

# Finapres tracking of systolic pressure and baroreflex sensitivity improved by waveform filtering

Paolo Gizdulich, Ben P.M. Imholz\*, Anton H. van den Meiracker<sup>†</sup>, Gianfranco Parati<sup>†</sup> and Karel H. Wesseling\*\*

**Objective** Arterial pressure waveforms distort between brachial and finger arteries, causing differences mainly in systolic pressure. Distortion, reportedly, can be removed by applying a waveform filter to the finger pressure.

**Design** We analysed the data from two studies that detected discrepancies in systolic tracking between Finapres and brachial pressures. The first set comprised waveforms of seven volunteers during incremental bicycle exercise to exhaustion and the second set comprised waveforms of eight volunteers during increasing phenylephrine infusion.

**Methods** We applied the filter and compared 1 min averaged unfiltered and waveform-filtered finger and brachial pressures.

**Results** During exercise, finger systolic pressure overestimated brachial increasingly, from 7 (SD 10) mmHg at rest to 27 (17) mmHg at maximal exertion. Differences were reduced by waveform filtering from 3 (SD 9) mmHg at rest to 1 (SD 15) mmHg at maximal exertion. During phenylephrine infusion finger systolic pressure overestimated brachial pressure, but the magnitude of the overestimate decreased from 14 (SD 15) mmHg at baseline to -1 (SD 16) mmHg at maximal rate. After waveform filtering overestimation was an almost constant 6 (SD 11) mmHg.

Median baroreflex sensitivities from brachial, unfiltered and waveform-filtered finger pressure were 5.8, 7.5 and 5.3 ms/mmHg and correlation increased after filtering. The results indicate improved systolic pressure tracking after waveform filtering.

**Conclusions** Finger pressure distortion follows a general pattern correctable by waveform filtering. Waveform filtering allows a 'brachial' view to be obtained from Finapres data.

Journal of Hypertension 1996, 14:243-250

**Keywords:** Finapres waveform distortion, digital filtering, waveform correction, systolic pressure, exercise testing, phenylephrine infusion, vasoconstriction, baroreflex sensitivity

From the Clinical Physiopathology Department, University of Florence, Italy, \*Department of Internal Medicine, Academic Medical Centre, Amsterdam, The Netherlands, †Department of Internal Medicine I, University Hospital Dijkzigt, Rotterdam, The Netherlands, ‡Istituto Scientifico Ospedale San Luca, Milan, Italy, and \*\*TNO Biomedical Instrumentation, Academic Medical Centre, Amsterdam, The Netherlands.

Requests for reprints to Dr P. Gizdulich, Clinical Physiopathology Department, University of Florence Viale Morgagni 85, 50134 Firenze, Italy.

Date of receipt 10 July 1995 Revised 8 October 1995 Accepted 16 October 1995

© Rapid Science Publishers ISSN 0263-6352

## Introduction

In clinical practice both intra-arterial and cuff pressures are preferably obtained at the upper arm. With Finapres (Finapres is a trade mark of Ohmeda Monitoring Systems, Louisville, CO, USA), arterial pressure waveforms can be recorded continuously in the finger without an invasive procedure. However, pressure pulsations in the finger differ from those in the brachial artery. Since Finapres became available, therefore, several studies have compared finger arterial pressures measured with Finapres with pressures recorded invasively [1-6]. They concluded that discrepancies are small enough to be acceptable for many applications [4,5,7]. Two papers [8,9] studied how Finapres tracked intrabrachial pressures during incremental bicycle ergometry and during graded phenylephrine infusion. The latter was performed to test Finapres reliability during vasoconstriction and to check the estimation of baroreflex sensitivity. These studies showed that Finapres followed

changes in diastolic and mean blood pressures well but overestimated increases in systolic pressure during exercise [8] and underestimated increases in systolic pressure during vasoconstriction [9]. In addition, in the latter study a variable waveform distortion was demonstrated during vasoconstriction.

Waveform distortions between brachial and finger arteries can reportedly be corrected by application of a filter [10]. The filter was developed and tested in supine resting volunteers. Since systolic pressure changes in response to bicycle ergometry were overestimated [8] but those response to phenylephrine were underestimated [9], this seemed to represent a challenging situation for filter application. We decided to investigate the published filter on the data obtained during exercise and vasoconstriction in which Finapres tracking of systolic pressure was reported to show substantial discrepancies.

## Methods

### Study participants

We took the original continuous blood pressure waveform recordings of the two studies [8,9]. The exercise study comprised blood pressure tracings from seven volunteers, aged 22–40 years, obtained in the sitting position during incremental bicycle ergometer exercise until exhaustion [8]. The vasoconstriction study comprised blood pressure tracings from eight patients, aged 18–60 years, with mild to moderate essential hypertension recorded in the supine resting condition during graded phenylephrine infusion [9].

The studies were approved by the institutional review committees, and all participants had given informed consent.

### Protocol

In the exercise study participants sat quietly on the bicycle ergometer for 5 min, after which pedalling was started at 20 W. The power level was increased by 20 W each subsequent minute until exhaustion. The participant then rested motionless on the ergometer with the recording continuing for another 5 min. Maximum exercise level differed between individuals and ranged from 200 to 320 W, reached 10–16 min after the start of the exercise. Thus, continuous recordings of 15–21 min duration were obtained.

In the vasoconstriction study 0.9% saline was infused at 50 ml/h for 15 min, after which the solution in the syringe was changed to a phenylephrine solution infused at rates of 0.4, 0.8 and 1.6  $\mu\text{g}/\text{kg}/\text{min}$  for 6, 5 and 5 min respectively. Thus, continuous recordings of 31 min duration were obtained.

### Pressure recording

For the intrabrachial recordings the non-dominant arm was used for cannulation. After local anaesthesia with a 1% lidocaine solution, a Travenol Quick Cath (N1113), 20 gauge, 11-cm-long Teflon cannula was inserted into the brachial artery using the Seldinger technique. The cannula was connected, for the exercise study, via a 10-cm-long polyethylene tube to a Gould-Statham P23 IO, and for the vasoconstriction study via a 70-cm-long polyethylene tube to an Akers B22 transducer mounted in an Oxford Medilog mark II recording system. Transducers were installed with a continuous flush system and strapped to the upper arm at heart level. The resonance frequency of these systems was checked with the fast flush or the tap method. It ranged from 11 Hz with sufficient damping to 50 Hz underdamped in individual cases. According the criteria of Gardner [11], this means that at least 'adequate' recording fidelity was always obtained, even in the one case with only 11 Hz resonance frequency. Pressure channel sensitivity and zero were checked against a well-maintained mercury mano-

meter and against the Finapres with differences less than 2 mmHg over a 0–300 mmHg range.

Finger pressure was recorded for the exercise study with a TNO model 5 Finapres device [12] connected to a well-fitting TNO finger cuff. Ohmeda's model 2300 Finapres [13] was used in the vasoconstriction study, using properly fitting TNO finger cuffs also. The finger cuff was wrapped around the mid-phalanx of the middle finger of the ipsilateral hand in the exercise study or of the contralateral hand in the vasoconstriction study and supported at heart level. Using the ipsilateral hand may cause errors if the proximal cannula partly blocks the radial artery [14]. However, in the present studies the larger brachial artery was probed with a small cannula and no signs of blocking, such as increased pulse systolic rise time or damped finger waves, were detected. The brachial and finger pressure signals were recorded on analogue instrumentation tape recorders. For inspection they were also output to a strip chart recorder and an oscilloscope.

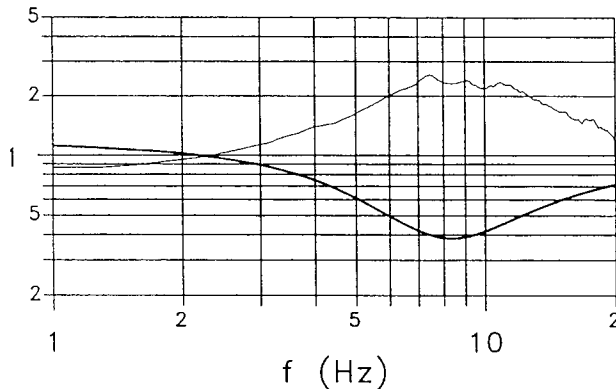
In this study arterial pressure recorded intrabrachially was the reference pressure against which Finapres non-invasive finger arterial pressure was compared, either unfiltered or waveform-filtered. Differences are expressed as finger minus brachial pressure. When finger systolic pressure is 110 mmHg and brachial systolic pressure is 100 mmHg, finger pressure overestimates brachial pressure by 10 mmHg and the pressure difference is +10 mmHg.

### Signal processing

Upon playback the signals were fed to program BEAT-FAST.EXE of the BMI-Modelflow [15] system. This program detects arterial pulsations and computes systolic, diastolic and mean pressure, pulse interval and other parameters beat to beat. Systolic pressure is taken as the highest pressure in arterial systole, diastolic pressure is the lowest pressure in diastole just before the upstroke of a beat and mean pressure is the true average blood pressure between consecutive upstrokes. Diastolic pressure is not always the lowest pressure in a heart beat. During strenuous exercise in some participants the blood pressure immediately after the arterial systolic phase was lower than at the end of arterial diastole. The waveform filter is incorporated in the program as a selectable digital filter. Its characteristics in Figure 1 show an antiresonant dip near 8 Hz compensating for the measured resonant character of pressure transfer from brachial to finger in the volunteers in the published study [10]. Sampling in the BMI-Modelflow system is at 100 Hz with a resolution of 0.25 mmHg. A prefilter removes 50 Hz hum and tape recorder noise from the waveforms. This hum and noise, if not suppressed, would lead to overestimation of systolic levels as the highest value in systole is increased by the noise. By the same argument diastolic levels would be underestimated.

Fig. 1.

### Brachial to finger transfer function and corrective filter



Thin line: the geometric average of the computed brachial to finger transfer functions obtained in the 25 participants in the study of Gizdulich and Wesseling [10]. Both scales are logarithmic. An ideal transfer function would be horizontal at transfer equal to 1 over the frequency range. However, a clear resonance, to an amplitude of 2.5, can be seen centred near 8 Hz. Thick line: response of the filter described by Gizdulich and Wesseling [10]. It shows an antiresonance that accurately compensates for the measured physiological resonance. Compensation for the observed attenuation at frequencies below 2 Hz is also achieved.

Three runs with BEATFAST.EXE were made. The first run analysed the brachial waveform, extracting the pressure levels and pulse interval beat-to-beat. The second run similarly analysed the finger waveforms. For the third run the waveform filter was put in place and the finger waveforms were analysed once more, this time producing waveform-filtered finger systolic, diastolic and mean pressures.

For evaluation the beat-to-beat pressure levels and pulse intervals of an individual were averaged over 1 min periods with periods overlapping by 50%. Thus, each 30 s, a 1 min average value was obtained. In the exercise study such averages were taken at rest and at each subsequent 30 s period and plotted. Further 1 min averages were taken at 3, 6, 9 and 12 min (at 60, 120, 180 and 240 W), at maximum exercise and 3 min after exercise and tabulated for comparison. In the vasoconstriction study averages were taken over the last minute at each infusion rate. These averages were also used to compute baroreflex sensitivities in each individual as the ratio of the difference in pulse interval between infusion rates and the difference in systolic pressure, and expressed in ms/mmHg.

#### Statistics

Means and standard deviations (in parentheses) are reported for the derived parameters and for differences between corresponding parameters obtained on different

waveforms. Statistical significance was based on Student's *t*-test except for baroreflex sensitivity, which was not normally distributed. Non-parametric Spearman rank correlation and Wilcoxon matched-pairs signed-rank tests were applied instead. A *P*-level of less than 0.05 was taken as significant.

## Results

### Exercise study

With exercise level increasing from zero to maximum, group average heart rate increased from an average of 71 beats/min at rest to 142 beats/min at 180 W and 173 beats/min at maximum exercise. Table 1 shows the extent to which unfiltered and waveform-filtered finger pressures differed from brachial pressure. At the seven sample instants in the exercise protocol unfiltered finger systolic pressure overestimated brachial pressure progressively with exercise level. All differences except the first and the last are significant. The other differences in the table are not significant. The standard deviation of the systolic differences decreased after waveform filtering but only by a small, non-significant amount.

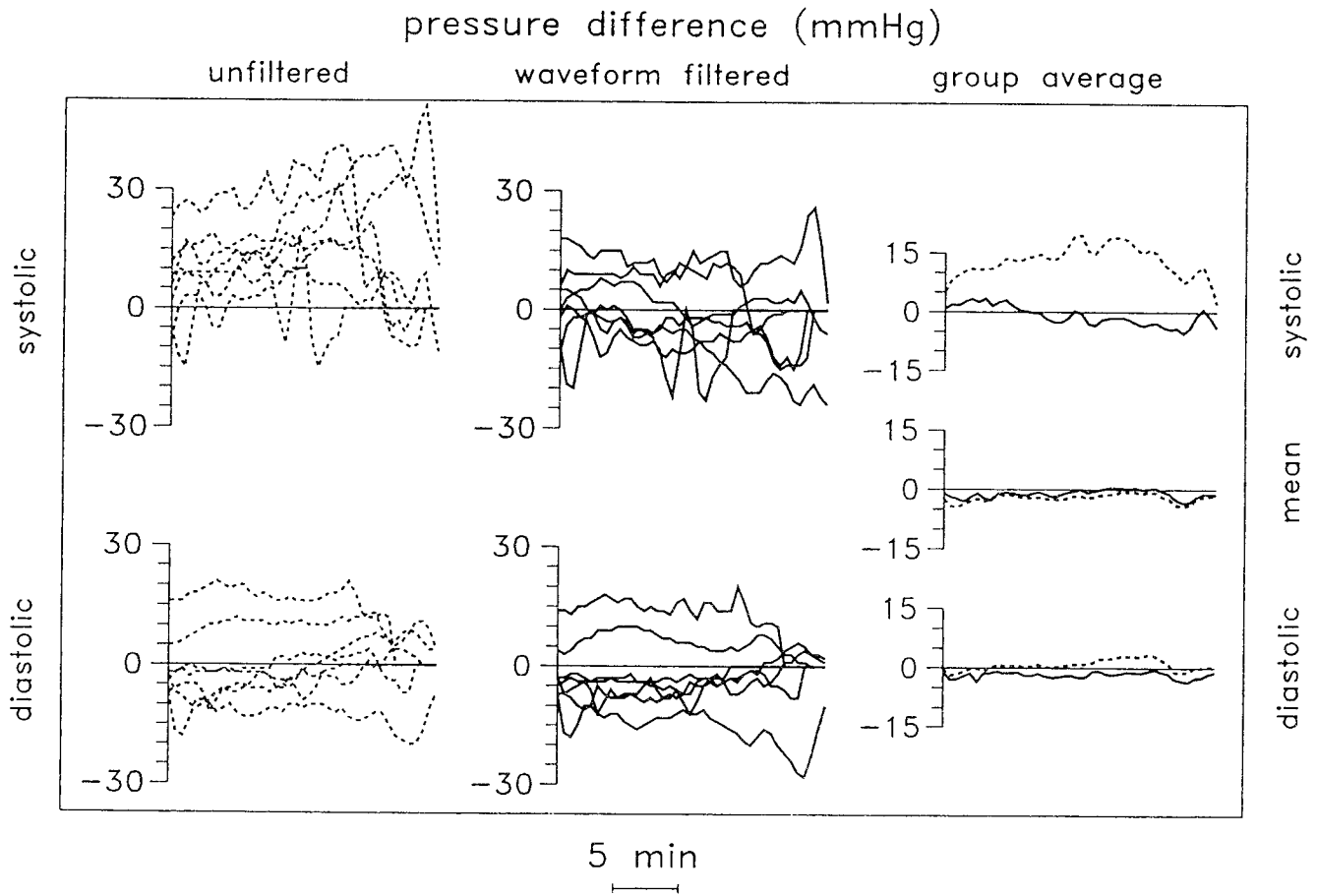
The unfiltered finger systolic differences entered each 30 s in Figure 2 show a general positive trend demonstrating increasing overestimation by Finapres. After exercise in each participant overestimation fell abruptly (Fig. 2). With the filter the progressive overestimate disappeared and differences remained near zero. The sharp 25 mmHg drop in systolic pressure after exercise was reduced to 8 mmHg although a true near-zero difference was not obtained on average (Table 1). Unfiltered diastolic finger pressures showed a much smaller but also increasing overestimate with exercise level, the increase again being removed by waveform filtering (Table 1).

Correspondence of the plotted values of Figure 2 with the numbers in Table 1 is not exact since the plotted averages are taken at each 30 s instant. Since participants did not exercise to the same peak level, from 10 min onwards average pressure differences include data from a progressively smaller number of volunteers. It is clear, however, in both presentations that waveform filtering strongly reduces pressure trend differences.

### Vasoconstriction study

Upon phenylephrine infusion pulse interval and brachial systolic pressure increased. Table 2 shows the results of waveform filtering on finger pressure. Finger systolic pressures started at a much higher level (14 mmHg) than brachial pressure during saline infusion, but ended near the same level (-1 mmHg) at the highest phenylephrine infusion rate. The increase of 47 mmHg in systolic pressure due to phenylephrine was thus underestimated in the finger at only 33 mmHg. Applying waveform filtering restored the steeper brachial trend. After waveform filtering standard deviations of the systolic differences

Fig. 2.



One minute average pressure differences in seven participants during incremental bicycle exercise to exhaustion, plotted each 30 s as a function of time. Left: individual unfiltered differences. Middle: individual waveform-filtered differences. Right: both differences pooled for the group per instant of time. Dashed curves, unfiltered finger pressure; bold curves, waveform filtered.

Table 1 Effects of waveform filtering on exercise finger arterial pressures.

| P (W)     | Brachial |     | fin - bra    |              | filt - bra   |              |
|-----------|----------|-----|--------------|--------------|--------------|--------------|
|           | SBP      | DBP | $\Delta$ SBP | $\Delta$ DBP | $\Delta$ SBP | $\Delta$ DBP |
| 0         | 123      | 70  | 6.9 (10)     | -1.3 (9)     | 2.6 (9)      | -2.7 (9)     |
| 60        | 141      | 67  | 12.3 (10)    | -0.7 (12)    | 2.3 (9)      | -2.6 (12)    |
| 120       | 158      | 71  | 15.3 (8)     | 1.1 (10)     | 1.3 (9)      | -0.9 (10)    |
| 180       | 178      | 79  | 16.9 (12)    | 0.7 (10)     | -2.7 (10)    | -2.6 (10)    |
| 240 (n=6) | 191      | 83  | 24.0 (13)    | 4.2 (10)     | -0.2 (12)    | -2.0 (10)    |
| max       | 191      | 84  | 26.9 (17)    | 3.6 (14)     | 0.7 (15)     | -3.3 (13)    |
| +3 min    | 134      | 67  | 1.4 (13)     | 0.4 (8)      | -7.4 (9)     | -1.1 (8)     |

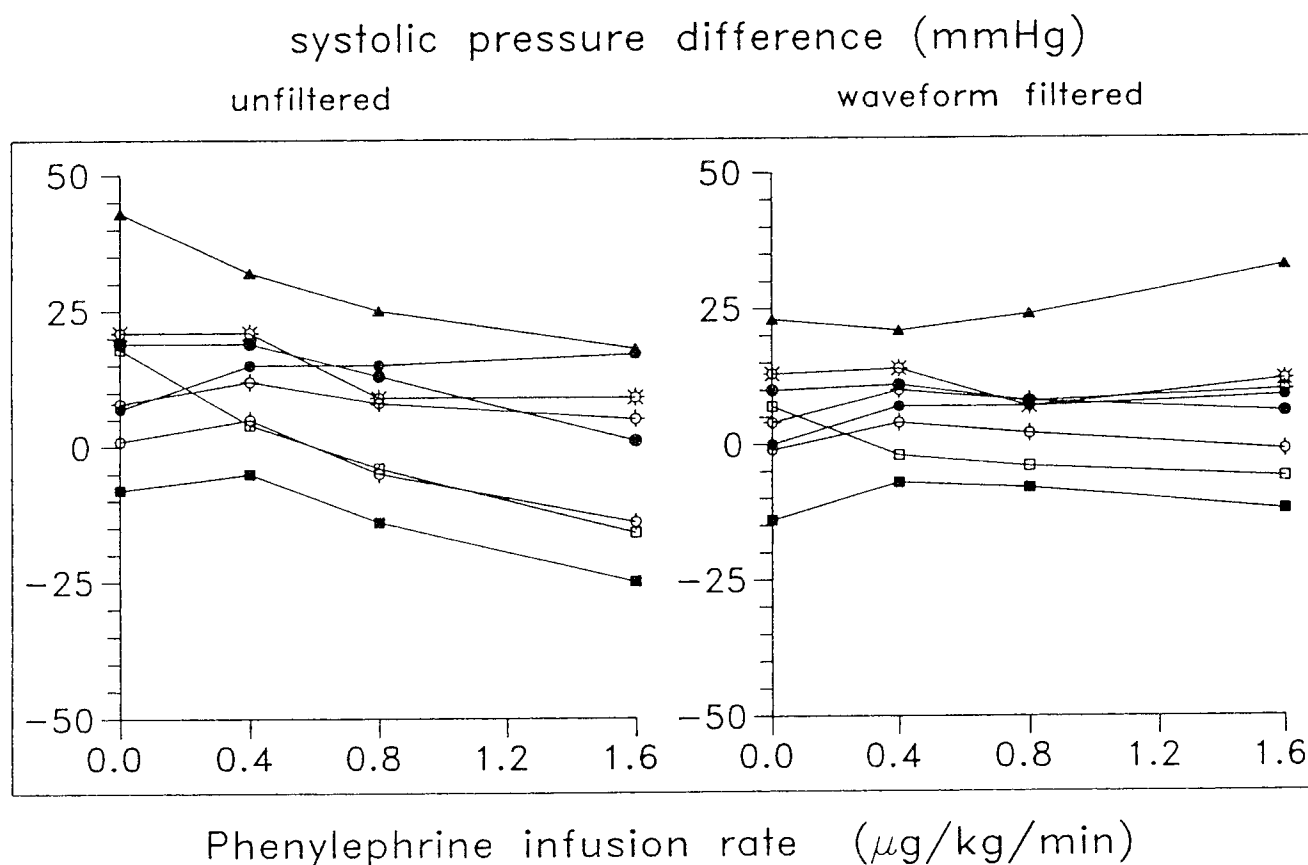
Group mean and standard deviation (in parentheses) results of seven participants using 1 min average brachial pressures and finger pressure differences (mmHg) at various levels of exercise, P, fin - bra, difference between unfiltered finger and intrabrachial pressures; filt - bra, difference between waveform-filtered and intrabrachial pressures; max, at maximal exercise; +3 min, 3 min after exercise.

were systematically reduced, although the reduction was not statistically significant.

Figure 3 shows the individual differences between finger and brachial systolic pressure. Differences decreased for unfiltered finger pressure, but remained almost constant

after waveform filtering. Thus, the erroneous underestimation of systolic increments during phenylephrine infusion disappeared after waveform filtering. This phenomenon can also be observed in Figure 4, which shows the performance of the filter in reconstructing the brachial from the finger pressure waveform. This figure is similar to

Fig. 3.



Systolic pressure differences of unfiltered (left) and waveform-filtered (right) finger pressures with intrabrachial pressure. Averages are given over the last minute of each phenylephrine infusion rate for each individual.

Table 2 Effect of waveform filtering on finger pressures under phenylephrine infusion.

| Phe ( $\mu\text{g}/\text{kg}/\text{min}$ ) | PI (ms) | $p_s$ (mmHg) | fin-bra (mmHg)     |                    | filt-bra (mmHg)    |                    |
|--|---------|--------------|--------------------|--------------------|--------------------|--------------------|
|  |         |              | $\Delta\text{SBP}$ | $\Delta\text{DBP}$ | $\Delta\text{SBP}$ | $\Delta\text{DBP}$ |
| 0.0  | 996     | 141          | 13.6 (15)          | 4.1 (6)            | 5.3 (11)           | 1.9 (6)            |
| 0.4  | 1107    | 148          | 12.9 (12)          | 4.5 (6)            | 7.3 (9)            | 2.5 (6)            |
| 0.8  | 1195    | 165          | 5.9 (13)           | 2.9 (7)            | 5.5 (10)           | 0.1 (7)            |
| 1.6  | 1257    | 188          | -0.6 (16)          | 2.8 (10)           | 6.4 (14)           | -0.4 (10)          |

Phe, rate of phenylephrine infusion; PI, pulse interval;  $p_s$ , brachial systolic pressure. fin-bra (unfiltered) and filt-bra (waveform-filtered) finger systolic and diastolic pressure differences.  $n=8$ . Mean and SD in parentheses are reported.

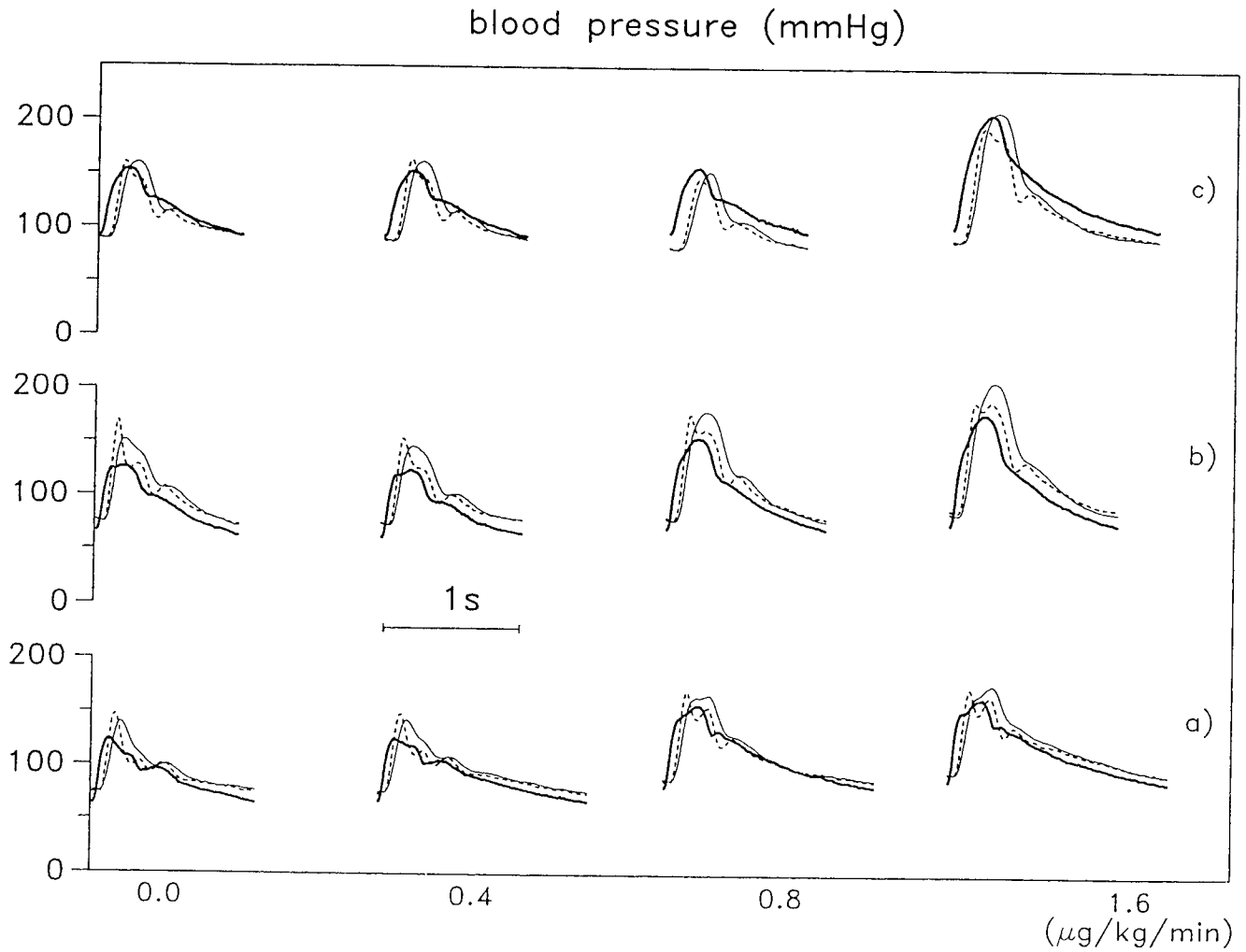
the one shown in Imholz *et al.* [9], and the same individuals are represented. Note that the waveform-filtered finger pressure pulsations were as smooth as the brachial pressure pulsations, although slight differences in waveform remained. Diastolic pressure levels were not much affected by filtering.

Group statistics of baroreflex sensitivity are given in Table 3. Median brachial baroreflex sensitivities (bra) decreased as expected with increasing infusion and pressure level. The same trend was seen in waveform-filtered (filt) but not in original finger pressure (fin)-derived sensitivities.

Baroreflex sensitivity between the highest infusion rate and no infusion was correctly estimated from waveform-filtered but significantly overestimated from unfiltered finger pressures.

Spearman rank correlation coefficients were used as a measure of individual correspondence between baroreflex sensitivities estimated from different pressure signals. Correlation between brachial and unfiltered finger pressures ranged from a non-significant 0.40 to a significant 0.95. After waveform filtering all correlation coefficients were significant (Table 3). For the change from 0.4 to

Fig. 4.



Single pressure pulsations obtained in the same three individuals as in Imholz *et al.* [9] at control and three rates of phenylephrine infusion. Bold, brachial; dashed, unfiltered finger; thin, waveform-filtered finger pulsation. Mean pressures are not affected by the filter and further time shifts by the filter occur as the filter is a real-time filter for which no propagation delay compensation can be made. Unfiltered finger systolic pressures are higher than brachial at control, but often lower than brachial during phenylephrine infusion. This is effectively corrected by the waveform filter. However, brachial waveform reconstruction, although close, is not exact in individual volunteers with the generalized filter.

Table 3 Effects of waveform filtering on Finapres-estimated baroreflex sensitivities by the phenylephrine method.

| $\Delta P_{Phe}$ | Median |     |      | Range   |         |         | $r_s$ with bra |      |
|------------------|--------|-----|------|---------|---------|---------|----------------|------|
|                  | bra    | fin | filt | bra     | fin     | filt    | fin            | filt |
| 0.0→0.4          | 12.6   | 5.4 | 13.6 | -0.5-92 | 0.0-86  | 0.2-65  | 0.40           | 0.90 |
| 0.4→0.8          | 5.2    | 9.4 | 5.2  | 2.9-18  | 3.9-57  | 3.3-19  | 0.76           | 0.73 |
| 0.8→1.6          | 1.2    | 0.8 | 0.6  | -0.6-8  | -0.9-15 | -0.6-10 | 0.93           | 1.00 |
| 0.0→1.6          | 5.8    | 7.5 | 5.3  | 1.9-7   | 1.2-24  | 1.3-10  | 0.95           | 0.95 |

Median and range for the group of eight patients are given. Baroreflex sensitivity in ms/mmHg, phenylephrine infusion rate in  $\mu\text{g}/\text{kg}/\text{min}$ .  $r_s$  is Spearman's rank correlation. One  $r_s$  (0.40) is not significant. The fourth row presents estimates between the highest infusion rate and no infusion.

0.8 µg/kg/min and from 0.0 to 1.6 mg/kg/min infusion rate significant differences in baroreflex sensitivity existed between unfiltered finger and brachial pressures. Between waveform-filtered finger and brachial baroreflex sensitivities no difference was significant.

## Discussion

Distortion (transformation) of pulse waves, originally called the 'preanacrotic phenomenon', was known and investigated in a rubber tube model as early as 1925 by Bramwell [16] and soon thereafter discussed theoretically by Frank [17]. The arteries form a frequently branching system. At each branching point and also along the length of an artery its properties change, causing distortion of the pulse wave. Rowell *et al.* [18] described disparities between the responses to upright exercise in aorta and radial artery pressure. In clinical practice cannulation of the superficial brachial or the radial artery is preferred over the aorta and Finapres can be applied only at the finger. Intrabrachial recordings allow comparisons with Riva-Rocci/Korotkoff systolic and diastolic pressures, on which nearly all diagnostic insight is based.

Addressing the problem of the relation between more proximal and more peripheral pulses, Karamanoglu *et al.* [19] demonstrated recently that a generalized transfer function can be used to estimate central from peripheral (brachial or radial) pressure in adult humans. Finger pressures, however, have not yet been studied this way, and it is not immediately obvious that the conclusions of Karamanoglu *et al.* remain valid for an acral measurement site such as the finger.

Our data clearly show that the waveform filter was able to correct almost perfectly the systolic overestimation of intrabrachial pressure by Finapres during exercise (Fig. 2). The filter also reduced the standard deviation of the difference between finger and brachial pressure moderately. The filter failed to improve finger systolic pressure levels 3 min post exercise (Table 1). At this time both blood pressure and peripheral resistance are low but heart rate is still high. It is possible, therefore, that combinations of blood pressure, peripheral resistance and heart rate exist for which the filter is ineffective.

Our data also show that the increases in systolic blood pressure induced by phenylephrine infusion are faithfully reproduced by finger blood pressure recordings after waveform filtering both on average for the group (Table 2) and individually (Fig. 3). As a result, baroreflex sensitivities are estimated with sufficient precision when derived from waveform-filtered finger blood pressure tracings (Table 3). The improved tracking of systolic levels is caused by a closer reconstruction of brachial pressure pulsations from finger pressure after filtering (Fig. 4).

Finger arterial pressure was measured in the exercise study by an original TNO model and in the vasoconstriction study by an Ohmeda device. Although the earlier versions of Ohmeda devices overestimated systolic pressures more than the TNO models, the waveform filter greatly reduced distortion for both devices, and corrected trends, although Ohmeda finger pressures are still higher than in the brachial artery.

It appears then that pressure pulse distortion between brachial and finger arteries can indeed be described by a sufficiently identical physiological resonance for all tested volunteers. This supports the conclusion of Karamanoglu *et al.*, extending it for the finger measurement site. The physiological resonance in peripheral pulsations can effectively be corrected by an antiresonance filter as was suggested previously [10]. Our data show for the first time that this antiresonance filter works effectively not only in normotensive, steady-state resting volunteers but also under conditions of high blood pressure and brady- and tachycardia, as was the case in our studies.

## Conclusion

The results of the present study provide experimental evidence that a simple waveform filter can remove waveform distortion from non-invasive finger blood pressure tracings, making them more similar to brachial blood pressure pulses. The filter's performance is good even when blood pressure and heart rate are outside their normal resting ranges. Brachial blood pressures levels and trends as well as the indices of baroreflex sensitivity are reproduced better with than without waveform filtering of Finapres waveforms. Using the proposed filter may thus allow more standard, 'brachial' clinical conclusions to be drawn for patients evaluated by means of Finapres devices.

## References

- Molhoek GP, Wesseling KH, Settels JJ, Van Vollenhoven E, Weeda HWH, De Wit B, *et al.*: Evaluation of the Peñáz servo-plethysmo-manometer for the continuous, non-invasive measurement of finger blood pressure. *Basic Res Cardiol* 1984, **79**:598-609.
- Smith NT, Wesseling KH, De Wit B: Evaluation of two prototype devices producing noninvasive, pulsatile, calibrated blood pressure measurement from a finger. *J Clin Monit* 1987, **1**:17-29.
- Wesseling KH, Settels JJ, Van der Hoeven GMA, Nijboer JA, Butijn MWT, Dorlas JC: Effects of peripheral vasoconstriction on the measurement of blood pressure in a finger. *Cardiovasc Res* 1985, **19**:139-145.
- Imholz BPM, Van Montfrans GA, Settels JJ, Van der Hoeven GMA, Karemaker JM, Wieling W: Continuous non-invasive blood pressure monitoring: Reliability of Finapres device during the Valsalva manoeuvre. *Cardiovasc Res* 1988, **22**:390-397.
- Imholz BPM, Settels JJ, Van den Meiracker AH, Wesseling KH, Wieling W: Non-invasive continuous finger blood pressure measurement during orthostatic stress compared to intra-arterial pressure. *Cardiovasc Res* 1990, **24**:214-221.
- Parati G, Casadei R, Gropelli A, Di Rienzo M, Mancia G: Comparison of finger and intra-arterial blood pressure monitoring in rest and during laboratory test. *Hypertension* 1989, **13**:647-655.
- Imholz BPM, Wieling W, Langewouters GJ, van Montfrans GA: Continuous finger arterial pressure; utility in the cardiovascular laboratory. *Clin Auton Res* 1991, **1**:43-53.
- Idema RN, Van den Meiracker AH, Imholz BPM, Man in't Veld AJ, Ritsema van Eck AD, Settels JJ, *et al.*: Comparison of Finapres non-invasive beat

- to beat finger blood pressures with intrabrachial artery pressures during and after bicycle ergometry. *J Hypertens* 1989, 7(suppl 6):S58-59.
- 9 Imholz BPM, Parati G, Mancia G, Wesseling KH: **Effects of graded vasoconstriction upon the measurement of finger arterial pressure.** *J Hypertens* 1992, 10:979-984.
- 10 Gizdulich P, Wesseling KH: **Reconstruction of brachial arterial pulsation from finger arterial pressure.** *Proc 12th Ann Int Conf IEEE-EMB* 1990:1046-1047.
- 11 Gardner RM: **Direct blood pressure measurement - dynamic response requirements.** *Anesthesiology* 1981, 54:227-236.
- 12 Wesseling KH, De Wit B, Settels JJ, Klauer W H, Arntzenius AC: **On the indirect registration of finger blood pressure after Peñáz.** *Funkt Biol Med* 1982, 1:245-250.
- 13 Boehmer RD: **Continuous, real-time, noninvasive monitor of blood pressure: Penaz methodology applied to the finger.** *J Clin Monit* 1987, 3:282-287.
- 14 Kurki T, Smith NT, Head N, Dec-Silver H, Quinn A: **Noninvasive continuous blood pressure measurement from the finger: optimal measurement conditions and factors affecting reliability.** *J Clin Monit* 1987, 3:6-13.
- 15 Wesseling KH: *The BMI-FAST-mfl-cZ system User Manual.* Amsterdam: TNO-Biomedical Instrumentation, Academic Medical Centre, 1993.
- 16 Bramwell JC: **The change in form of the pulse wave in the course of transmission.** *Heart* 1925, 12:23-71
- 17 Frank O: **Die Theorie der Pulswellen.** *Z Biol* 1926, 85:91-130.
- 18 Rowell LB, Brengelmann GL, Blackmon JR, Bruce RA, Murray JA: **Disparities between aortic and peripheral pulse pressures induced by upright exercise and vasomotor changes in man.** *Circulation* 1968, 37:954-964.
- 19 Karamanoglu M, O'Rourke MF, Avolio AP, Kelly RP: **An analysis of the relationship between central aortic and peripheral upper limb pressure waves in man.** *Eur Heart J* 1993, 14:160-167.