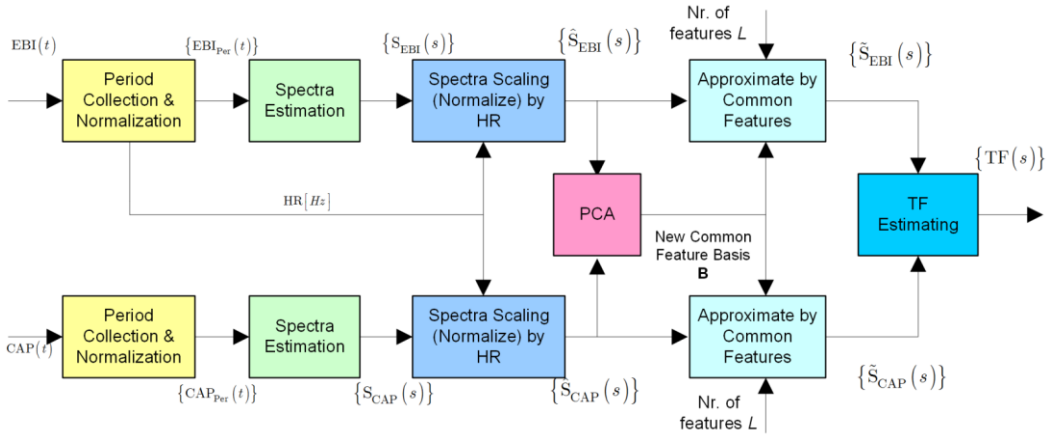

Figure 1. *A block diagram describing the TF estimating algorithm from the real invasively measured CAP and from the radially measured EBI waveforms.*

The proposed algorithm is shown in Fig. 1. Firstly, the time domain CAP and EBI signals simultaneously measured intervals are selected manually using a user interface for now. After that cardiac periods are collected into respective ensembles for both signals (yellow boxes in Fig. 1). The period collecting algorithm is described in [Krivoshei et al., 2015] and shortly presented in the section 5.

The FFT (green boxes) is applied to each period and the spectra ensembles are saved. In opposite to [Krivoshei et al., 2014], where the estimated transfer functions were normalized along the X axis by the heart rate, in the proposed algorithm the harmonic spectra of the EBI and CAP signals periods are normalized in the same manner along the X axis by the HR value.

To extract common features the PCA is applied to concatenated EBI and CAP spectra ensembles, which are normalized along the axis X by respective HR and normalized in amplitude to have unit standard deviation ($\mathrm{std}(\mathbf{x}) = 1$).

The PCA is applied separately to real and imaginary parts of the complex spectra ensembles. And each cardiac period spectrum from the EBI and CAP ensembles is represented in the estimated common feature basis (eigenvectors of the ensemble) by coefficients vector $\mathbf{c}$:

$$\mathbf{c} = \mathbf{B}^{\mathrm{T}} \bar{\gamma} \mathbf{x} \tag{1}$$

where in $\mathbf{x}$ is a column vector of a single cardiac period, $\mathbf{B}$ is common feature basis (eigenvectors of $\mathbf{X}^{\mathrm{T}}\mathbf{X}$ in columns) and $\mathbf{c}$ is row vector of coefficients in the new basis. Equation (1) can presented in matrix form as

$$\mathbf{C} = \mathbf{B}^{\mathrm{T}} \bar{\gamma} \mathbf{X} \tag{2}$$

Approximation of the individual spectra by the first L common feature basis components is described by

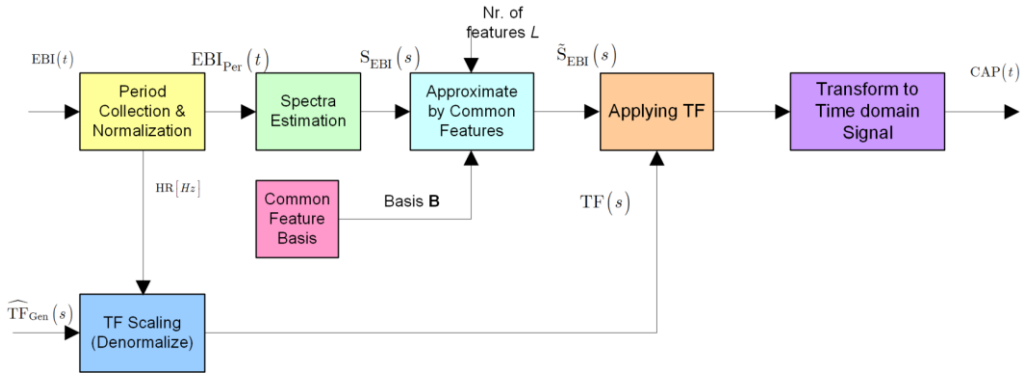

Figure 2. *A block diagram describing the CAP period waveform restoration from the generic TF and radially measured EBI cardiac periods.*

$$\mathbf{X}_{M \times N} = \mathbf{B}_{M \times L} \mathbf{C}_{L \times N} \quad (3)$$

where N is the number of cardiac harmonic spectra in the ensemble, M is the number of samples in the harmonic spectra and L is number of common features to leave in spectra.

4. Transfer Function Estimation

The last block in Fig. 1 shows the transfer function estimation procedure, which is applied to all respective EBI and CAP periods in the ensemble individually. In detail the TF estimation algorithm is described in [Krivoshei et al., 2014] and here, we shortly describe this procedure.

Each individual transfer function between the EBI and the CAP spectra is estimated by dividing the complex spectra of EBI $S_{EBI}(s)$ and CAP $S_{CAP}(s)$.

$$TF(s) = S_{EBI}(s) / S_{CAP}(s) \text{ , where} \quad (4)$$

$$\begin{aligned} S_{EBI}(s) &= DFT(EBI(t)) \\ S_{CAP}(s) &= DFT(CAP(t)) \end{aligned} \text{ , and} \quad (5)$$

where s ホ「 are the index numbers of spectral components. Constant level, equal to 1, was added both to the EBI and to the CAP periods to eliminate division by numbers close to zero in (4).

Further, an ensemble of the estimated transfer functions ($TF(s)$ in (5)) is averaged to obtain the generic TF.

Restoration algorithm of the CAP period waveform from the radially measured EBI period is shown in Fig. 2 for individual cardiac periods. It is similar to estimation algorithm shown in Fig. 1, but differs in using the already known common feature basis $\mathbf{B}$ to approximate the EBI period spectrum and in applying denormalization procedure along the axis X by the heart rate to the generic TF (bottom blue block in Fig. 2).

5. Collecting Cardiac Periods

A waveform slope between the first and last samples of the each individual EBI and the CAP waveform periods is subtracted. As it was mentioned above all the periods are normalized in their amplitudes by standard deviation.

A criterion for the selection of the beginnings of cardiac cycles was defined experimentally with the reference to the faster front of the EBI signal. The CAP signal periods were selected synchronously with the defined EBI signal periods.

In the current research work the period beginning is marked at the maximum level of the first order derivative of the EBI period (see Fig. 3). More advanced description and analysis is presented in [Krivoshei et al., 2014].

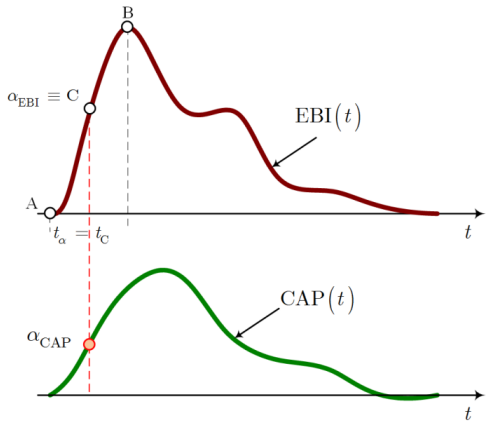

Figure 3. *An illustration for the heart pulse selection criterion. The points A and B correspond to the minimum and maximum of the EBI signal respectively and the point C corresponds to the maximum of first derivative (not shown in figure). The point* ^{a} *corresponds to the found beginning of a period and placed to C point position for this study.*

6. Discussion

The proposed algorithm is describing the possibility to select dominating features in the EBI and CAP signal periods spectra by processing periods ensemble with PCA. The common feature basis is found from the principal component analysis and used for selection of these dominating features in periods spectra. Therefore the resulting generic TF will contain that selected mutual features.

The research work is in active development stage. The proposed algorithm is implemented in LabView programming environment as a software tools. Some promising qualitative results are obtained already, however more detailed analysis is needed.

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