AVERAGING OSCILLOMETRIC NON-INVASIVE BLOOD PRESSURE RECORDINGS: TRANSFORMATION INTO THE NORMALISED VIEW

V. Jazbinsek*, J. Luznik* and Z. Trontelj*

* Institute of Mathematics, Physics and Mechanics, University of Ljubljana, Ljubljana, Slovenia

vojko.jazbinsek@imfm.uni-lj.si

Abstract: We have studied oscillometric pulses obtained by non-invasive blood pressure measuring device. We have introduced a transformation of data into the normalised heart beat view to get these pulses independent on variations of the heart beat duration. The transformed arterial pressure pulses obtained from different recording sessions can be compared with each other, or they can be averaged to obtain the normalised reference pulses. We have found that such reference can be used for extracting artefacts from measured data.

Introduction

Many oscillometric non-invasive blood pressure (NIBP) measuring devices are based on recording the arterial pressure pulsation in an inflated cuff wrapped around a limb during the cuff pressure deflation [1]. The deflation can be removed from the recorded NIBP data by a digital band pass filtering [2]. The obtained arterial pressure pulses are known as the oscillometric pulses. However, some NIBP measurements are contaminated with the external artefacts arising mainly from person's movements. In most cases, these artefacts generate pressure changes in the cuff, which have similar frequency response as the oscillometric pulses and it is therefore difficult to separate them. In order to get oscillometric pulses independent on variations of each heart beat duration, we have introduced a transformation of data into the normalised heart beat view. The transformed pulses can be averaged to obtain the normalised reference pulses. We have used such reference to extract artefacts from measured data.

Materials and Methods

For NIBP measurements, we have used the same device as explained in [2] that was designed by LODE (Groningen, NL) for the EU-project ”Simulator for NIBP” [3]. We performed measurements on the upper arm of healthy volunteers. Altogether, we have recorded data on 23 persons (11 females and 12 males) between 20 and 66 years old. For each person, we made at least two measurements without external artefacts. In addition, we performed measurements, where external artefacts were induced. Most of attention was paid to the external artefacts that could be repeated for every volunteer and arose from known effects: beating the cuff, external sound in the environment, moving of the arm support, tremor, coughing, speaking, walking, muscle contraction in the upper arm induced by moving the arm, hand, finger or fist, etc. We instructed each volunteer before the recording session, how to produce these types of external artefacts. Some of the artefacts were periodically repeated during the measurements. These measurements were triggered visually by the volunteer looking at the computer monitor that changing the background colour with the desired frequency.

Most of applied external artefacts generate changes of pressure in the cuff that are similar in shape and frequency response as the arterial pressure pulses. For analysing measured pressure data with artefacts included, it thus would be useful to have a reference, artefacts free oscillometric waveform for comparison. However, during NIBP measurements heart beat varies. In order to get shapes of oscillometric pulses independent on variations of heart beat duration, we presented data in the normalised heart beat view, where the variable duration (Δt_{var}) of each measured heart beat is re-scaled to a fixed value (Δt_{fix}). The first step in this procedure is a segmentation of measured data into heart beats (Figure 1b). Rescaling of Δt_{var} into Δt_{fix} is then obtained by re-sampling of measured data for each heart beat. Suppose that the measured data in the time interval Δt_{var} are sampled with a frequency ν_m and we want to re-scale these data with a sampling frequency ν_{fix}, then each heart beat will be represented with the same number of points, N_{fix}, where

$$N_{fix} = \Delta t_{fix} \cdot \nu_{fix}\,. \tag{1}$$

The core of the forward transformation ($\Delta t_{var} \rightarrow \Delta t_{fix}$) is to determine a re-sampling frequency (ν_{re}) to represent each heart beat (Δt_{var}) with N_{fix} points:

$$N_{fix} = \Delta t_{var} \cdot \nu_{re}\,, \tag{2}$$

while the originally measured data are represented by N_{var} points:

$$N_{var} = \Delta t_{var} \cdot \nu_m\,. \tag{3}$$

Combing Eqs. 1, 2 and 3 leads to

$$\nu_{re} = \frac{N_{fix}}{\Delta t_{var}} = \frac{\Delta t_{fix}}{\Delta t_{var}} \nu_{fix} = \frac{N_{fix}}{N_{var}} \nu_m\,. \tag{4}$$

For the backward transformation ($\Delta t_{fix} \rightarrow \Delta t_{var}$) one has to re-sample ”normalised” data on Δt_{fix} with a frequency

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v_b to obtain original N_{var} points again

$$N_{var} = \Delta t_{fix} \cdot v_b \,. \tag{5}$$

Combing Eqs. 3, 5 and 2 leads to

$$v_b = \frac{N_{var}}{\Delta t_{fix}} = \frac{\Delta t_{var}}{\Delta t_{fix}} v_m = \frac{N_{var}}{N_{fix}} v_{fix} \,. \tag{6}$$

The above forward and backward transformations are not exactly reversible, because each re-sampling itself is not reversible. The original data (**D**) sampled on Δt_{var} is sampled with the v_m at time points **t**:

$$\mathbf{D} = (D_1, D_2, \dots, D_{N_{var}}) \,, \quad \mathbf{t} = (t_1, t_2, \dots, t_{N_{var}}) \,, \tag{7}$$

while the re-sampled (with v_{fix}) data (**F**) at time points τ (forward transformation):

$$\mathbf{F} = (F_1, F_2, \dots, F_{N_{fix}}) \,, \quad \tau = (\tau_1, \tau_2, \dots, \tau_{N_{fix}}) \,, \tag{8}$$

where each F_i $(i = 0, 1, \dots, N_{fix})$ is determined by linear interpolation of **D**:

$$F_i = D_k + \frac{D_{k+1} - D_k}{t_{k+1} - t_k} \tau_i \,, \; \tau_i \in [t_k, t_{k+1}] . \tag{9}$$

With the backward transformation we obtained data ($\tilde{\mathbf{D}}$) sampled with the v_m at the original time points **t**:

$$\tilde{\mathbf{D}}_\mathbf{k} = F_i + \frac{F_{i+1} - F_i}{\tau_{i+1} - \tau_i} t_k \,, \; t_k \in [\tau_i, \tau_{i+1}] \,, \tag{10}$$

where $\tilde{\mathbf{D}} \simeq \mathbf{D}$. We found that typical relative differences between $\tilde{\mathbf{D}}$ and **D** were less than 0.5 %, which was below the noise level.

Results

Figure 1 shows an example NIBP measurement. The recorded data are filtered with the band pass (0.3-20 Hz) digital filter [2, 4] (Figure 1a) to remove the deflation signal from the measured NIBP data. The deflation can be also removed from the NIBP data with the segmentation of data into pulses (Figure 1b). The deflation signal, calculated by the interpolation of data between subsequent segment borders, is subtracted from the measured data to obtain only pulses with positive deflections. Such pulses are known as oscillometric pulses. Note, that segmentation borders coincide with time points, which determine the minimal envelope of filtered pulses in Figure 1a.

Figures 2a,b show two oscillometric waveforms obtained from measurements on the same person. The first recording is the same as in Figure 1. We first transform both waveforms of oscillometric pulses into the normalised heart beat view. Each pulse of data presented in the time view is re-sampled by using Eq. 4 to obtain oscillometric pulses in the normalised heart beat view. Then we average them to obtain a normalised reference waveform. When comparing waveforms obtained from different recordings, we allowed shifts of N (usually N is set to 5 beats) to reach the best match between them. We called this procedure waveform optimisation (WO). The average waveform is then calculated by summing optimally shifted waveforms. Criteria for the WO include minimum value of relative difference (RD), maximum value of correlation coefficient (CC) and minimum value of maximum difference (MD) between waveforms.

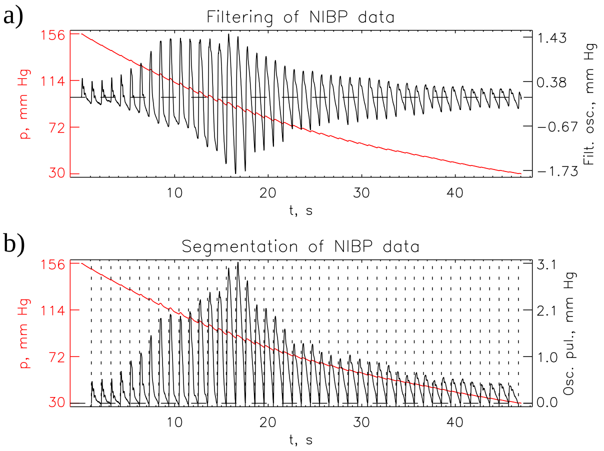


Figure 1: a) Measured NIBP data (left scale) and filtered pulses (right scale) obtained by bandpass (0.3–20 Hz) filtering. b) Measured NIBP data (left scale) and oscillometric pulses (right scale) obtained by segmentation of data into heart beats. Segmentation borders (vertical dashed lines) coincide with time points that determine the negative envelope of filtered pulses.

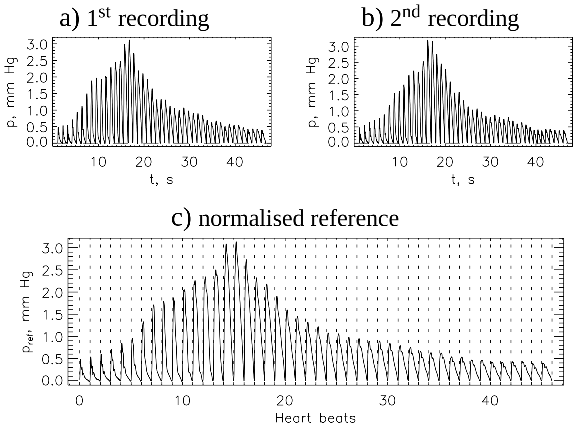


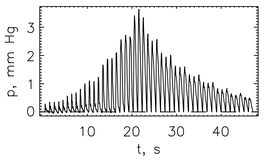
Figure 2: Oscillometric pulses from the a) 1^{st} recording and b) 2^{nd} recording, and c) the normalised reference obtained by averaging those two recordings.

To get the reference signal for given measured oscillometric pulses in a real (measured) time scale, one has to transform the normalised reference oscillation waveform back to the real time scale of the given measured data using Eq. 6 to re-sample each pulse. However, since oscillometric pulses slightly differ from measurement to measurement, we have used beside the WO (see above) also a single beat optimisation (SBO) during the transformation. In both types, we first convert a given waveform into the normalised heart beat view and then compare it with the normalised reference waveform. In the case of WO, the whole waveform is compared with the normalised reference. The optimised shift in the range N beats is found and optimally shifted reference waveform is converted back into the real time scale of a given waveform. In the case of SBO, a single heart beat pulse at a given cuff pressure (deflation) level is compared with the heart beat pulses from the normalised reference. When comparing a single heart beat, we can choose between the following options

- *ref_beat* - using the reference beat at a given deflation level,
- *amp_ref* - optimisation of amplitude for a reference beat at a given deflation level.
- *ref_shift* - finding the best reference beat in the range N beats around a given deflation level,
- *ref_shift_amp* - finding the best reference beat in the range N beats around a given deflation level, then optimisation of amplitude for the best reference beat,
- *shift_t_amp* - finding the best reference beat in the range N beats around a given deflation level, then optimisation of time shift and amplitude for the best reference beat,
- *t_amp_shift* - optimisation of time shift and amplitude for beats in the range N beats around a given deflation level, then selection of best matching optimised reference beat.

Additionally, there are some constraints included in the SBO, especially for the amplitude corrections. Final results can be also visually inspected and interactively corrected. Figure 3 shows results of backward transformation on the third recording (Figure 3a) performed on the same person as the first two recordings (Figures 2b,c). We have transformed the normalised waveform shown in Figure 2c into the time scale of the third recording using both WO and SBO to obtain the reference waveforms in the time view. Figures 3b,c display results of subtraction of these waveforms from the third recording. Results show that the SBO generate better reference waveforms than the WO. With this procedure most of the arterial pressure pulses can be subtracted from the measured data. This is important when external artefacts are included in NIBP recordings. In most cases, these artefacts generate pressure changes in the cuff, which have similar frequency response as the arterial pressure pulses and it is therefore difficult to separate them. In all such cases, we have used the normalised reference waveform, obtained from reference recordings for a given volunteer, as a template to calculate the reference oscillometric waveform. Figure 4 demonstrates such procedure in the case of periodic fist closing artefact. The person was closing her/his fist every 5 seconds during the NIBP measurement. We performed the following steps during the analysis

a) 3^{rd} recording



b) Subtracted reference (WO) c) Subtracted reference (SBO)

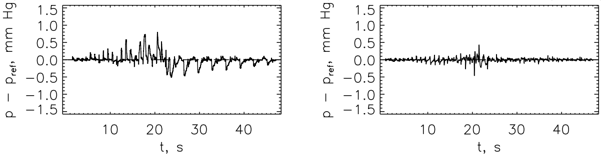


Figure 3: Oscillometric pulses from the a) 3^{rd} recording and residuals after reference subtracting obtained by using b) WO and c) SBO.

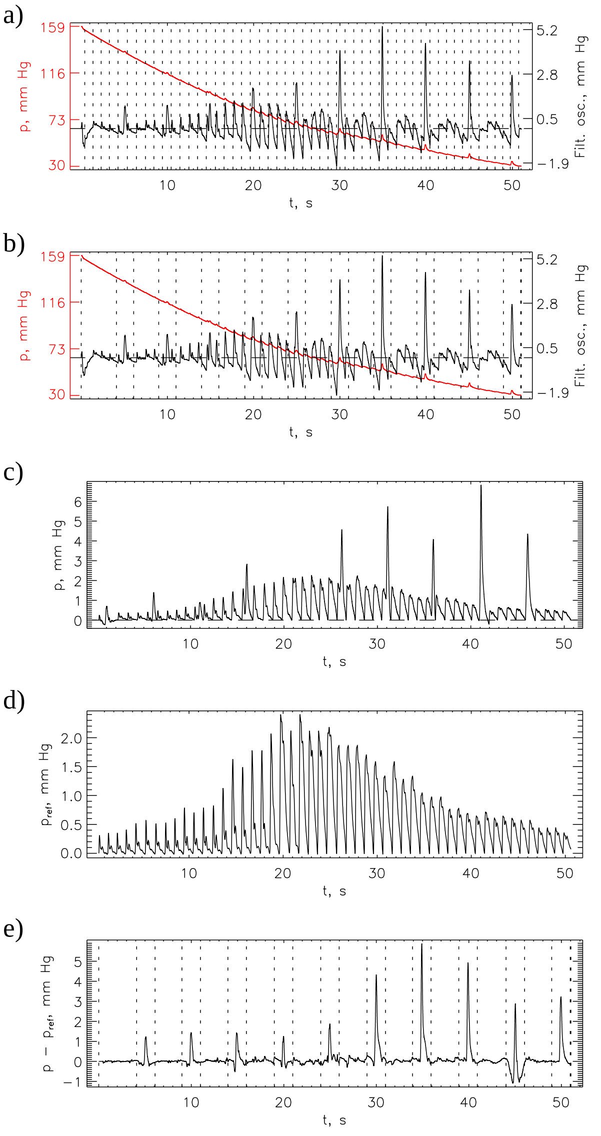


Figure 4: Steps in the fist artefact extraction: a) heart beat segmentation, b) artefact segmentation, c) calculation of pulses, d) estimation of oscillometric waveform from the normalised reference waveform, e) subtraction of estimated oscillometric waveform.

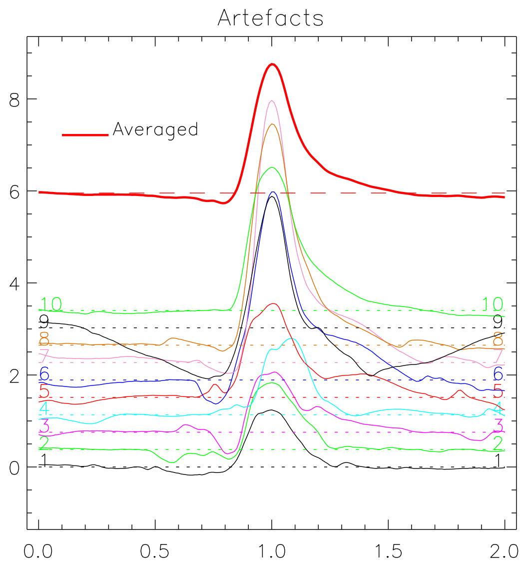


Figure 5: All ten extracted artefacts from Figure 4e are displayed above each other. Averaged shape is shown on the top and plotted with a thicker line.

- heart beat segmentation (Figure 4a) using filtered data (see also Figure 1),
- artefact segmentation - 2 s interval around the artefact peak (Figure 4b),
- calculation of pulses (Figure 4c) using heart beat segmentation from Figure 4a,
- estimation of the oscillometric waveform (Figure 4d) using the normalised reference obtained from artefact-free recordings,
- subtraction of the estimated oscillometric waveform, shown in Figure 4d, from Figure 4c to obtain only artefacts (Figure 4e),
- extraction of artefacts from Figure 4e using artefact segmentation in Figure 4b, and averaging these extracted artefacts (Figure 5).

This type of movements generates short positive spike-like deflections of duration 1 to 2 heart beats, see Figures 4a-c,e. Amplitudes are in the range from approximately 1 mm Hg to 6 mm Hg. These amplitudes depend mainly on the intensity of fist closing movements. We found out that amplitudes of most artefacts, which were induced by person's movements, depended on how much the upper arm muscles (around which the cuff was wrapped), were contracted during these movements.

Conclusions

In this work we showed that the transformation of oscillometric waveforms into the normalised heart beat view enabled comparison of arterial pressure pulses and their waveforms obtained from different NIBP recordings. The normalised reference waveform can be calculated by averaging. In cases, where NIBP measurements are contaminated with external artefacts, this normalised reference can be used as a template to extract a normal oscillometric waveform from such data.

Acknowledgment

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