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Reproducibility of twenty-four-hour finger arterial blood pressure, variability and systemic hemodynamics

Albertus J. Voogel and Gert A. van Montfrans

Objective At present, non-invasive continuous monitoring of finger arterial blood pressure by the volume-clamp technique is considered the best approach to obtain reliable assessments of beat-to-beat blood pressure. However, data on the reproducibility (accuracy and precision) of prolonged recordings and of the hemodynamics derived from wave-form analysis are not available.

Design Ten patients with untreated essential hypertension and eight normotensive subjects were monitored by Portapres over 24 h in the hospital on two occasions with 1–4 weeks in-between. Physical and mental activities were standardized as far as possible to minimize intra- and intersubject biological variability. Stroke volume was obtained by the Modelflow method. Differences between the two recordings were computed separately for the day (0700 to 2300 h) and the night (2300 to 0700 h) and for all hours. Differences in stroke volume were calculated as percentage change from the first recording.

Results Accuracy was good in both groups and bias was close to zero. Precision was also remarkable in the daytime, and at least as good as values reported in studies that used the standard intra-arterial recording. The SD of the differences in systolic and diastolic

pressure in the hypertensives in the daytime were 6.6 and 4.7 mmHg, respectively. At night, precision was less good, possibly because of the 30 min finger-cuff switching: 12.5 and 6.5 mmHg for systolic and diastolic pressure, respectively. The average stroke volume did not change more than 8% at most between the first and the second recordings.

Conclusion These results indicate that the Finapres and Portapres devices are a reliable substitute for intra-arterial recording, and are most useful instruments for the study of blood pressure regulation.

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Keywords: finger arterial blood pressure, Finapres, Portapres, reproducibility, blood pressure measurement, volume-clamp, blood pressure variability

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Introduction

Arterial blood pressure varies continuously, subject to complex short- and long-acting control systems which are aimed at adjusting flow to the needs of the body. For many years the impact of this biological variability on seemingly simple matters such as making a diagnosis of hypertension has been well known [1,2]. As is the case with all biological parameters that fluctuate, multiple blood pressure readings increase its reproducibility. For maximal reproducibility, the optimal number of intermittent upperarm blood pressure readings by the occlusion technique during everyday conditions is now agreed upon at circa 30–40 measurements, equally spaced within 24 h. This limited number provides 30% better reproducibility than conventional single office readings [3]. Using continuous ambulatory intra-arterial monitoring, no further benefit was observed by increasing the number of readings to all the available 100 000 values that are generated in 24 h [4].

However, in view of the large, at times instantaneous, blood pressure oscillations this guideline does not hold when the variability of blood pressure itself is the main endpoint. Recent research suggests that the variability of blood pressure may contain prognostic information, independently of mean blood pressure levels [5–7]. When proper assessment of blood pressure variability is the goal, sampling should be done much more frequently. Test–retest correlations of blood pressure variability as assessed by intermittent automatic measurements are notoriously poor [8], although standardizing the activity pattern can improve reproducibility, giving *r* values of 0.60 [9].

Until recently, continuous intra-arterial monitoring was the best approach to describe accurately the behaviourally induced alterations in blood pressure in daily life. Now this invasive method is being replaced by non-invasive continuous monitoring of finger arterial blood pressure

by the volume-clamp technique [10,11], widely acknowledged as a reliable alternative to the intra-arterial approach [12]. However, some situation- or procedure-related errors are not uncommon [13,14]. For example, patients with acrocyanosis are less suitable for Finapres or Portapres recordings. In view of the large amount of methodological work on the original Péñáz volume-clamp technique [10], a formal study on the reproducibility of both the level and the variability of finger arterial blood pressure over 24 h in normotensives and hypertensive patients has been conspicuously lacking.

In this study we present data on the reproducibility of the blood pressure averages obtained by 24 h Portapres recordings, short-term variabilities and systemic hemodynamics as derived from wave-form analysis. We studied all subjects during maximally standardized physical and mental conditions in the hospital, in order to minimize as far as possible, the effect of environmental noise from variable activities on the blood pressure.

Subjects and methods

Subjects

The study group comprised 10 subjects, seven men and three women, with confirmed uncomplicated essential hypertension (untreated ambulatory awake diastolic blood pressure > 90 mmHg, as measured by a SpaceLabs recorder; Redmond, Washington, USA), aged 45 years (range 29–57) and eight normotensive volunteers, six men and two women, aged 42 years (range 33–66). Secondary hypertension was excluded by history, a physical examination and other routine investigations. No vasoactive medication had been taken for at least 3 weeks at the time of the study. The normotensive volunteers were recruited by advertisement.

Measurement protocol

Continuous finger arterial blood pressure was performed using the Portapres equipment over 24 h in the hospital, on two occasions. The male subjects were investigated with 1 week between recordings and the female subjects with 4 weeks between recordings. During both Portapres recordings the subjects were admitted to the metabolic ward of the hospital. Recording started at 1800 h. At 2300 h lights were switched off, and at 0700 h the subjects were served early morning tea. Meal times and all other activities were fully standardized to minimize intra- and intersubject biological variability; these included a 45 min guided walk through the hospital premises, 45 min sitting quietly, 90 min of supine bedrest without sleeping and 15 min of submaximal bicycle ergometer exercise. The protocol was approved by the Medical Ethical Committee, and written informed consent was obtained from all subjects.

Blood pressure measurements and signal analysis

The finger arterial pressure signal was recorded continuously and non-invasively alternating between the third

and fourth finger each 30 min. A Portapres M1 or M2 (TNO-BMI, Amsterdam, The Netherlands), the portable version of the Finapres was used [10]. In the daytime the patients kept the measurement arm suspended in a sling to reduce movement artefacts. The Portapres has a height-correcting system which measures the position of the finger relative to the heart level. When the M1 was used, data were stored on the built-in TEAC minicassette recorder (TEAC Corporation, Japan) and AD converted off-line at a sampling rate of 100 Hz with 0.25 mmHg resolution. Beat-to-beat systolic, mean and diastolic blood pressures were derived.

The left ventricular stroke volume was computed with the Modelflow method [15]. This computation method has been shown to reliably estimate stroke volume in comparison with thermodilution in anaesthetized humans during open-heart surgery. The method computes aortic flow pulsations from the central or peripheral arterial pressure waveform using a nonlinear, time-varying model of aortic input impedance, which consists of three elements representing the major properties of the arterial tree: the aortic characteristic impedance, the aortic compliance and a time-varying peripheral vascular resistance [16]. Thus, the aortic flow curve can be computed from measured pressure by simulation with continuous correction for variations in diameter and compliance of the aorta during one arterial pulsation. To derive accurate absolute values the method has to be calibrated against a standard. Without calibration, as in the present study, changes in cardiac output can be expressed as percentage deviations from the 24 h average.

Data analysis

Averaged blood pressures and stroke volume were calculated separately for the day (0700 to 2300 h) and the night (2300 to 0700 h). The differences between the first and the second recording were computed with standard deviations.

The systolic mean and diastolic values of each beat were also calculated to produce hourly averages with SD of the frequency histograms. These SDs are considered a measure of short-term variability in blood pressure [17].

Stroke volume was expressed as the percentage change from the first recording, separately for the day and the night, and also in (uncalibrated) absolute individual values averaged for the whole 24 h period.

Statistics

Results are presented as means and SD. Differences in the day- and night-time averages between normotensives and the hypertensive subjects were tested with the Wilcoxon signed matched rank test. $P < 0.05$ was taken to indicate a significant difference.

Results

Blood pressure

All Portapres recordings were of good quality and the percentage of rejected data was less than 5% in all subjects. Table 1 lists the grouped differences between the two recordings separately for daytime and night-time blood pressure, for the normotensive and the hypertensive subjects. These differences were close to zero. The SDs of the differences were remarkably low, particularly for blood pressures obtained during the day. In the hypertensives, precision was less for the night-time recordings, but the heart rate was identical.

Figures 1 and 2 show the reproducibility of hourly blood pressure averages in the normotensive and hypertensive subjects. The curves follow identical patterns in both groups. However, as can be seen from the lower panels, the standard deviations of the differences (SDD) of these hourly blood pressure values were sizeable, rising to a peak of 18 mmHg between 0500 and 0600 h in the hypertensives.

Table 2 lists the differences for the short-term blood pressure variabilities (averaged individual hourly SDs). Again, all differences were close to zero, apart from that for systolic blood pressure in the normotensive subjects for the daytime period.

Stroke volume

The scatter diagram (Fig. 3) shows the relationship between the individual duplicate 24 h stroke volume averages in the two groups (expressed in absolute values). Expressed as percentage changes from the first recording, values in the hypertensives for the day and the night, respectively, were -0.6 (SD 11.2; range -15.5 to 21%) and 8 (SD 14.4; range -12 to 41%). For the normotensives the corresponding values were 3 (SD 9.5; range -13 to 15%) and 4 (SD 13; -13 to 25%).

Discussion

In this study the reproducibility of repeated, prolonged finger arterial blood pressure measurements under standardized ambulatory conditions was assessed in a simple fashion. We compared the differences and their respective SDs of blood pressure averaged over the day and the

Fig. 1

Hourly values (SD) for systolic (SBP) and diastolic (DBP) finger arterial blood pressure in eight normotensive, hospitalized, ambulatory subjects on two occasions, 1 to 4 weeks apart. Mean hourly differences between the two recordings (SD) are shown on the lower two panels. Lights off 2300 to 0700 h. Black dots, first recording; open dots, second recording.

Table 1 Average differences during the day (0700 to 2300 h) and the night (2300 to 0700 h) between two 24 h recordings of non-invasive finger arterial blood pressure (BP), 1 to 4 weeks apart

Parameter	Normotensives (n = 8)		Hypertensives (n = 10)	
	Day	Night	Day	Night
Systolic BP (mmHg)	2.5 ± 2.9	1.0 ± 4.4	0.3 ± 6.6	3.2 ± 12.5
Diastolic BP (mmHg)	0.9 ± 3.2	1.0 ± 2.7	-1.0 ± 4.7	0.2 ± 6.5
Mean BP (mmHg)	0.7 ± 2.6	0.5 ± 2.8	-0.5 ± 4.6	1.1 ± 8.2
Heart rate (beats/min)	3.0 ± 5.5	3.9 ± 5.4	-0.9 ± 2.7	1.0 ± 1.8

Values are means $\pm$ SD. All differences were non-significant.

Table 2 Average differences in short-term blood pressure variability during the day (0700 to 2300 h) and the night (2300 to 0700 h) between two recordings of non-invasive finger arterial blood pressure (BP), 1 to 4 weeks apart. Values are averages of the SD of the hourly frequency distributions

Parameter	Normotensives (n = 8)		Hypertensives (n = 10)	
	Day	Night	Day	Night
Systolic BP (mmHg)	$1.5 \pm 0.9^*$	0.4 ± 0.6	-0.5 ± 1.2	0.5 ± 2.6
Diastolic BP (mmHg)	0.5 ± 0.8	0.1 ± 0.7	0.0 ± 0.8	0.5 ± 1.7
Mean BP (mmHg)	0.6 ± 0.8	0.0 ± 0.6	-0.1 ± 0.8	0.5 ± 1.9
Heart rate (beats/min)	$2.3 \pm 2.5^*$	$0.7 \pm 0.3^*$	0.0 ± 1.1	0.4 ± 0.7

Values are means $\pm$ SD. $^*P < 0.05$ versus hypertensives.

Fig. 2

Hourly values (SD) for systolic (SBP) and diastolic (DBP) finger arterial blood pressure in 10 hypertensive, hospitalized ambulatory subjects on two occasions, 1 to 4 weeks apart. Mean hourly differences between the two recordings (SD) are shown on the lower two panels. Lights off 2300 to 0700 h. Black dots, first recording; open dots, second recording.

night, and also on an hourly basis. During the daytime we found reproducibility excellent, at least as good as that obtained with intra-arterial recording using the Oxford system in hospitalized patients [18]. The SDDs were larger in the hypertensive subjects than in the normotensive volunteers, as usual when variability is expressed in absolute figures rather than normalized for the height of the blood pressure. During the night agreement was also remarkably good, albeit with a fairly large scatter, possibly because the quality of sleep during prolonged finger arterial blood pressure recording differed in individuals.

There are two other reproducibility studies using intra-arterial recording, but in both conditions were less stan-

Fig. 3

Scatter plot of 24 h averaged values of Modelflow stroke volume between two recordings 1 to 4 weeks apart. Dots represent the patients with essential hypertension ($n = 10$), stars represent the normotensive subjects ($n = 8$).

dardized. Mann [19] reported data on 27 non-hospitalized subjects studied twice 2 months apart, and found systolic SDD in daytime well above 11 mmHg and diastolic SDD above 7 mmHg. In an earlier outpatient-based study in which untreated hypertensive subjects who followed their daily business were studied twice with a 1-year interval, we found a similar, fairly large scatter with good average agreement [20]. In the latter study the reproducibility of short-term variability was also assessed, and was found to be identical, as in the present study. This point deserves to be highlighted, since Omboni *et al.* [21] recently investigated in detail the agreement of Portapres-derived frequency- and time-domain components of blood pressure variability with values obtained by intra-arterial recording (Oxford system). Satisfaction about overall performance was expressed, but low-frequency oscillations of systolic blood pressure appeared to be magnified by finger arterial blood pressure tracings. A detailed discussion of this phenomenon, which appears at least reproducible, falls outside the scope of the present paper.

These findings emphasize the well-known profound influence of everyday routine on blood pressure variability, and also illustrate the necessity of performing beat-to-beat monitoring of blood pressure, when variability is the primary endpoint.

Several reports have dealt with the technicalities of finger arterial blood pressure measurement and various sources

of procedure-related errors have been identified [13,14]. Cold fingers and malapplication of the cuff may cause important errors and reduce repeatability. By meticulously heeding these and rigidly standardizing activities the present results were obtained. In a sense this was a study of the efficacy of finger arterial blood pressure measurement; in daily practice or by sending patients home with the Portapres, repeatability will no doubt be less favourable.

The reproducibility of stroke volume seemed adequate, with SDDs not much above 10%. This should come as no surprise, since reproducible waveforms underlie these computations. The ability to provide non-invasive reproducible hemodynamic assessments simultaneously with calibrated blood pressures as often and as long as required is of course a major asset of the Finapres and Portapres.

The large scatter of hourly blood pressures with its implications for power calculations and, for example, trough: peak ratio assessments, which we observed has been reported before by Mancia *et al.* [18] using the Oxford system for intra-arterial recording. This feature was also faithfully reproduced by the Portapres, which serves as a case in point that in every aspect the Portapres may be viewed as a reliable alternative to intra-arterial recording.

Tolerance of the finger cuff was good with switching every 30 min. However, the feeling of slight numbness at the end of each 30 min with venous congestion of the finger might cause some alteration in sleep architecture at night in susceptible subjects, which may help to explain the large scatter for the blood pressure values at night.

In conclusion, repeated prolonged, finger arterial blood pressure measurements showed excellent reproducibility, at least as good as the standard of continuous ambulatory intra-arterial monitoring. These results further support the role of Finapres and Portapres as indispensable instruments for the study of blood pressure regulation and pathophysiology.

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