Continuous Recording of the Oscillometric Mean Arterial Pressure by the Differential Servo System with Two Photoplethysmographic Sensors

Rein Raamat, Kersti Jagomägi, and Jaak Talts

***Abstract*—A differential servo system with two photoplethysmographic sensors is described for beat-to-beat recording of the finger mean arterial pressure (MAP). The mean arterial pressure for every cardiac cycle is a more reliable parameter than the highest and lowest levels of the pressure signal (i.e. systolic and diastolic pressures). In the case of MAP measurement a better accuracy is achieved and the applied servo-system is cost-effective and robust. Frequency requirements to the proposed system are about 2 orders lower than those for a volume-clamp monitor to record the full arterial pressure waveform. At the same time, the beat-to-beat MAP entirely characterizes circulatory dynamics. Comparison between the proposed differential servo-oscillometric and conventional volume-clamp devices revealed a good agreement in MAP during hand elevation, orthostatic maneuver and light physical exercise.**

I. Introduction

Several studies have revealed that blood pressure measured indirectly in a finger artery is similar to that measured simultaneously in the brachial or radial artery [1]–[2]. Despite the fact that the magnitude of the intra-arterial pressure was sometimes over- or underestimated in individual patients, the group-averaged relative changes to cardiovascular stimuli were well reproduced in finger measurements even in patients with vascular disease [3].

For some time already, non-invasive beat-to-beat measurement of finger arterial blood pressure has been available with the help of volume-clamp monitors Finapres and Portapres [4], and also by the new volume-clamp developments Finometer and Task Force Monitor [5].

For the recording of the arterial waveform by a volume-clamp instrument, a sophisticated servo system is needed. However, for many scientific and clinical purposes it is sufficient to measure the mean arterial pressure (MAP) in every cardiac cycle. In the case of MAP measurement the servo system can be more simple and robust. At the same time, beat-to-beat MAP entirely characterizes circulatory dynamics.

In the present study we present a differential oscillometric device for beat-to-beat MAP measurement containing a relatively simple differential servo system with two photoplethysmographic sensors adjusted on adjacent fingers.

II. Methods

Volume-clamp instruments follow the dynamic unloaded arterial wall principle introduced by Peňáz [4]. During initialization the finger cuff is automatically inflated to a pressure level at which the maximum pulse volume oscillations are obtained (usually at the level of MAP). Then the servo loop is closed and the cuff pressure is changed by a very fast servo control system to maintain a zero transmural pressure in the artery [6]. As a result, the cuff pressure continuously equals intra-arterial pressure. The feedback system is controlled by the pulse volume signals from a photoelectric sensor, incorporated into the finger cuff. From a full arterial pressure wave systolic, mean and diastolic blood pressure values for every cardiac cycle can be estimated. Since the full waveform of the arterial pressure is registered, the applied control system must extend a tracking rate of about 2000 mm Hg/s.

The proposed oscillometric device also measures the continuous blood pressure at fingers and contains a servo system to control the counter pressure in the finger cuff. In the differential oscillometric instrument the counter pressure level is kept constant during the systolic part of every cardiac cycle (pressure measurement) and is changed during the diastolic part of the cycle (pressure regulation). Modulating the counter pressure level according to the criterion of getting maximum volume oscillations in every cardiac cycle, the cuff pressure is automatically kept equal to MAP in finger arteries (Marey's principle). The tracking rate of this system can be about 2 orders lower than that needed for the volume-clamp system.

Thus, the differential oscillometric device does not record the whole pressure wave with its maximum and minimum values (systolic and diastolic pressures), but determines the MAP value in every cardiac cycle. From the technical point of view it is meaningful to make the control system

Manuscript received June 10, 2008. This work was supported by Estonian Science Foundation Grants No 6487 and No 6947.

R. Raamat is with the Department of Physiology, University of Tartu, Estonia (phone: 372 7374 330, fax: 372 7374 332, e-mail: rein.raamat@ut.ee)

K. Jagomägi is with the Department of Physiology, University of Tartu, Estonia (e-mail: kersti.jagomagi@ut.ee)

J. Talts is with the Department of Physiology, University of Tartu, Estonia (e-mail: jaak.talts@ut.ee)

differential. Then the system operates with two cuffs on adjacent fingers. The counter pressure in one cuff is shifted from the mean pressure for a constant difference towards higher values, and in the other cuff towards lower values. Due to that the principle of maximum oscillations becomes the principle of equality of the amplitudes of the simultaneous volume oscillations in both cuffs. Oscillations under both cuffs are picked up by means of two photoelectric sensors. The schematic diagram of the differential oscillometric device with two photosensors is shown in Fig. 1.

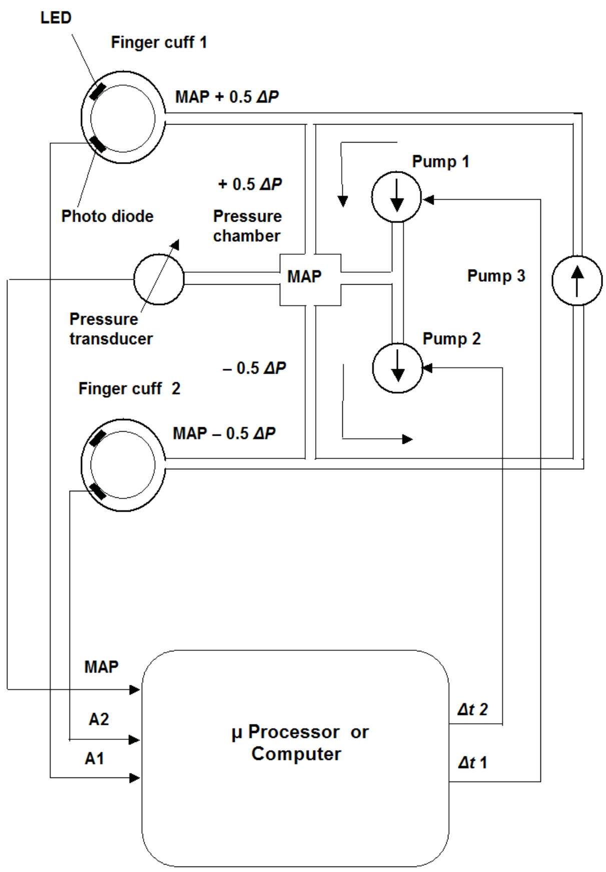

Fig. 1. Schematic diagram of the oscillometric device with two photoplethysmographic sensors.

Photoplethysmographic signals A1 and A2 from inflatable finger cuffs 1 and 2 are supplied to the feedback system compiled on the basis of a microprocessor or computer. The latter compares the input signals and forms corresponding output signals as time intervals during which pump 1 (for increasing the counter pressure) or pump 2 (for decreasing the counter pressure) are active. To get the maxima of oscillometric envelopes shifted, the constant airflow pump 3 is used to create a small pressure difference ΔP of a controlled value (about 30 mm Hg) between the cuffs. Thus, the counter pressures in the cuffs 1 and 2 are kept equal to MAP + 0.5 ΔP and MAP – 0.5 ΔP, respectively. The pressure in the central point of the pneumatic circuit (in the pressure chamber) is equal to MAP.

For pressure measurement integrated silicon pressure sensors MPX5050DP (Motorola) were applied. Infrared emitting diodes TSMF3700 (Vishay Semiconductors) and photodiodes SFH2400FA (Osram Opto Semiconductors) were used to record the finger volume pulses.

The experimental oscillometric device and a volume-clamp instrument (Finapres) were applied to simultaneously measure beat-to-beat MAP in two volunteers. Subject A was a 54-year-old female; she had no history of vascular disease and gave her informed consent to participate in the study. The study was a part of a project approved by the Ethics Committee of the University of Tartu.

The volume-clamp finger cuff was placed on the middle finger while the oscillometric cuffs were attached to the index and ring fingers of the left hand (Fig. 2). Special attention was paid to a proper attachment of finger cuffs to avoid tight or loose fixation.

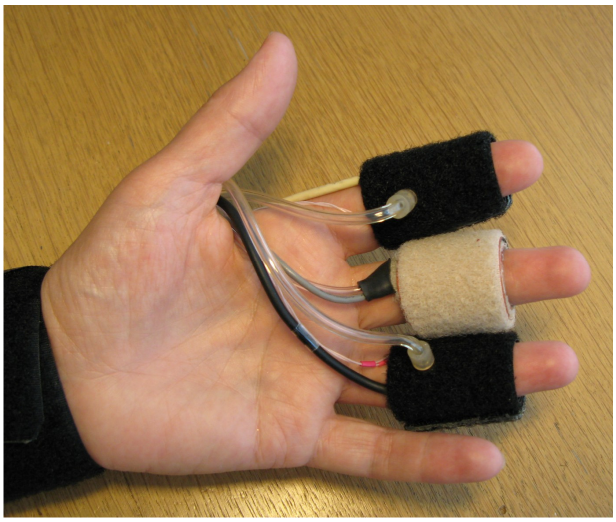

Fig. 2. The volume-clamp cuff is attached to the middle and the oscillometric cuffs to the index and ring fingers.

During the experiment the subject was seated comfortably with the left arm resting at heart level on the table. After an initial equilibrium period, the subject's left hand was raised to the height of 40 cm from the initial level where it remained during one minute. By elevation of the hand a hydrostatic pressure change in the fingers equal to about -30 mm Hg was induced. Then the hand was brought back to the initial position. At 150 s an orthostatic maneuver was performed (active standing from the sitting position). During stand-up the subject's left hand remained at heart level.

Another session of comparison was performed in Subject B, a 22-year-old male student. In this experiment we aimed to estimate simultaneous beat-to-beat MAP changes by means of two devices during light physical exercise (two successive handgrips).

As in the previous experiment, the subject's left hand was used for measuring MAP. With the right hand the subject performed handgrip compression at the level of approximately 50 % of maximum voluntary contraction force. After an initial equilibrium period, two successive one-minute handgrip compressions were conducted with a two-minute interval between them.

The analog signals from the volume-clamp and oscillometric instruments were digitized by an ADC (16-bit accuracy, sampling rate 200 Hz). Cardio-synchronized MAP for the Finapres was estimated from a full arterial pressure wave.

III. Results

The beat-to-beat MAP changes were quite similarly tracked by both the volume-clamp and oscillometric device. This is most distinctly evident during large blood pressure variations during the hand elevation and postural change in Subject A (Fig. 3). At 30 s the hand was raised and at 90 s lowered; at 150 s the subject quickly stood up from the sitting position.

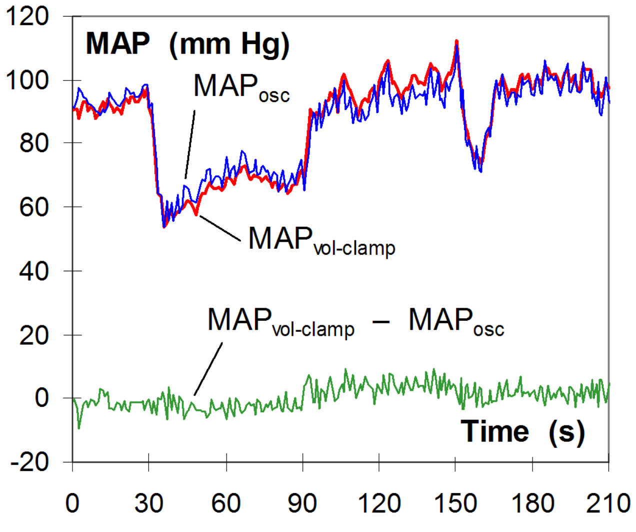

Fig. 3. Original recording of beat-to-beat mean arterial pressure by the volume-clamp (MAPvol-clamp) and oscillometric (MAPosc) instruments in Subject A during hand elevation and stand-up test. The difference between pressures is also indicated.

A good accordance between the MAP readings of both devices is evident also in Subject B during light exercise. At 180 s the first and at 360 s the second handgrip compression started (Fig. 4).

IV. Discussion

The comparison between the volume-clamp and oscillometric devices demonstrated that both instruments gave similar results. The difference $MAP_{vol\text{-}clamp} - MAP_{osc}$ in most cases was small (Fig. 3 and 4). It can be seen that the oscillometric device and the volume-clamp monitor both revealed similar directed responses during the whole tracking. Almost any change in the volume-clamp pressure was tracked by the oscillometric pressure.

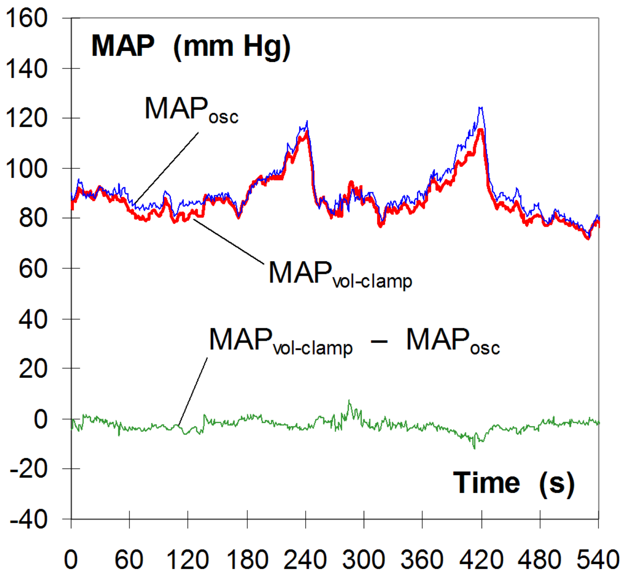

Fig. 4. Original recording of beat-to-beat mean arterial pressure in Subject B during two successive handgrip compressions. The symbols and units are the same as in Fig. 3.

We noticed MAP underestimation in the case of too tight application of cuffs in both devices. Otherwise, loose application of cuffs caused an overestimation of MAP. In the latter case a part of the cuff counter pressure is spent on the extensive inflation of the cuff bladders.

Another possible reason for differences between the devices may be connected with the fact that measurements were carried out on three different fingers (the volume-clamp cuff was attached to the middle finger, the oscillometric cuffs to the index and ring fingers). However, the results reported by other investigators have shown that all these three fingers (index, ring, middle) gave similar blood pressure readings of no greater variability than those attributable to the finger-insertion process [7]–[8].

It is important to point out that a good agreement between two methods was found during different physiological tests (hand elevation, orthostatic maneuver and physical load). A slight "overshoot" could be noticed in both MAP responses when the hand reached the upper level (Fig. 3). This is consistent with the findings of Tschakovsky and Hughson [9] reporting transient vasodilatation as a result of venous emptying at arm elevation. A fall in the arterial pressure accompanying the subject's stand-up is also known [10]. The blood pressure rise is an expected cardiovascular response to physical exercise (Fig. 4).

In the case of applying the differential servo-oscillometric method of beat-to-beat MAP registration, a relatively cheap and robust servo-system can be applied. For the recording of the arterial waveform by a volume-clamp instrument (e.g. by Finapres), the servo-system should extend the tracking rate of about 2000 mmHg/s, while for the MAP measurement by the servo-oscillometric device the rate of about 100 times lower is required. As a result, the price for the differential servo-oscillometric monitor is about three times lower than that for a volume-clamp instrument.

V. Conclusion

The results indicate that beat-to-beat mean arterial pressure can be recorded by a relatively simple and cost-effective servo-oscillometric system with two photoplethysmographic sensors.

References

[1] B. P. M. Imholz, W. Wieling, G. A. van Montfrans, and K. H. Wesseling, "Fifteen years experience with finger arterial pressure monitoring: assessment and technology," *Cardiovasc. Res.*, vol. 38, pp. 605–616, 1998.

[2] G. J. Langewouters, J. J. Settels, R. Roelandt, and K. H. Wesseling, "Why use Finapres or Portapres rather than intra-arterial or intermittent non-invasive techniques of blood pressure measurement?" *J. Med. Eng. Techn.*, vol. 22, pp. 37–43, 1998.

[3] W. J. W. Bos, B. P. M. Imholz, J. van Goudoever, K. H. Wesseling, and G. A. van Montfrans, "The reliability of non-invasive continuous finger blood pressure measurement in patients with both hypertension and vascular disease," *J. Hypertens.*, vol. 5, pp. 529–535, 1992.

[4] J. Peňáz, "Photoelectric measurement of blood pressure, volume and flow in the finger," in *Digest of the 10th Int. Conf. Med. Biol. Eng.*, Dresden, 1973, p. 104.

[5] G. Parati, G. Ongaro, G. Bilo, F. Glavina, P. Castiglioni, M. Di Rienzo, and G. Mancia, "Non-invasive beat-to-beat blood pressure monitoring: new developments," *Blood. Press. Monit.*, vol. 8, pp. 31–36, 2003.

[6] K. H. Wesseling, B. De Wit, G. M. A. van Der Hoeven, J. van Godoever, and J. J. Settels, "Physiocal: calibrating finger vascular physiology for Finapres," *Homeostasis*, vol. 36, pp. 67–82, 1995.

[7] T. Kurki, N. Smith, N. Head, H. Dec-Silver, and A. Quinn, "Non-invasive continuous blood pressure measurement from the finger: optimal measurement conditions and factors affecting reliability," *J. Clin. Monit.,* vol. 3, pp. 6–13, 1987.

[8] S. K. L. Lal, A. S. Mihailidou, M. Cejnar, R. J. Henderson, M. Jones, and S. N. Hunyor, "Continuous, non-invasive volume-clamp blood pressure: determinants of performance," *J. Hypertens.*, vol. 11, pp. 1413–1422, 1993..

[9] M. E. Tschakovsky, and R. L. Hughson, "Venous emptying mediates a transient vasodilation in the human forearm," *Am. J. Physiol. Heart Circ. Physiol.*, vol. 279(3), pp. H1007–H1014, 2000.

[10] B. P. M. Imholz, J. J. Settels, H. van den Meiracher, K. H. Wesseling, and W. Wieling, "Non-invasive continuous finger blood pressure measurement during orthostatic stress compared to intra-arterial pressure," *Cardiovasc. Res.*, vol. 24, pp. 214–221, 1990.