Blood pressure analysis on time scales from seconds to days
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Citation for published version (APA):
Westerhof, B. E. (2005). Blood pressure analysis on time scales from seconds to days

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Chapter 8

Variable day/night bias in 24-h non-invasive finger pressure against intrabrachial artery pressure is removed by waveform filtering and level correction

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In previous studies we showed (1,2) that non-invasive arterial finger pressure (FAP) and intrabrachial pressures (BAP) differ systematically. The frequency transfer function from brachial to finger arteries has a resonance near 8 Hz. In addition, the finger diastolic and mean pressures may be some 8–10 mmHg less than brachial values. By application of a generalized waveform filter, the 8 Hz resonance can be compensated by an 8 Hz anti-resonance, and near-brachial waveforms can be derived from FAP waveforms (3). The subsequent application of a generalized regression-type equation with the filtered finger systolic and diastolic pressures as independent variables restores the BAP values, on average (1,2). This brachial reconstruction technique was developed on a database of short, steady-state sections of individual waveforms available from previous studies, and the results were correct for the population concerned.

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Later, we demonstrated that waveform filtering also improved the tracking of changes in (systolic) pressure and baroreflex sensitivity during states of vasodilatation from bicycle ergometer exercise and vasoconstriction from graded phenylephrine infusion (3), situations for which tracking of BAP by FAP was considered inadequate (4,5). This was the first result showing that waveform filtering not only improves resting blood pressures, but is also effective in correcting the response of an individual person’s FAP to changes in circulatory state.

In a previous study (6) we demonstrated the ability of non-invasive continuous ambulatory FAP recording with Portapres to track BAP with limited bias and acceptable precision, but that the important day-to-night blood pressure dip (7) was overestimated in the finger. We therefore decided to evaluate the effectiveness of the combined waveform filtering and level correction techniques on 24-h recordings of FAP and BAP, with particular interest in the changes in bias between day and night.

**Methods**

**Participants**

We recorded non-invasive FAP and BAP continuously during 24 h in eight normotensive volunteers and 16 patients with hypertension. Details of the patients and measurements have been published previously (6). Briefly, the volunteers were aged 19–32 years and the patients were aged 20–60 years. The patients had discontinued their antihypertensive medication 2 weeks before they were studied. FAP was measured on the dominant (right) arm using a TNO Model 1 Portapres device. BAP was recorded in the brachial artery of the non-dominant arm with the Oxford Medilog Mark II, but the pressure signal was recorded on a separate channel of the Portapres, guaranteeing synchronous recording. Because we measured BAP and FAP on contralateral arms, we required that the average of six simultaneous left- and right-arm auscultatory systolic and diastolic pressures should agree to within 5 mmHg. Hydrostatic height differences between the finger and the Oxford pressure transducer were also recorded and continuously subtracted from the FAP waveform. Measurements were started at 1300 h and lasted until 1300 h on the following day. A standardized activities procedure was strictly adhered to, as follows. Siesta: 1400–1530 h; cycling at 50 W: 1645–1715 h; sleep: 2200–0600 h; outside walk: 1000–1030 h and 1100–1130 h. In the remaining
periods, the participants were free to move in the hospital. The study procedure was approved by the ethics committees of both hospitals and informed consent was obtained from each participant.

Analysis

In the case of some participants, not all periods of interest were successfully recorded, because of various instrumental failures (6). Two patients of whom we had no sufficiently complete recordings were excluded from the present study, thus eight volunteers and 14 patients remained. In the results, the number of included participants is given for each period. A generalized waveform filter was applied to the FAP records to remove the near 8 Hz resonance (3) and level correction was applied to the waveform filtered FAPs as previously described (1,2). In addition to the continuous FAP and BAP signals, we thus had a third signal channel named ‘reconstructed BAP’ (reBAP). Original FAP, reBAP and original BAP waves were analyzed for beats. Those beats that were simultaneously present were compared after artifacts had been rejected, in exactly the same way (using the original files) as in the previous study (6). In the 22 participants, 90% of the beats were simultaneously available. Finally, level differences were obtained per beat for systolic, diastolic and mean pressures, as the difference between original FAP and BAP values and between reBAP and BAP values.

Statistics

Mean values and standard deviations (SD) were calculated for each individual for the entire 24-h period, for each 30 min and for the following specific periods: daytime, siesta, sleep, cycling and walking. Next, the mean values were pooled for the group of the eight volunteers, for the 14 patients, and for all 22 participants. This was permissible, in view of the strict scheduling of the specific activities and rest periods during the 24-h period. Averages for specific periods were not always available for each individual, because of artifacts, so for each period we specify the number of participants involved. When the mean values and SD of the pressure differences are calculated in this way, bias and precision statistics are obtained. The principal differences were original FAP minus BAP (FAP – BAP) and reBAP minus BAP (reBAP – BAP), which were tested for the significance of their bias from zero using the t-test. Significance was assumed at $P < 0.05$. 

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Continuous systolic (Syst.), diastolic (Dias.) and mean blood pressures averaged per 30 min and pooled for the group of 22 participants in the study for whom the full 24-h signal data were available. Measurements started at 1300 h and continued until 1300 h on the following day. Periods of scheduled and exactly timed activities are indicated on the time axis. Continuous lines, intrabrachial artery pressures (BAP); dashed lines, non-invasive finger artery pressures (FAP); dotted lines, reconstructed brachial artery pressures (reBAP). The lower panels show the individual pressure differences before (left) and after (right) brachial reconstruction. To show tracking ability, the individual mean bias has been removed.
Results

The left upper panel of Figure 1 presents the 30-min mean values for the systolic, diastolic and mean values of FAP and BAP, pooled for the entire group. Bias was clearly smallest for systolic pressure. For all three pressures, FAP showed a greater dip than BAP during siesta and at night. Exercise in the forms of cycling and walking caused FAP values to increase more than those for BAP. The right upper panel compares the same pressures, but original FAP values are replaced by reBAP. Differences are reduced, and the larger dips in FAP during siesta and at night have disappeared. The lower panels show the individual hourly pressure differences before (left) and after (right) brachial reconstruction.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Systolic (mmHg)</th>
<th>Diastolic (mmHg)</th>
<th>Mean (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FinAP – BAP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volunteers (n = 8)</td>
<td>5 ± 10</td>
<td>−7 ± 7 *</td>
<td>−9 ± 8 *</td>
</tr>
<tr>
<td>Patients (n = 14)</td>
<td>−1 ± 10</td>
<td>−9 ± 7 *</td>
<td>−11 ± 8 *</td>
</tr>
<tr>
<td>All (n = 22)</td>
<td>1 ± 10</td>
<td>−8 ± 7 *</td>
<td>−10 ± 8 *</td>
</tr>
<tr>
<td>reBAP – BAP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volunteers (n = 8)</td>
<td>3 ± 10</td>
<td>1 ± 7</td>
<td>1 ± 7</td>
</tr>
<tr>
<td>Patients (n = 14)</td>
<td>−1 ± 11</td>
<td>−4 ± 6 *</td>
<td>−3 ± 7</td>
</tr>
<tr>
<td>All (n = 22)</td>
<td>1 ± 11</td>
<td>−2 ± 7</td>
<td>−2 ± 7</td>
</tr>
</tbody>
</table>

Differences expressed as mean ± SD. * Significant difference from zero ($P = 0.05$); all other differences, NS.

Table 1 presents the 24-h statistics after averaging over the volunteers (n = 8), the patients (n = 14), and the entire group. Whereas the diastolic and mean differences for the three groups before reconstruction (FAP – BAP) were significantly different from zero, after reconstruction (reBAP – BAP) they were not, except for diastolic pressure in the patient group. Note that, although bias decreased to statistically insignificant amounts, precision as expressed by the SD of the data was not improved by the reconstruction. The reconstruction technique functioned nearly equally well in normotensive and hypertensive individuals.
Table 2
Nocturnal pressure dip (night - day) differences in intrabrachial (BAP), finger (FinAP) and reconstructed brachial (reBAP) artery pressures

<table>
<thead>
<tr>
<th></th>
<th>Systolic (mmHg)</th>
<th>Diastolic (mmHg)</th>
<th>Mean (mmHg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volunteers (n = 8)</td>
<td>−20 ± 6</td>
<td>−10 ± 4</td>
<td>−13 ± 4</td>
</tr>
<tr>
<td>Patients (n = 13)</td>
<td>−20 ± 9</td>
<td>−15 ± 7</td>
<td>−16 ± 7</td>
</tr>
<tr>
<td>All (n = 21)</td>
<td>−20 ± 8</td>
<td>−13 ± 6</td>
<td>−15 ± 5</td>
</tr>
<tr>
<td>FinAP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volunteers (n = 8)</td>
<td>−27 ± 9 *</td>
<td>−14 ± 8</td>
<td>−17 ± 7</td>
</tr>
<tr>
<td>Patients (n = 13)</td>
<td>−28 ± 12 *</td>
<td>−19 ± 10</td>
<td>−20 ± 11 *</td>
</tr>
<tr>
<td>All (n = 21)</td>
<td>−28 ± 11 *</td>
<td>−17 ± 10 *</td>
<td>−19 ± 10 *</td>
</tr>
<tr>
<td>reBAP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volunteers (n = 8)</td>
<td>−20 ± 7</td>
<td>−12 ± 5</td>
<td>−15 ± 6</td>
</tr>
<tr>
<td>Patients (n = 13)</td>
<td>−18 ± 10</td>
<td>−15 ± 8</td>
<td>−16 ± 9</td>
</tr>
<tr>
<td>All (n = 21)</td>
<td>−19 ± 9</td>
<td>−14 ± 7</td>
<td>−15 ± 7</td>
</tr>
</tbody>
</table>

Differences expressed as mean ± SD. * Significant difference from BAP (P = 0.05); all other differences, NS.

Table 2 shows that nocturnal arterial pressure dipping is significantly enhanced in the FAP values: by 8, 4 and 4 mmHg for systolic, diastolic and mean values, respectively, all participants taken together. These differences reduced to less than 1 mmHg after reconstruction, or by a clear factor of 4, disregarding the sign of the bias. Variability estimates also improved.

Figure 2 illustrates the reduction in FAP/BAP bias after reconstruction, displayed for the 24-h period and per scheduled activity. During the day, the night, the siesta and during cycling, bias reduced to negligible values after reconstruction. Only during walking was diastolic bias significantly positive.
Bias and precision of original finger artery pressure (FAP: left panel) and reconstructed brachial artery pressure (reBAP: right panel) against intrabrachial artery pressure (BAP) pooled for the group and averaged over the 24-h period (24h), the day period (day), the night period (night), the siesta (sies), 50 W bicycle exercise (cycl), and two 30-min periods of outside walk (walk). n, number of participants with sufficient recording time available for a realistic average. *Significant difference from zero ($P < 0.05$).
Discussion

The present results show clear benefits of generalized waveform reconstruction on bias, and slighter benefits on precision, against BAPs. Remarkably, the greater biases during siesta and night automatically received the required greater correction. This finding was not necessarily to be expected, as the reconstruction algorithms were developed for a population cross-section on short (30 s) sections of waveform data for individuals in almost identical, resting circulatory states. The findings of the present study suggest that the same reconstruction algorithms can be applied in individuals, over time, to improve the tracking of BAP changes by non-invasive FAP measurement over a period of 24 h.

Causes of waveform distortion and pressure gradient

FAP pulse waveform distortion and reductions in FAP values are caused by the pulse wave transmission effects present in the arm arteries between brachial and finger measurement sites, and by a pressure gradient that develops as a result of flow in the rather narrow peripheral arteries of the forearm and hand. As shown in the left panel of Figure 1, the pressure gradient appeared to increase when the participant was inactive during siesta and night, and to decrease during the scheduled moderate activities of 50 W cycling and walking. This seems, at first sight, unexpected. It is, however, well known that peripheral vasoconstriction occurs in the arteries of the arm during non-arm exercise (8), which might have caused a decrease in forearm flow and thus a decrease in flow-related pressure gradient. The level correction formula largely accounts for this effect on the basis of the relative values of systolic and diastolic FAP, but not completely so, as the residual differences in Figures 1 and 2 suggest.

Bias and precision

The bias was almost completely removed by waveform reconstruction. After reconstruction, it was well within the limit of 5 mmHg, as required by the Association for the Advancement of Medical Instrumentation (AAMI) protocol (9). The precision was only marginally improved. After reconstruction, the precision for mean and diastolic pressure, but not for systolic pressure, was within the 8 mmHg required by the AAMI protocol. Systolic values are more affected by motion artifacts, shifts in finger height with respect to heart level, and systolic overshoot, damping and limited bandwidth of the
catheter–manometer systems used to obtain the reference pressure (10). Furthermore, the
generalized waveform filter used in the brachial waveform reconstruction is based on a
population average, and is possibly suboptimal in individual cases. Although the effects
of suboptimal behavior are reportedly small (11), they are expected to affect systolic
values when blood pressure and heart rate are quite variable, such as during a 24-h
recording. However, we did not observe such deviant behavior of systolic pressure
values.

Night–day differences
The nocturnal decline in blood pressure (7), or its absence, has become the subject of
many studies (12). FAPs measured with Portapres tend to exaggerate the nocturnal blood
pressure dip but, for this group of patients, the reconstruction technique restored the
correct BAP changes, to within 2 mmHg for all pressures (Table 2). The suggested cause
for changes in blood pressure gradient has been changes in forearm flow. It should be
realized, however, that changes in flow can only cause changes in the pressure gradient
if arterial diameter and thus small artery resistance remain constant. It has been shown
(13) that localized intra-arm arterial application of sodium nitroprusside, which probably
relaxes both arterial and arteriolar vasomotor tone, does not affect the BAP-to-FAP
gradient. However, during the night, when arteriolar peripheral tone relaxes and arterial
diameter decreases subsequent to reductions in arterial distending pressure, an increased
pressure gradient can be expected, and was indeed observed (Figure 1, left panel).

Application of the methodology
We have developed three ways to improve the relationship between FAP and BAP. Two
methods, generalized waveform filtering and generalized level correction, were applied
in the present study; the third is an individual level calibration (2). The first method,
waveform filtering, reshapes the non-invasive FAP waveform to near-brachial contours,
with pulse pressure amplitude reduced to brachial values. The second, level correction,
reduces bias between FAP and BAP recordings in a manner correct for a population, and
even reduces bias variability in individuals during a 24-h period. However, precision
does not improve after generalized level correction. The third way to improve the
FAP/BAP relationship – level correction with a return-to-flow brachial systolic pressure
estimate – improves both bias and precision, but requires an additional measurement
with extra hardware. It is important to note that the first two methods, waveform filtering
and level correction, can be applied retrospectively, by means of computer software, to

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previously recorded FAPs, without further effort. That these generalized methods also reduce bias variability during the day suggests that an individual calibration needs to be performed only once during the day. The observation that waveform filtering and level correction are less perfect during the activity of walking outside the hospital should be taken as cautionary in this context.

**Conclusion**

We conclude that reconstruction of BAP from non-invasive FAP strongly reduces the FAP/BAP bias over a period of 24 h, and improves tracking of nocturnal blood pressure changes for all three blood pressure levels.
References


