Interaction Between Beat-to-Beat Variability of Pulse Wave Velocity and Blood Pressure in Healthy Young Subjects: Fighter Pilots and Non-Sporting Controls

Jana Svacinova[1], Lucie Vasikova[1], Radek Ligursky[2], Magdalena Sudakova[1], Anna Vravcova[1], Michaela Bittnerova[1], Tomas Fordinal[1], Frantisek Garncarz[1], Jan Boril[2], Zuzana Nováková[1]

[1]Masaryk University, Brno, Czech Republic
[2]University of Defence, Brno, Czech Republic

Abstract

Pulse wave velocity (PWV) indirectly reflects arterial stiffness, but it is also influenced by arterial blood pressure (BP). Aim of the study is analysis of the interaction between beat-to-beat changes of BP and PWV in dependence on postural change.

Continual BP in the finger and ECG were simultaneously recorded during phases: supine (sup) and head-up-tilt in 45° (hut) in two groups of healthy man (23-24 years): fighter pilots (9) and non-sporting controls (8). Sequences of systolic (SBP), diastolic (DBP), pulse pressure (PP) and PWV (from heart to finger) were detected beat-to-beat. Gains of tranfer function from SBP/DBP/PP to PWV were calculated as a mean in the low frequency band (0.04 – 0.15 Hz).

Supine $Gain_{dbp\text{-}pwv}$, hut $Gain_{dbp\text{-}pwv}$ and $Gain_{pp\text{-}pwv}$ were significantly higher in pilots than in controls. $Gain_{sbp\text{-}pwv}$ and $Gain_{pp\text{-}pwv}$ in pilots increased from the sup to hut.

Gain from BP to PWV is a new complex variable containing information about arterial stiffness and BP control difficult to interpretation. Increased values in pilots during hut could be given by well trained baroreflex control of arterial tonus or by better condition of arterial wall. Gain seems as the potentiall marker of the arterial health.

1. Introduction

Pulse wave velocity (PWV) is an independent predictor of future cardiovascular events and all-cause mortality.[1] PWV increases with increasing arterial stiffness i.e., with decreasing arterial compliance. Arterial compliance is influenced by various factors, constant and variable. Steady-state compliance of arterial wall depends on its structure - structural remodelation and atherosclerotic process.[2] Arterial compliance decreases with increasing blood pressure and arterial filling, so PWV is directly influenced by hypertension and blood pressure variability. [3] PWV of peripheral arteries is affected by arterial wall tonus – vasoconstriction and vasodilatation change mechanical wall properties.[4] Arterial tonus is controlled by the sympathetic nervous system as well as vasoactive substances and hormones.[5] Condition of endothelial function is an important part influencing the arterial ability to response to the regulation.[6]

PWV is usually evaluated in a supine position as a mean value from several cardiac cycles. For simple PWV analysis mostly aortic PWV is used. Contrary PWV variability of the muscular arteries with variable tone controlled by the autonomic nervous system (ANS) is more suitable.[5], [7] In our study we focused more on short-term changes of arterial activity. Information about the vascular regulatory mechanism could be hidden in spontaneous variability of PWV without any provocation during steady-state conditions. However, most pathological changes can appear only after some provocation such as exercise, position change, or application of vasoactive drugs. [8], [9]

As we mentioned, PWV variability is linked to blood pressure. The connection between PWV and blood pressure can be divided into two inseparable components: 1) direct mechanical effect of pressure to the arterial wall compliance and 2) factor influencing blood pressure through changes of arterial tonus. The first factor is associated with arterial filling, blood redistribution, and cardiac work. [4], [10] the second one is given by sympathetic control over the arterial wall tonus, vasoactive substances, and endothelial function. [5], [7] We expect different connection of PWV variability to systolic blood pressure (SBP), diastolic blood pressure (DBP) and pulse pressure (PP).[11], [12]

The question is, how much is short-term PWV variability connected with the blood pressure variability. The aim of this study is the evaluation of coupling between beat-to-beat PWV and blood pressure variability using the cross-spectral method. [13] We calculated the transfer function where the input was beat-to-beat sequence of systolic, diastolic and pulse pressures and output was beat-to-beat PWV. The gain of transfer function described the amount of blood pressure variability transferred to the PWV variability. And the coherence built in the transfer function describes a level of synchronicity between both signals. We worked at a low-frequency band 0.04 – 0.15 Hz where we expect the fastest vascular reactivity.[14]

 ISSN: 2325-887X DOI: 10.22489/CinC.2021.330

The coherence and gain were estimated in two groups of young healthy men: fighter pilots, ie. extremely healthy person, and non-sporting healthy controls. We examined, how much the autonomic nervous system, excited by an orthostatic challenge on tilt table, influences coherence and gain between blood pressure and PWV.

2. Methods

2.1. Subjects and study protocol

Two groups of young healthy male subjects were examined. The first group consisted of 9 fighter pilots (age 23 – 26 years, 180 ± 6 cm, 77 ± 11 kg). The second one was a control group consisting of 7 non-sporting men (21– 26 years, 178 ± 5 cm, 83 ± 15 kg). Subjects were non-smokers. They did not ingest any substances influencing the cardiovascular system on the day of the measurement.

Protocol of measurement consisted of two phases: 6 minutes in the supine position and consequently 6 minutes of head-up-tilt on the tilt table. Continual blood pressure was recorded from the finger cuff by the volume-clamp method (Finapres NOVA). ECG was recorded simultaneously with blood pressure (Finapres NOVA).

2.2. Signal processing

Sequences of systolic (sbp) and diastolic (dbp) blood pressure were detected beat-to-beat from continually recorded blood pressure. Sequences of pulse pressure (pp) were calculated as the difference between DBP and consecutive SBP. RR intervals were detected from the ECG.

PWV was calculated as a length of the artery (distance from the manumbrium sterni to finger cuff) divided by the time interval between R peak in ECG and following diastolic minima in blood pressure. PWV was also calculated beat-to-beat (sequence pwv). A 400 samples long sequences sbp, dbp, pp and pwv for each subject and phase were used as input to spectral analysis.

2.3. Cross-spectral analysis

We used a cross-spectral analysis to calculate parameters of interaction between blood pressure (SBP, DBP, or PP) and PWV in the frequency domain: coherence and gain.[15] Coherence represents a synchronization between SBP/DBP/PP and PWV in independence on frequency. Gain is a gain of the transfer function from SBP/DBP/PP to PWV in dependence on frequency. $Coh_{sbp\text{-}pwv}$ and $Gain_{sbp\text{-}pwv}$ were calculated as mean coherence and gain in low-frequency band (0.04-0.15 Hz). [13] Similarly, $Coh_{dbp\text{-}pwv}$ and $Gain_{dbp\text{-}pwv}$, $Coh_{pp\text{-}pwv}$ and $Gain_{pp\text{-}pwv}$ were calculated. Low frequency band was chosen because of its association with the activity of the sympathetic nervous system.

2.3. Statistics

Non-parametric methods were used, because of non-normal distribution of data. Difference between pilots and control group was estimated by Man-Whitney test. Difference between supine and hut phase was estimated by Wilcoxon paired test. Significant difference was detected when p-value of the test was lower than 0.05.

3. Results

Supine RR intervals were longer in pilots, and they significantly shortened during HUT (Table 1). DBP increased in controls during HUT in compare to supine. PP decreased in pilots during HUT. PWV in pilots during HUT was decreased compared to supine and controls in both phases.

Table 1. Mean values of blood pressure, cardiac cycles, and pulse wase velocity.

Phase: supine	Controls	Pilots
RR [ms]	825	1021*
	(675 - 1001)	(719 - 1415)
DBP [mmHg]	76	76
	(66 - 89)	(59 - 95)
SBP [mmHg]	134	125
	(115 - 159)	(111 - 147)
PP [mmHg]	55	51
	(39 - 74)	(42 - 55)
PWV [m/s]	5.62	5.34
	(5.13 – 5.91)	(4.88 – 5.65)
Phase: HUT 45°	**Controls**	**Pilots**
RR [ms]	765	825┼
	(621 - 846)	(586 - 1134)
DBP [mmHg]	89┼	84
	(73 - 10)	(65 - 10)
SBP [mmHg]	144	123
	(110 - 171)	(114 - 157)
PP [mmHg]	48	48┼
	(36 - 77)	(38 - 53)
PWV [m/s]	5.29┼	4.73*┼
	(4.77 – 5.83)	(4.44 – 5.31)

Description: SBP: systolic blood pressure; DBP: diastolic blood pressure; PP: pulse pressure; RR: cardiac cycle; HUT: head-up-tilt in 45°. Statistics: Controls vs. Pilots (Mann-Whitney test): *$p < 0.05$; Supine vs. HUT 45° (Wilcoxon test): ┼$p < 0.05$

All coherences increased in pilots during HUT. $Coh_{sbp-pwv}$ and Coh_{pp-pwv} was during HUT higher in pilots than in controls (Figure 1). $Gain_{dbp-pwv}$ was higher in pilots than in controls during both phases of measurement (Figure 2). $Gain_{sbp-pwv}$ and $Gain_{pp-pwv}$ increased during HUT in pilots. $Gain_{pp-pwv}$ during HUT was higher in pilots than in controls.

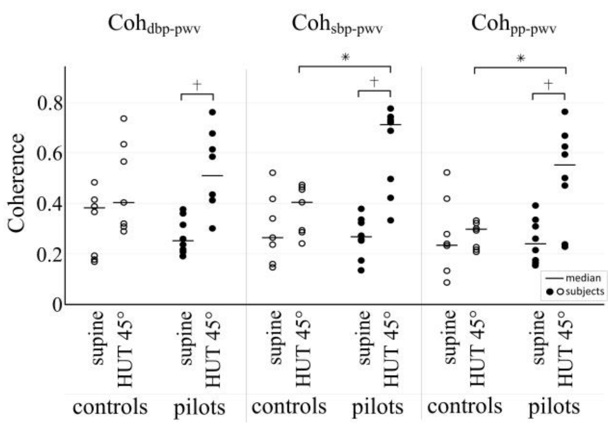

Figure 1. Coherence as parameter of synchronization between SBP/DBP/PP to PWV in low-frequency band (0.04-0.15 Hz). SBP: systolic blood pressure; DBP: diastolic blood pressure; PP: pulse pressure; RR: cardiac cycle; HUT: head-up-tilt in 45°.
Statistics:
Controls vs. Pilots (Mann-Whitney test): $^*p < 0.05$;
Supine vs. HUT 45° (Wilcoxon test): $^+p < 0.05$

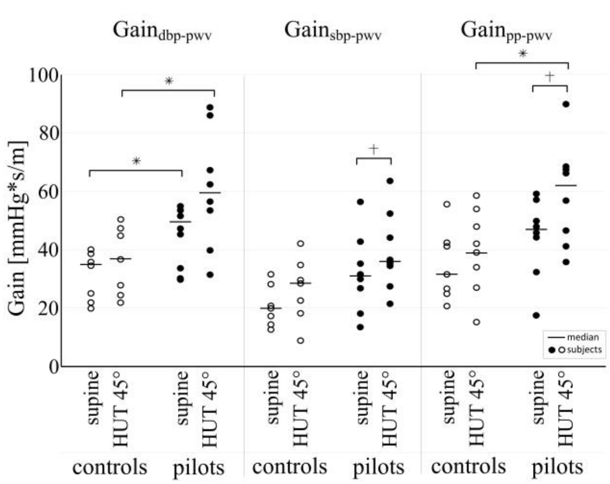

Figure 2. Gain of transfer function from SBP/DBP/PP to PWV in low-frequency band (0.04-0.15 Hz). SBP: systolic blood pressure; DBP: diastolic blood pressure; PP: pulse pressure; RR: cardiac cycle; HUT: head-up-tilt in 45°.
Statistics: Controls vs. Pilots (Mann-Whitney test): $^*p < 0.05$;
Supine vs. HUT 45° (Wilcoxon test): $^+p < 0.05$

4. Discussion

Beat-to-beat variability of PWV is a poorly studied.[16] Coherence and gain between blood pressure and PWV have been newer studied. This study provide first results describing these variables.

Mean blood pressure was almost unchanged during HUT, only heart rate increased in pilots. Pilots had generally lower blood pressure as well as heart rate, suggesting their sympatho-vagal balance is shifted to vagal predominance. Decreased PWV in pilots during HUT is probably a sign of higher arterial compliance. It could be given by different blood redistribution in upper limbs, lower blood pressure, and longer RR.

The coherence significantly increased in pilots during HUT compared to controls, who had coherence almost unchanged. We can only hypothesize which mechanism is responsible for our findings. Higher compliance in pilots during HUT provides a wider range for its variability with better response to blood pressure variability. [17] Vasoconstriction leads to decrease of arterial stiffnes. [7] It is a question if the PWV variability directly reflected blood pressure variability or there is a another common factor influencing blood pressure and arterial compliance together. Possibly fluctuation of arterial tonus and diameter directly affected arterial compliance as well as blood pressure. [5], [18]

In case the higher coherence in pilots is given by sympathetic control of arterial tonus, we can consider baroreflex as a main mechanism responsible for the variability in blood pressure as well as in PWV. [19] It is supported by the fact, that the coherence was increased during the orthostatic challenge, where baroreflex regulates blood pressure. Fighter pilots had trained baroreflex regulation of blood pressure and we assume great ability to control arterial tonus. Moreover, coherence was calculated in low-frequency band, where we expected oscillations caused by baroreflex.[20] In our previous study, we proved, that the variability of upper limb PWV increased during HUT in healthy subjects and lower limb PWV in diabetics. Therefore we expect a contribution of blood redistribution. [21], [22]

Gain showed similar changes as coherence. The strongest transfer of variability was from DBP to PWV during HUT in pilots compared to gain from SBP to PWV. Therefore, we suppose the PWV variability was influenced more by changes in vascular resistance than by variability of cardiac work. [11], [12]

5. Conclusion

Interaction between blood pressure and PWV is increased in pilots and especially during the orthostatic challenge. It seems, that for differences between pilots and controls during HUT may be responsible many factors: autonomic nervous system control, blood pressure, blood redistribution, arterial wall structure and endothelial condition determining reactivity of arterial tonus. And it is not clear, which one is most important. Coherence and gain between blood pressure and PWV are very complex variables concentrating much information about arterial state. Decryption of this results requires further research. However, the fact, that there is a significant difference between two small groups of the young healthy subject shows a potential of the coherence and gain to become a marker of early arterial changes in such diseases as diabetes mellitus, hypertension or cardiovascular toxicity of anthracycline therapy [21], [23].

Acknowledgments

Study was supported by grants MUNI/A/1246/2020 and ROZV/28/LF/2020.

References

[1] J. Blacher, R. Asmar, S. Djane, G. M. London, and M. E. Safar, "Aortic pulse wave velocity as a marker of cardiovascular risk in hypertensive patients," *Hypertens. Dallas Tex 1979*, vol. 33, no. 5, pp. 1111–1117, May 1999.

[2] H.-L. Kim and S.-H. Kim, "Pulse wave velocity in atherosclerosis," *Front. Cardiovasc. Med.*, vol. 6, p. 41, Apr. 2019.

[3] C. Stefanadis *et al.*, "Aortic function in arterial hypertension determined by pressure-diameter relation - Effects of diltiazem," *Circulation*, vol. 96, no. 6, Art. no. 6, 1997.

[4] J. Moudr, J. Svacinova, E. Zavodna, and N. Honzikova, "The vibration plethysmographic method of arterial compliance analysis in dependence on transmural pressure," *Physiol. Res.*, vol. 63, pp. S489–S495, 2014.

[5] P. Boutouyrie, P. Lacolley, X. Girerd, L. Beck, M. Safar, and S. Laurent, "Sympathetic activation decreases medium-sized arterial compliance in humans," *Am. J. Physiol.-Heart Circ. Physiol.*, vol. 267, no.4, pp. H1368–H1376, Oct. 1994.

[6] McEniery Carmel M. *et al.*, "Endothelial function is associated with pulse pressure, pulse wave velocity, and augmentation index in healthy humans," *Hypertension*, vol. 48, no. 4, pp. 602–608, Oct. 2006.

[7] R. Joannides, V. Richard, N. Moore, Godin, and Thuillez, "Influence of sympathetic tone on mechanical properties of muscular arteries in humans," *Am. J. Physiol.-Heart Circ. Physiol.*, vol. 268, no. 2, pp. H794–H801, Feb. 1995.

[8] M. Matejkova *et al.*, "Measurement of pulse wave velocity during valsalva and mueller maneuvers by whole body impedance monitor," in *Computing in Cardiology 2014*, Sep. 2014, pp. 1117–1120.

[9] P. Langer *et al.*, "Respiratory-induced hemodynamic changes measured by whole-body multichannel impedance plethysmography," *Physiol. Res.*, vol. 67, no. 4, pp. 571–581, 2018.

[10] S. Kamoi *et al.*, "Relationship between stroke volume and pulse wave velocity," *IFAC-Pap.*, vol. 48, no. 20, pp. 285–290, Jan. 2015.

[11] E. J. Kim *et al.*, "Relationship between blood pressure parameters and pulse wave velocity in normotensive and hypertensive subjects: invasive study," *J. Hum. Hypertens.*, vol. 21, no. 2, Art. no. 2, Feb. 2007.

[12] J. Nürnberger, S. Dammer, A. Opazo Saez, T. Philipp, and R. F. Schäfers, "Diastolic blood pressure is an important determinant of augmentation index and pulse wave velocity in young, healthy males," *J. Hum. Hypertens.*, vol. 17, no. 3, pp. 153–158, Mar. 2003.

[13] G. Parati, J. P. Saul, M. Dirienzo, and G. Mancia, "Spectral-analysis of blood-pressure and heart-rate-variability in evaluating cardiovascular regulation - a critical-appraisal," *Hypertension*, vol. 25, no. 6, Art. no. 6, 1995.

[14] J. Svacinova, M. Javorka, Z. Novakova, E. Zavodna, B. Czippelova, and N. Honzikova, "Development of causal interactions between systolic blood pressure and inter-beat intervals in adolescents," *Physiol. Res.*, vol. 64, no. 6, pp. 821–829, 2015.

[15] N. Honzikova, B. Fiser, and J. Honzik, "Noninvasive determination of baroreflex sensitivity in man by means of spectral-analysis.," *Physiol. Res.*, vol. 41, no. 1, Art. no. 1, 1992.

[16] N. R. Gaddum *et al.*, "Beat-to-beat variation in pulse wave velocity during breathing maneuvers," *Magn. Reson. Med.*, vol. 72, no. 1, pp. 202–210, Jul. 2014.

[17] K. R. Casali *et al.*, "Correlation between very short and short-term blood pressure variability in diabetic-hypertensive and healthy subjects," *Arq. Bras. Cardiol.*, vol. 110, no. 2, pp. 157–165, Feb. 2018.

[18] L. J. Cymberknop, F. Gabaldón Castillo, and R. L. Armentano, "Beat to beat modulation of arterial pulse wave velocity induced by vascular smooth muscle tone," in *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Jul. 2019, pp. 5030–5033.

[19] E. G. Vaschillo, B. Vaschillo, J. F. Buckman, R. J. Pandina, and M. E. Bates, "Measurement of vascular tone and stroke volume baroreflex gain," *Psychophysiology*, vol. 49, no. 2, pp. 193–197, 2012.

[20] C. W. Myers, M. A. Cohen, D. L. Eckberg, and J. Taylor, "A model for the genesis of arterial pressure Mayer waves from heart rate and sympathetic activity," *Auton. Neurosci. Basic Clin.*, vol. 91, no. 1–2, pp. 62–75, Aug. 2001.

[21] J. Svačinová *et al.*, "Variability of peripheral pulse wave velocity in patients with diabetes mellitus type 2 during orthostatic challenge," *Physiol. Res.*, pp. S433–S441, Jan. 2021.

[22] V. Vondra *et al.*, "A multichannel bioimpedance monitor for full-body blood flow monitoring," *Biomed. Tech. (Berl)*, vol. 61, no. 1, pp. 107–118, Feb. 2016.

[23] K. Budinskaya *et al.*, "Non-invasive assessment of vascular system function and damage induced by anthracycline treatment in the pediatric cancer survivors," *Physiol. Res.*, vol. 66, pp. S553–S560, 2017.

Address for correspondence:

Jana Svacinova
Masaryk University (Department of Physiology, Faculty of Medicine), Kamenice 5, Brno 62500, Czech Republic
svacinova@med.muni.cz