USE OF DIGITAL ARTERIAL PRESSURE AND VOLUME WAVEFORMS FOR ASSESSMENT OF ARTERIAL COMPLIANCE DURING CHANGES OF ARM VERTICAL POSITION

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Abstract. Finger arterial compliance has been studied on the beat-to-beat basis by using the digital arterial pressure and volume waveforms and performing measurements at zero transmural pressure during arm elevation in 11 volunteers. Continuous non-invasive finger blood pressure was measured by applying the Finapres monitor (Ohmeda, USA) and the finger volume pulses were recorded by the UT9201 physiograph (University of Tartu, Estonia) by using the photo-plethysmographic principle of registration. Estimation of the beat-to-beat finger arterial compliance is based on 1) the recorded volume and pressure wave amplitudes (*V*pulse and *P*pulse) and 2) on the calculation of the slope of the pressure-volume relationship from the first derivatives *dV/dt* and *dP/dt* of the recorded volume and pressure pulses near the point of the maximum slope. The results of the study demonstrate that the applied two methods similarly (correlation coefficient *r* = 0.97) describe the changes of the beat-to-beat compliance during hand elevation test. At the same time the second estimate was 18% higher than the first one (*p* = 0.003).

Keywords: beat-to-beat arterial compliance, finger pulse pressure, Finapres

Introduction

Elasticity or compliance is an essential parameter of the arterial wall, which might be useful to estimate the risk for vascular diseases [1–4]. Vascular compliance (*C*) expresses changes of volume with respect to changes of pressure. In beat-to-beat implication, very often, the compliance is measured by simultaneously observing the pulsatile blood volume change and the corresponding change in blood pressure. In this case compliance is estimated as a ratio of volume pulse (*V*pulse) to pressure pulse (*P*pulse) amplitudes during the cardiac cycle. It should be pointed out that owing to the non-linearity of the arterial *P*–*V* relationship, the obtained values of compliance are related to the local mean arterial pressure (MAP). A number of available techniques do not take into account that *C* is a pressure-dependent parameter. This shortcoming can be overcome by performing measurements at a fixed transmural pressure.

Transmural pressure is defined as the difference between the internal pressure *P*arterial and external cuff pressure *P*cuff (*P*transm = *P*arterial – *P*cuff).

In this study we aimed to estimate non-invasively beat-to-beat changes in the finger arterial compliance by using two different approaches:

1) estimation on the basis of the recorded volume and pressure pulse amplitudes (*V*pulse and *P*pulse), and

2) estimation on the basis of the first derivatives *dV/dt* and *dP/dt* near the point of the maximum slope of the corresponding pulses.

Materials and Methods

Subjects: A group of 11 volunteers were studied at room temperature 23-25°C.

Experimental design: The subject was seated comfortably with the left arm resting at heart level on the table. After an initial equilibrium period (approximately 12 minutes) the subject's left hand was passively (by help of an assistant) raised to the height of 40 cm from the initial level where it remained during one minute.

Beat-to-beat digital pressure waveform was recorded by the Finapres 2300 BP monitor [5]. The Finapres finger cuff was placed on the index finger.

Beat-to-beat digital volume waveform was recorded by the UT9201 physiograph, University of Tartu, Estonia [6–7]. Being originally constructed for finger mean blood pressure measurement, this instrument could also be used for photoplethysmographic recording of volumetric pulses from finger arteries. An advantage of this servo-based photoplethysmograph is that finger volume pulses *V*pulse are recorded at a fixed transmural pressure *P*transm = 0. The volumetric signal was measured in arbitrary units (*au*). The UT9201 finger cuffs were attached to the middle and ring fingers.

Neither of the applied pressure monitors was equipped with the height level compensation unit. By elevation of the hand, a hydrostatic pressure change in the fingers equal to -30.4 mm Hg was introduced.

Data processing: The analog signals from the Finapres and UT9201 instrument were digitised by an

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ADC (12-bit accuracy, sampling rate of 60 Hz) and transferred to the computer.

The recorded photoplethysmographic pulses together with the simultaneous arterial pressure pulses were used for calculating the instantaneous values of the finger dynamic compliance by two methods:

1) *C*pulse = *V*pulse/*P*pulse, where *P*pulse is the finger arterial pulse pressure and *V*pulse is the corresponding pulsatile volumetric change (Figure 1). This method is generally accepted as a standard one to estimate the digital artery compliance.

2) *C*der = *dV/dP*, where *dV/dP* is the slope of the pressure-volume (*P*–*V*) relationship. We computed the slope from the first derivatives *dV/dt* and *dP/dt* of the recorded volume and pressure pulses near the point of their maximum slope (Figure 1). For greater reliability, before dividing *dV/dt* by *dP/dt*, the derivatives were averaged over a moving window 65 ms.

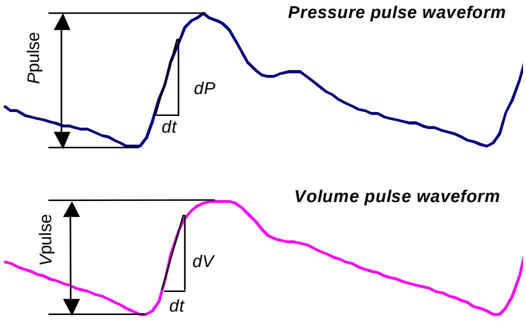

Figure 1. Arterial pressure and volume pulses. The commonly used type of calculation technique estimates beat-to-beat compliance by formula *C* = *V*pulse/*P*pulse (pulse amplitude based estimation). The derivative based technique estimates beat-to-beat compliance from derivatives *dV/dt* and *dP/dt*.

It should be pointed out that a specific feature of photoplethysmographic registration is the fact that the measured volumetric pulses are in arbitrary units, and their scaling factors can be considered constant only during a single experimental session in one person. Measurement on another person may have a different scaling factor thus making the between-individual comparison complicated. However, as our aim was to estimate changes in the arterial compliance rather than the absolute values, it was sufficient to measure the volumetric signal in arbitrary units and to express the beat-to-beat change in the compliance for every individual during hand elevation procedure as ratio of the compliance measured at hand elevated position to that before the test (as reference). In this way a normalization of the compliance signal was produced, and the compliance should have been regarded further as a relative variable.

In a similar way, an agreement between the two calculation techniques for an estimation of the compliance can be assessed by dividing the values obtained by one technique, by values obtained by the other technique. Basis for this decision lies in the fact that the both mentioned methods calculate beat-to-beat compliance from the simultaneously recorded pressure and volume waveforms. Therefore, an assumption can be made that the scaling factor changes from person to person in the volumetric channel of the UT9201 instrument, if they exist, should affect the both compliance estimates in the similar way (i.e. to cause proportional changes in both of them).

The reference values were measured 20 seconds before the hand elevation (Figure 2). Values during hand elevation were measured 20 s after the hand elevation during 20 s. We did not analyse the transition period because of motion artefacts during changes in arm position.

To test for the presence of significant differences in the readings obtained at two different positions of fingers and differences between the two techniques of compliance estimation, the Wilcoxon matched pairs signed rank test was used. A level of significance of 0.05 was applied. The correlation between two compliance estimates *C*pulse and *C*der was analysed by using Spearman's rank correlation analysis.

We conducted our experiments at a fixed transmural pressure *P*transm = 0. This feature should remarkably reduce an influence of the local mean blood pressure level on the results of compliance estimation.

The group-averaged values are expressed as a median with a 95% confidence interval (CI) for the median.

Results

Figure 2 demonstrates a multiparameter recording in one subject. Note the essential decrease in the MAP during hand elevation. At the same time, changes in the heart rate, HR, and compliance estimates, *C*pulse and *C*der, are less pronounced.

Group-averaged values of changes, evoked by hand elevation in 11 individuals, are listed in Table 1. Changes in both compliance estimates *C*pulse and *C*der, including alterations in their components are given as relative (dimensionless) changes. The individual changes in Cpulse and in Cder following hand elevation are graphically demonstrated in Figure 3. As it can be seen, despite of the essential individual variation, the group-averaged values (medians) did not reveal significant changes in both compliance estimates.

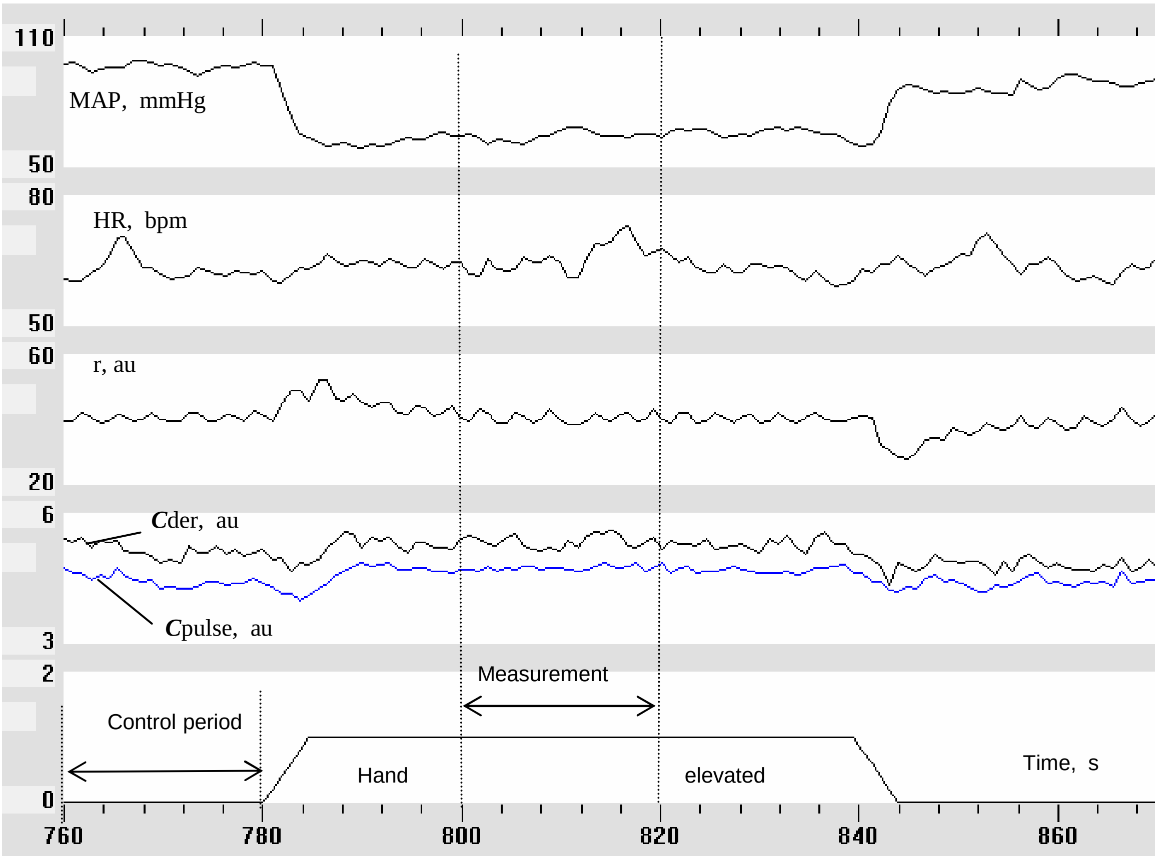

Figure 2. Example of a multiparameter recording in one subject. Beat-to-beat finger mean arterial pressure MAP (mmHg), heart rate HR (bpm), compliance estimates *C*der and *C*pulse (arbitrary units, au) and respiratory movements r (upwards – inspiration, downwards – expiration) are shown.

Table 1. Group-averaged values of changes caused by hand elevation in 11 individuals.

		Before test (reference)		Hand elevated		*p* -value, elevated vs. reference
		Median	95% CI for the median	Median	95% CI for the median	
HR, bpm		67	59 to 83	68	58 – 81	NS
MAP, mmHg		99	92 to 109	68	55 – 81	0.003
Pulse amplitude based estimation	*V*pulse norm.	1		0.88	0.77 – 1.00	0.047
	*P*pulse norm.	1		0.95	0.70 – 1.00	0.03
	*C*pulse norm.	1		1.01	0.82 – 1.15	NS
Derivative based estimation	*dV/dt* norm.	1		0.80	0.69 – 0.90	0.01
	dP/dt norm.	1		0.81	0.51 – 0.93	0.003
	*C*der norm.	1		0.98	0.79 – 1.30	NS

Heart rate (HR) and finger mean arterial pressure (MAP) are in absolute units; the rest variables are normalised (dimensionless). The reference values are measured 20 seconds before the hand elevation; the values during hand elevation are measured 20 s after the hand was raised during 20 s. Significance of differences is tested by the Wilcoxon matched pairs signed rank test. NS – not significant.

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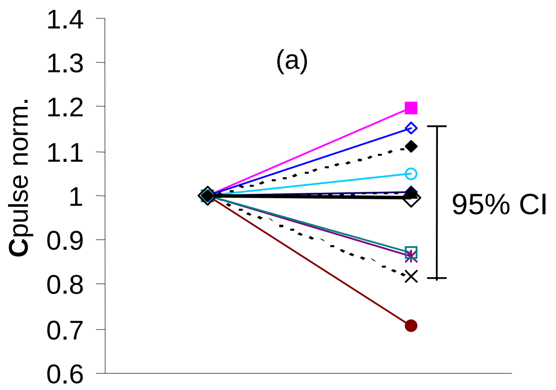

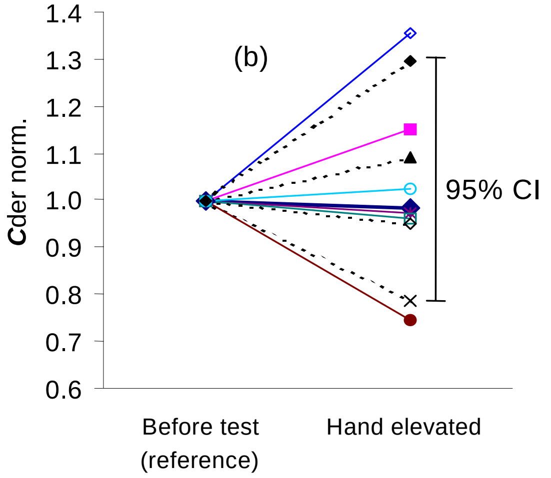

Figure 3. Individual changes in normalised compliance caused by hand elevation. The normalised compliance is calculated as a ratio of the compliance, measured in every subject at hand elevated position to that before the test (as reference). Median (bold line) and 95% confidence intervals are presented. (a) Pulse amplitude based estimation. (b) Derivative based estimation.

As much as comparison between the two compliance estimates is concerned, there was found a very high correlation between the pulse amplitude based technique and the derivative based estimation (r = 0.97, p < 0.002). At the same time the derivative based estimate was systematically higher than the pulse amplitude based estimate for the control period as well as for the hand elevated position. The corresponding regression equation is exposed in Figure 4. This shows that the slope of the regression line for all the measurements was equal to 1.18 (p = 0.003). In other words, the readings of the beat-to-beat compliance obtained by the derivative based estimation are 18% higher than those calculated by the pulse amplitude based technique.

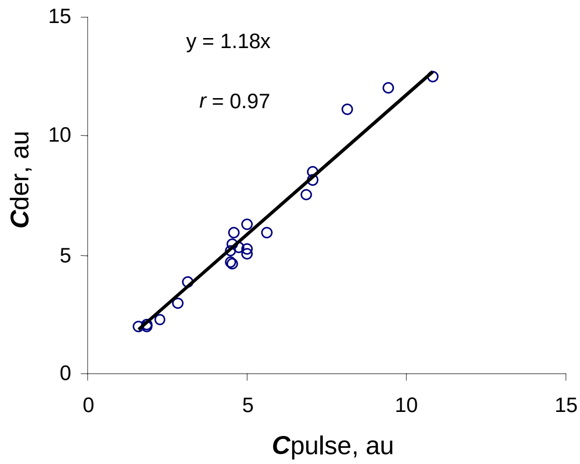

Figure 4. Scatterplot derivative based estimate *C*der vs. pulse amplitude based estimate *C*pulse in all the subjects (n = 11). Linear regression is denoted with a solid line. The linear regression formula and value of correlation coefficient are also presented. Each point represents one of 22 readings (hand elevated + control period). au - arbitrary units.

Discussion

Many noninvasive techniques have been developed to measure the arterial elastic mechanics in humans [1–4]. Although each technique has its relative advantages, there are some important limitations. Most of the techniques measure arterial elastic mechanics over a limited pressure range (at mean pressure or between systole and diastole). Although the lower end of the pressure range is not physiological, there are reasons for studying the artery at low *P*transm. Because vessels are not as stiff at pressures below the physiological range, it may be easier to separate diseased from normal vessels by studying the vessels at low transmural pressure.

It has been demonstrated that under very low pressure or stress, the elastic modulus of the arterial wall is very close to the elastic modulus of elastin alone, because little or no collagen bears stress under this condition [8].

Recording of pressure and volume waveforms on the adjacent fingers gives opportunity to estimate the compliance (stiffness) of small blood vessels selectively, without the disturbing influence of large blood vessels. A research paper recently published by Grey et al. [9] proved that a decrease in the elasticity of small blood vessels is a significant and independent cardiovascular risk factor.

Results of this study demonstrate (Table 1), that at hand elevated position the pulse amplitude values *V*pulse and *P*pulse as well as the pulse derivative values *dV/dt* and *dP/dt* are lower than those during the control measurement before the test (all these changes are statistically significant, p < 0.05). At the same time corresponding changes in the both calculated compliance estimates *C*pulse and *C*der are not statistically significant (p = 0.93 and p = 0.79, respectively). This occurs because the variables used for compliance calculation had changes in the same direction in most cases.

Results show that evoked responses in different subjects were of different extent.

Changes in the compliance of digital arteries like those described in literature [10], related to the position of the hand, were eliminated in our study by conducting experiments at an automatically controlled transmural pressure equal to 0. It can also be concluded that alterations in the hand's position related to the level of the heart did not cause considerable local neural regulatory responses.

Conclusions

The results of the study demonstrate that the applied two methods similarly (correlation coefficient r = 0.97) describe the changes of the beat-to-beat compliance during hand elevation test. At the same time the derivative based estimate was 18% higher than the amplitude based method (p = 0.003).

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References

[1] MACKENZIE I.S., WILKINSON I.B., and COCKCROFT J.R. (2002): 'Assessment of Arterial Stiffness in Clinical Practice', *Q.J.M.*, 95, pp. 67–74

[2] PANNIER B.M., AVOLIO A.P., HOEKS A., MANCIA G., and TAKAZAWA K. (2002): 'Methods and devices for measuring arterial compliance in humans', *Am. J. Hypertens.*, 15, pp. 743–753

[3] VAN BORTEL L.M., DUPREZ S., STARMANS-KOOL M.J., SAFAR M.E., GIANNATTASIO C., COCKCROFT J., KAISER D.R., and THUILLEZ C. (2002): 'Clinical applications of arterial stiffness, Task Force III: recommendations for user procedures', *Am. J. Hypertens.*, 15, pp. 445–452

[4] WOODMAN R.J., KINGWELL B.A., BEILIN L.J., HAMILTON S.E., DART A.M., and WATTS G.F. (2005): 'Assessment of central and peripheral arterial stiffness: Studies indicating the need to use a combination of techniques', *Am. J. Hypertens.*, 18, pp. 249–260

[5] PEÑÁZ J. (1973): 'Photoelectric measurement of blood pressure volume and flow in the finger', Digest of the Int. Conf. on Med. and Biol. Eng. Conf. Committee of the 10th Int. Conf. on Med. and Biol. Eng., Dresden, p. 104

[6] REEBEN V., and EPLER M. (1983): 'Indirect Continuous Measurement of Mean Arterial Pressure', in GHISTA, D.N. (Ed.): 'Adv. cardiovascular Phys., vol.5, Cardiovascular Engineering. Part II: Monitoring' (Karger, Basel), pp. 90-118

[7] JAGOMÄGI K., TALTS J., RAAMAT R., and LÄNSIMIES E. (1996): 'Continuous non-invasive measurement of mean blood pressure in fingers by volume-clamp and differential oscillometric method', *Clin. Physiol.*, 16, pp. 551–560

[8] ROACH MR, BURTON AC. (1957): 'The reason for the shape of the distensibility curves of arteries', *Can. J. Biochem. Physiol.*, 35, pp. 681–690

[9] GREY E., BRATTELI C., GLASSER S.P., ALINDER C., FINKELSTEIN S.M., LINDGREN B.R., and COHN J.N. (2003): 'Reduced small artery but not large artery elasticity is an independent risk marker for cardiovascular events', *Am. J. Hypertens.*, 16, pp. 265–269

[10] BOCHMANN R.P., REUTER U., LIST A., GRUNDIG M., and SINZ V. (1995): 'Compliance of the digital artery is decreased in patients with essential hypertension', *J. Hum. Hypertens.*, 9, pp. 627–631

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