Chapter 10
Algorithm for the Joint Analysis of Beat-To-Beat Arterial Pressure and Stroke Volume for Studying Systemic Vasoconstrictor and Vasodilator Responses

Elizaveta Agapova, Aleksei Anisimov, Maria Kuropatenko, Tatiana Novikova, Nikolay Suvorov, Timofey Sergeev, and Alexander Yafarov

Abstract Prolonged hypokinesia causes a decrease in functional reserves of the organism. The study of physiological mechanisms and the degree of their decrease and, in particular, the role of vasoconstrictor and vasodilator reactions is an urgent task. This paper describes an algorithm for studying these reactions on the basis of the beat-to-beat pressure and stroke volume signals. The electrodynamic model of the cardiovascular system (Windkessel model) was the theoretical basis for the algorithm development. The signals obtained during functional tests based on postural oscillatory loads were used as test signals. As a result, we obtained an algorithm for determining the total peripheral resistance (by linear regression) and the limits of vasoconstrictor and vasodilatation reactions. This, in turn, makes it possible to judge about the functional reserves of the whole organism.

Keywords Functional reserves · Algorithm · Electrodynamic model · Vasoconstriction · Vasodilation

10.1 Introduction

Reduction of motor activity leads to a significant decrease in functional reserves of the human organism, which is clearly manifested during tests with postural (ortho- and anti-orthostatic) loads. Such postural loads cause a complex of conjugate reactions from the cardiovascular system of human organism. Severity of these reactions

E. Agapova · A. Anisimov (✉) · M. Kuropatenko · T. Novikova · N. Suvorov · T. Sergeev · A. Yafarov
Institute of Experimental Medicine, Acad. Pavlov St. 12, 197376 St. Petersburg, Russia
e-mail: aaanisimov@etu.ru

A. Anisimov · T. Sergeev
Saint Petersburg Electrotechnical University, Popova St. 5, 197376 St. Petersburg, Russia

E. Velichko et al. (eds.), *International Youth Conference on Electronics, Telecommunications and Information Technologies*, Springer Proceedings in Physics 268, https://doi.org/10.1007/978-3-030-81119-8_10

depends on the intensity of the effects (angles of elevation/inclination, speed of movement, sequence and duration of loads) and the initial state of organism [1, 2].

The hemodynamic response to the change of passive ortho- and anti-orthostatic positions is based on the alternating deposition of blood in vessels of the lower and upper body, accompanied by vasoconstrictor and vasodilator vascular reactions. At the same time, changes are occurred in the inotropic response of heart, cardiac output, arterial and venous pressures, heart rate, changes in the circulating blood volume [3, 4, 7, 8].

These changes are associated with the action of the cardiovascular system regulatory mechanisms, including the arterial baroreceptor reflex (ABR), acting according to the principle of negative feedback. For example, the result of decreasing arterial blood pressure (BP), and, consequently, the frequency of impulses from ABR coming to the vasomotor center, is a reflex reaction aimed at increasing ABP, i.e., decreasing the activity of parasympathetic nerve endings in heart and activating vasomotor sympathetic nerves. As a result, the heart rate and its contractility increase simultaneously with the narrowing of arterioles and veins in most body organs, except for the brain and heart [3, 4].

In conclusion, we can say that, for research and diagnostic purposes, it is rather important to consider degree of different components of ABR involvement in cardiovascular system regulation and, in particular, the role of vasoconstrictor and vasodilator reactions. It can be studied by the means of synchronous analysis of beat-to-beat values of ABP and stroke volume (SV) dynamics. Such analysis provides information about value of total peripheral vascular resistance (TPR) and its changes. At the same time, this paper does not consider the effect of ABR itself.

Thus, the aim of this study was to develop an algorithm for the joint analysis of beat-to-beat arterial blood pressure and stroke volume signals for studying systemic vasoconstrictor and vasodilator responses under various impacts, including postural loads. The development of such algorithm will make it possible to solve a number of tasks together with other techniques:

1. To determine the functional reserves of the whole organism, whose value is connected with the ability to regulate the TPR and hence the total volume of circulating blood;
2. To study the adaptive abilities of organism related to the rate of reactions to various influences;
3. To differentiate the diagnosis in pathologies of the cardiovascular system [5–7].

10.2 Materials and Methods

Proposed algorithm is based on the electrodynamic model of cardiovascular system, known as three-element Frank Windkessel (WK) model. Figure 10.1 shows schemes implementing this model: in hemodynamic (Fig. 10.1, a) and electrodynamic (Fig. 10.1, b) representations (according to [10]). There are also known variants of this simple model consisting of two, four and more elements. The history of this

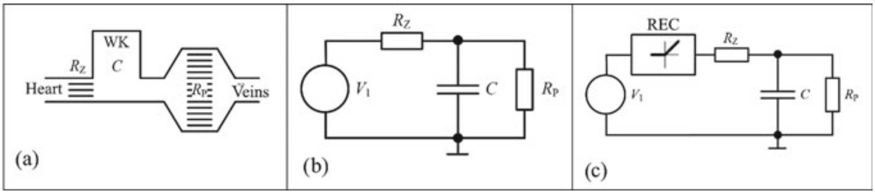

Figure. 10.1. Three-element WK model: a) in hemodynamic, b) and c) in electrodynamic representation, REC is single half-period rectifier

question is considered in details by N.Westerhof et al. [10]. In this scheme R_P corresponds to the total peripheral resistance, C to the total arterial compliance, R_Z to the characteristic aortic resistance.

As it was shown in earlier researches, the results of three-element WK model analysis have a significant contradiction with cardiovascular system functioning [11]. Current passing through R_Z resistance (similar to the flow entering the artery from heart) can have two directions: forward during the pulse simulating systole, and reverse during the pause simulating diastole (Fig. 10.1, b). This result contradicts cardiac function – there should be no return flow to the left ventricle.

This contradiction is eliminated by using an additional nonlinear element (Fig. 10.1, c), simulating the work of the heart left ventricle and corresponding to a single half-period rectifier (REC). At the same time, responses from the original circuit (Fig. 10.1, b) and the circuit with REC (Fig. 10.1, c), with equal values of R_Z, R_P and C in both circuits differ significantly. The main difference is expressed in the rise time and pressure drop. REC scheme provides a relatively constant P level and unidirectional flow. Estimated values of model parameters R_Z, R_P, C, and signal from V_1, obtained by using the scheme with half-period rectifier are more adequate [11], therefore used in further simulations.

As an example, let us consider the signals obtained from model on the 10 s simulation section (Fig. 10.2): ABP is voltage at the R_P resistor (red, green and blue

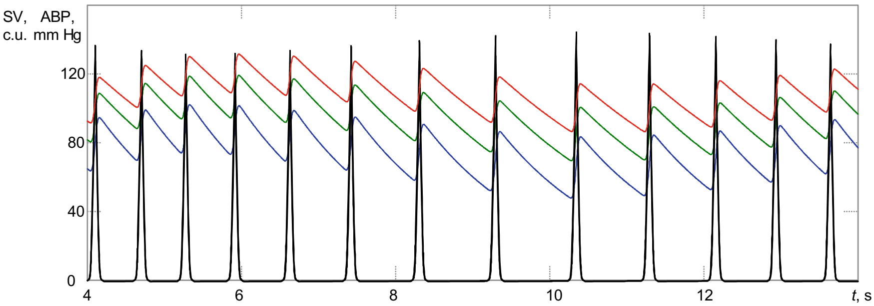

Figure. 10.2. Plot of signals: ABP is voltage across resistor R_P: $R_P = R_{P0}$ (green curve), $R_{P1} = 0.75\ R_{P0}$ (blue curve), $R_{P2} = 1.25\ R_{P0}$ (red curve); SV is current through resistor R_Z (three gray curves, made in conventional units and given for qualitative comparison with ABP curves)

curves) and stroke volume (SV) is current through resistor R_Z (three gray curves, they are visible only in the area of peaks, the scale of SV is chosen in conventional units). All these signals were obtained at different values of TPR –resistance of R_P resistor. If we take R_{P0} (green curve) as the reference value of R_P resistance, then $R_{P1} = 0.75\ R_{P0}$ (blue curve), $R_{P2} = 1.25\ R_{P0}$ (red curve). Values of arterial pressure, as well as systolic (SBP) and diastolic (DBP) blood pressures depend on the values of TPR, and the absolute values of SV also change.

10.3 Results

The first stage of proposed algorithm is the extraction of maximal beat-to-beat values from all the signals. For blood pressure, this is SBP, for stroke volume – peak values in the ejection phase. The next step is to compare these maximal values and plot them on the phase plane. At this stage, the assumption is made that these maximal values are synchronous. Figure 10.3, a shows an example of such construction for three different R_P (TPR) values: $R_P = R_{P0}$ (green markers), $R_{P1} = 0.75\ R_{P0}$ (blue markers), $R_{P2} = 1.25\ R_{P0}$ (red markers).

The third step is devoted to determining the limits of vasoconstriction and vasodilation (Fig. 10.3, b). For each of the R_P values, not a specific value but some set of values is obtained. These sets intersect at the selected change of R_P. The boundaries of the sets are found as straight lines passing through the extreme points of these sets and the origin of the coordinates. Accordingly, the limits of vasoconstriction and vasodilation are the extreme upper and extreme lower limits. The average value of TPR over the measurement period is determined by the standard formula.

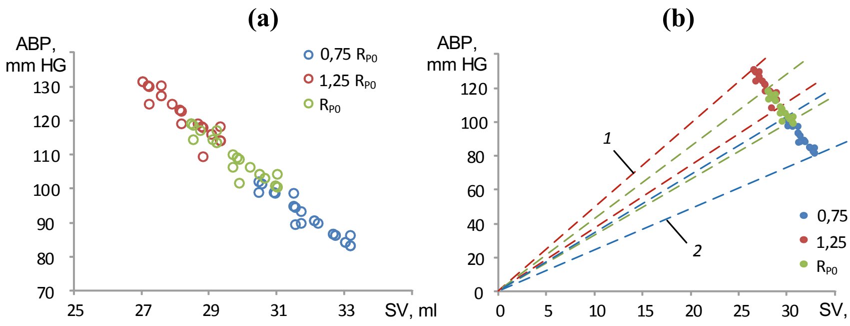

Figure. 10.3. Phase plane of SBP, SV: (a) in enlarged and (b) normal scales (1 for vasoconstriction boundary, 2 for vasodilation boundary)

10.4 Discussion

It should be noted that the obtained scattergrams for three R_P values are not concentrated at certain points, but have a significant scatter. Moreover, as can be seen from Fig. 10.3, a, the same pairs of SBP-SV at different R_P values are possible (see distribution boundaries). This means that in the case of definition TPR values as the ratio of SBP to TRP, we would obtain different values despite the constancy of R_P (Fig. 10.4). This effect is related to the presence of C (total arterial elasticity) and R_Z (aortic characteristic resistance). Consequently, it is reasonable to determine non-specific (absolute) value of total peripheral resistance, but some set of values when assessing TPR. For this purpose the duration of ABP and SV records at calm position of test subject should exceed 2 min as it is related to durations of regulatory processes [12–14].

In order to induce meaningful changes in TPR, sufficient physiological loads are required. As it was mentioned in the introduction section, the most adequate and universal for this purpose are postural loads performed on a special tilt-table.

In addition, during calculation of TPR we must take into account values of C and R_Z. The development of appropriate methods for this challenge are the main directions for future work.

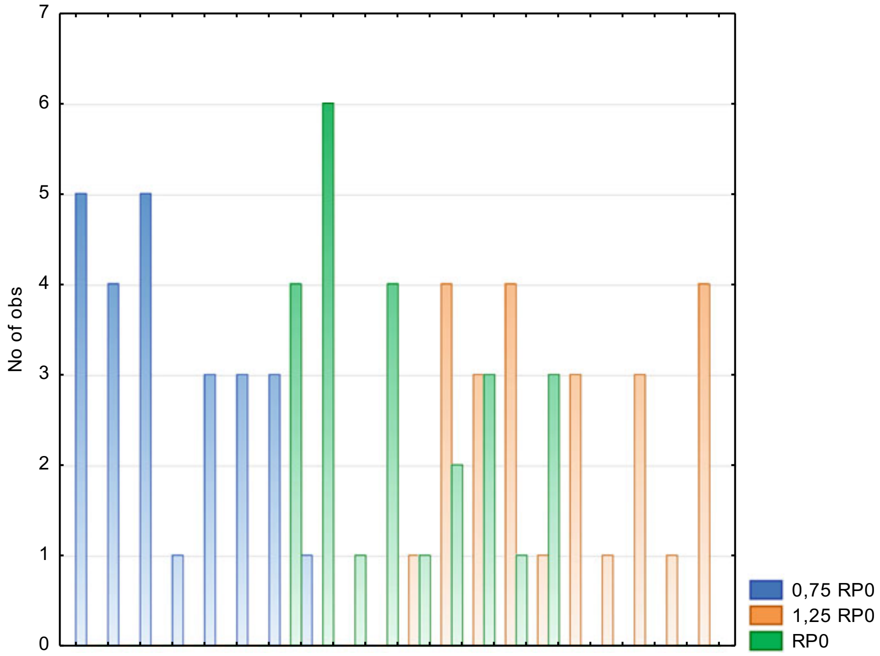

Figure. 10.4. The qualitative distribution of TPR values, calculated as the ratio of ABP to SV values

Thus, the use of the developed algorithm makes it possible to study the limits of systemic vasoconstrictor and vasodilator responses under various loads. When the algorithm described above and the one presented earlier (devoted to evaluation of the arterial baroreceptor reflex effectiveness [16]) are used together, it makes it possible to determine the types of response as well as the variants of functional reserves reduction, i.e., the ways for their recovery. The developed algorithm is intended for use in research and diagnostic systems.

References

1. G.A. Sofronov, N.B. Suvorov, P.I. Tolkachev, T.V. Sergeev, Influence of postural correction of hemodynamics on heart rhythm parameters. Medical Academic Journal **3**, 38–51 (2014)
2. E.M. Lesova, Individual differences of hemodynamic parameters during combination of hypoxic and orthostatic loads. Bulletin of Russian Military Medical Academy **1**(49), 157–163 (2015)
3. D. Morman, L. Heller, Physiology of the cardiovascular system. Piter, St. Petersburg, Russia (2000)
4. L.I. Osadchii, Postural systemic vascular reactions. Phys. J. Named After I.M. Sechenov **3**(79), 66–72 (1993)
5. K. Berganzo, B. Tijero, J.J. Zarranz, J.C. Gómez-Esteban, Postural orthostatic tachycardia syndrome, neurally mediated syncope, and joint hypermobility: a case report. Neurologia **29**, 447–449 (2014)
6. G. Cybulski, *Ambulatory Impedance Cardiography* (Verlag Berlin Heidelberg, The Systems and Their Applications Springer, 2011)
7. J.M. Stewart, Common Syndromes of Orthostatic Intolerance. Pediatrics **131**(5), 968–980 (2013)
8. D.D. Sheriff, I.-H. Nadland, K. Toska, Hemodynamic consequences of rapid changes in posture in humans. J. Appl Physiol **103**, 452–458 (2007)
9. K. Toska, L. Walloe, Dynamic time course of hemodynamic responses after passive head-up tilt and tilt back to supine position. J. Appl. Physiol. **92**, 1671–1676 (2002)
10. N. Westerhof, J.-W. Lankhaar, B.E. Westerhof, The arterial Windkessel. Med Biol Eng Comput **47**, 131–141 (2009)
11. A. Anisimov, T. Sergeev, Postural stress tests for evaluation of pulse wave propagation time based method for indirect blood pressure measurement, in *Young Researchers in Electrical and Electronic Engineering* (IEEE, 2018), pp. 1195–1198
12. C. Julien, The enigma of Mayer waves: Facts and models. Cardiovasc. Res. **70**, 12–21 (2006)
13. A.M. Whittam, R.H. Clayton, S.W. Lord et al., Heart rate and blood pressure variability in normal subjects compared with data from beat-to-beat models developed from de Boer's model of the cardiovascular system. Physiol Meas. **2**(21), 305–318 (2000)
14. R.M. Baevsky, Analysis of heart rate variability: history and philosophy, theory and practice. Clinical Informatics and Telemedicine **1**, 54–63 (2004)
15. A.V. Belov, A.A. Anisimov, T.V. Sergeev, N.B. Suvorov, Tunable band-pass filter for continuous spectral analysis of cardiointervalogram, in *Journal of Physics: Conference Series, International Scientific Conference "Metrological Support of Innovative Technologies - ICMSIT-2020*", vol. 1515 (IOP Publishing Ltd, 2020)
16. A.A. Anisimov, N.B. Suvorov, N.L. Frolova, A.V. Belov, E.A. Agapova, T.V. Sergeev, Assessment of Baroreflex Mechanism by Joint Analysis of Arterial Blood Pressure and Heart Rate, in *International youth conference on electronics, telecommunications and information technologies*, ed. by E. Velichko, M. Vinnichenko, V. Kapralova, Y. Koucheryavy. Springer Proceedings in Physics, vol. 255 (Springer, Cham, 2020), pp. 565–571