Report

Diagnostic value of measured hemodynamic parameters: cardiac output, minute volume and a complete set of phase-related volumes of blood

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Abstract

The paper reviews the existing methods for hemodynamic parameters measurement, namely the Fick method, the thermodilution technique and the Cardiocode technology. Comparative analysis of the above methods is presented. Strong and weak points in each method and their informative values are identified. Distinctive features of the Cardiocode method, as the only noninvasive one, are described.

Keywords

Hemodynamics • The Fick method • Thermodilution • Cardiocode

Imprint

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Introduction

It is commonly believed that cardiac output and minute volume of blood are most indicative signs of the cardiovascular system performance which may be used as reliable functional diagnostics tools [1-3].

Up to now, the above parameters have been measured using either direct method or an indirect one. The thermodilution technique with the Swan-Ganz catheter is classified as a direct, an invasive method to measure cardiac output in patients [4,5]. But it should be stressed that the thermodilution technique is always associated with a huge volume of preparatory workin patients which sometimes may take even several days. The cardiac catheterization techniques a special thermistor-tipped catheter (Swan-Ganz catheter) to be inserted from a peripheral vein into the pulmonary artery. A cool indicator of known temperature and volume is injected into the right atrium from a catheter port. The indicator is mixed with the blood, thus cooling the blood. The blood temperature is measured by a thermistor at the catheter, and the changes in blood temperature are calculated with a computer obtaining from the data the respective cardiac output parameters from the right ventricle.

An echocardiographic imaging technique being an indirect method can also be used to determine cardiac output for the purpose of diagnostics. It estimates real-time changes in ventricular dimensions. Then the volumetric parameters can be computed according to some specific formulas.

But why have these parametric indicators not gained the popularity in practical cardiology despite the fact they are really needed for diagnostics?

It has been just cardiometry that has offered new instrumentation to improve accuracy in non-invasive measuring of phase-related blood volumes and simplify the measuring procedures, when obtaining these key diagnostic parameters. But it should be mentioned that unfortunately classical cardiologists ignore this unique opportunity increasing the value of diagnostics.

It seems that there is an expertise mythology in the cardiological community who relies on the commonly recognized diagnostic effectiveness of estimation of cardiac output and minute volumetric parameters that is practically always associated with supposedly inevitable difficulties both in their invasive procedural measuring and their real information value for the diagnostic purposes.

That has been the driving force for us to submit our own review to address this critical issue.

Materials and methods

It is known that used are two direct methods of measuring cardiac output: the Fick method and the thermodilution technique [6,7]. Let us consider their basics in general.

The Fick method

This method is based on the Fick principle according to which “the total uptake of (or release of) a substance by the peripheral tissues is equal to the product of the blood flow to the peripheral tissues and the arterial-venous concentration difference (gradient) of the substance." [Fick A. Uber die messung des Blutquantums in den Hertzventrikeln.SitzberPhysik Med Ges Wurzburg. July 9th: 36, 1870]. Following this principle, we can calculate the cardiac output as the quotient of oxygen uptake

(AVDO2, ml/100 ml) and the difference of the arterial and mixed venous oxygen content. The Fick technique supplies us with a blood flow rate in liters per minute. The arteriovenous difference is computed by receiving samples of arterial blood and mixed venous blood, and the said venous blood is received via a catheter reaching up to the right ventricular / the pulmonary artery [1].

The consumption of oxygen by the blood in the lungs per unit of time (VO2, ml/min) can be reliably determined with spirometry only. In fact, the oxygen consumption is often calculated by empirical formulas using variables like the body surface area (KO, m2) and age of the patient. The body surface area is calculated according to a special chart (nomogram)prepared on the basis of the Du Bois formula, taking into account the body height and weight. Sure it is a source of errors in calculations and measuring minute-related volume VO2.

The minute volume measurements according to the Fick method should be conducted adhering to the following procedure:

- Blood sampling from the pulmonary artery to determine the concentration of oxygen in the mixed venous blood
- Blood sampling from the left ventricle or the aortaline to identify the concentration of oxygen in the arterial blood
- Calculation of the oxygen content in both blood samples taking into account hematocrit (Hb, g/dl). Since 1 g of hemoglobin binds 1.34 ml of oxygen, the hemoglobin index Hb is multiplied by 1.34 (Hüfner's number as oxygen binding capacity).
- Calculation of the arteriovenous oxygen content difference (AVDO2).
- Calculation of the amount of oxygen (VO2) taken up by blood in the lungs using the empirical formulas taking into account the body surface area and the patient's age:

$$VO2 = KO\ (161 - 0{,}54 \cdot age) \quad \text{(for males)} \quad (1)$$

$$VO2 = KO(147{,}5 - 0{,}47 \cdot age) \quad \text{(for females)}$$

Minute blood volumeMV is calculated by the formula given below:

$$MV = VO2 / 10 \cdot AVDO2,\ l/min \quad (2)$$

Despite the fact that the Fick method is a well-known routine procedure utilized for a long time and considered to be one of the most accurate methods for CO measurements, there are many factors that may produce errors in the Fick technique application. In this connection, the following factors should be listed [1]:

1. The use of the empirical formulas with many conditional coefficients like KO, data to be taken from the nomograms and other variables involves as a rule risks of obtaining erroneous results.

2. The Fick method provides us with an integrated value of the MV and is not capable of delivering actual blood volume data in each cardiac cycle.

3. This method has limitations: it is not suitable for use in patients with lung abnormalities provoking oxygen diffusion disorders.

4. The direct Fick technique cannot be used for measuring cardiac output in case of intra-cardiac shunt, aortic or mitral regurgitation, since a fraction of blood bypasses the pulmonary circuit that also leads to measurement errors.

5. The Fick method demonstrates its highest accuracy in case with low minute volume at a large arteriovenous oxygen difference, but in patients with high minute volume this technique becomes more and more inaccurate.

Thermodilution method

The method of thermodilution is a derivation of the Fick principle [1, 6-10]. The only difference is that not oxygen, but a cold solution at a temperature below the body temperature, for example, isotonic sodium chloride solution or 5% glucose solution is used as an indicator.

The procedure of minute blood volume measurements with the use of the thermodilution technique covers the following steps:

- A standard quantity of coldsolutionis injected into the right atrium from a proximal catheter port. The cold solution causes a decrease in blood temperature which is measured by a thermistor inserted into the pulmonary artery catheter.Temperature change is detected by a thermistor tip at the end of the catheter in the pulmonary artery. Resultant changes in blood temperatures arerecorded, producing a curve (similar to an indicator dilution curve). Multi-lumen catheters are utilized for this purpose.

- Changes in pulmonary artery blood temperature over time are plotted, producing thermodilution curves. The area under the curves is inversely related to the flow rate. Cardiac output can be accurately computed provided that a practically ideal thermodilution curve is produced. Irregular or slurred curves should be discarded to exclude inaccuracy in measurements.

- The CO computer provides for integration of the area under the thermodilution curve.

- The cardiac minute volume (MV) is derived from the Stewart-Hamilton equation as follows:

$$MV = [K \bullet VI \bullet (TH - TI)] / S, \quad l/min \quad (3)$$

where: VI— injected volume;

TH – blood temperature;

TI – injectate temperature;

K – empirical corrections for specific heat and density of the injectate and for blood and dead space volume;

S – the area under the thermodilution curve.

This technique should consider a number of factors which may cause errors in minute blood volume measurements [1] similar to the Fick method:

1. It is essential to provide a rapid and even injection technique (>4 seconds), otherwise a slow or uneven mixing of the injectate with blood in the right atrium and the right ventricle may induce erroneous measurements.

2. Another problematic factor: extrasystole during measurement procedure.

3. As opposed to the Fick method, the thermodilution technique shows the greatest error in case of low cardiac output (<3,5 l/min).

Cardiocode method

As to cardiometry, there is a new method of heart cycle phase analysis offered. It has been successfully implemented with a new type of medical equipment: the Cardiocode device. Cardiocode utilizes a non-invasive measuring technology based on digital processing of a single channel ECG recorded [2]. This technique allows measuring not only the stroke and minute blood volumes, but also a complete set of phase-related volumetric data as listed below:

SV – stroke volume, ml;

PV1 – volume of blood entering the ventricle in the phase of early diastole that characterizes the ventricular suction function, ml;

PV2 – blood volume entering the left ventricle during the phase of atrial systole that characterizes the atrial contractile function, ml;

PV3 – blood volume ejected by the ventricle during the phase of rapid ejection, (ml);

PV4 – blood volume ejected by the ventricle during the phase of slow ejection, (ml);

PV5 – blood volume (a part of SV) pumped by the ascending aorta operating as a peristaltic pump,characterizing the tonus of the aorta, (ml).

Minute blood volumes according to the Cardiocode technology are non-invasively measured as described below:

1. An ECG of the ascending aorta is recorded. In principle, it is enough to record one cardiac cycle only in order to obtain all necessary hemodynamic data upon ECG digital processing. But as a rule 10 to 15 cardiac cycles are recorded and digitally processed to get the complete hemodynamic picture.

2. Durations of the phases and cardiac cycle intervals are digitally measured according to the actually produced ECG: QRS; RS; QT; PQ segment; TT (s).

3. The phase-related hemodynamic parameters are calculated by substituting the cardiac cycle phase durations into the Poyedintsev – Voronova equations. In addition to the phase durations, as mentioned above, the following values are also involved into the equations:

a – sound velocity in blood;

g – gravity acceleration;

Sa – ascending aorta lumen area for adults.

Functional dependence between the stroke volume (SV), minute volume (MV)and cardiac cycle phase durations can be described as follows:

$$SV = f(a, g, Sa, QRS, RS, Q\text{-}T), ml; \quad (4)$$

$$MV = 0.06\ SV / (T\text{-}T), l/min \quad (5)$$

Sources of possible errors when measuring minute volume according the above technique are as follows:

1. Sa being the area of the lumen of the ascending aorta utilized in the calculations is defined as an average value for adults. For this purpose, the area of the lumen of the ascending aorta is accepted to be a constant value. This may lead to an error in the measurements of the absolute values of the minute and stroke volumes, but it does not affect the dynamics of changes in these parameters with time under an influence of internal or external factors.

2. The novel technology demonstrates its high accuracy in measurements of the cardiac cycle phases, but at the same time it is very sensitive. This advanced technique is capable of capturing the slightest changes in the patient's cardiovascular system performance, including those in the patient's emotional state affecting hemodynamics.

Comparative data study

A comparative study of values obtained with the three considered methods was carried out. The results are presented in Fig. 1 with the Bland - Altman statistics analysis [11]. It is evident that when comparing the two methods, namely, the Fick technique and thermodilution, which are the same in their essence, they demonstrate a difference in their results similar to that when comparing the Cardiocode hemodynamic data with each of them.

At the same time it should be mentioned that the Cardiocode method is a non-invasive technology, and it is capable of measuring not only the minute and the stroke volumes, but also 5 phase-related volumetric parameters as well. To obtain this huge amount of information, no special clinical preparatory measures are required. The complete set of hemodynamic parameters is computed for each cardiac cycle recorded. The Cardiocode technology is absolutely safe for patients, and that is of great importance, too. In this connection, it should be noted that the application of the above invasive measuring techniques involves high risks of complications for patients, and the associated lethality rate is evaluated to be about 5 % [12].

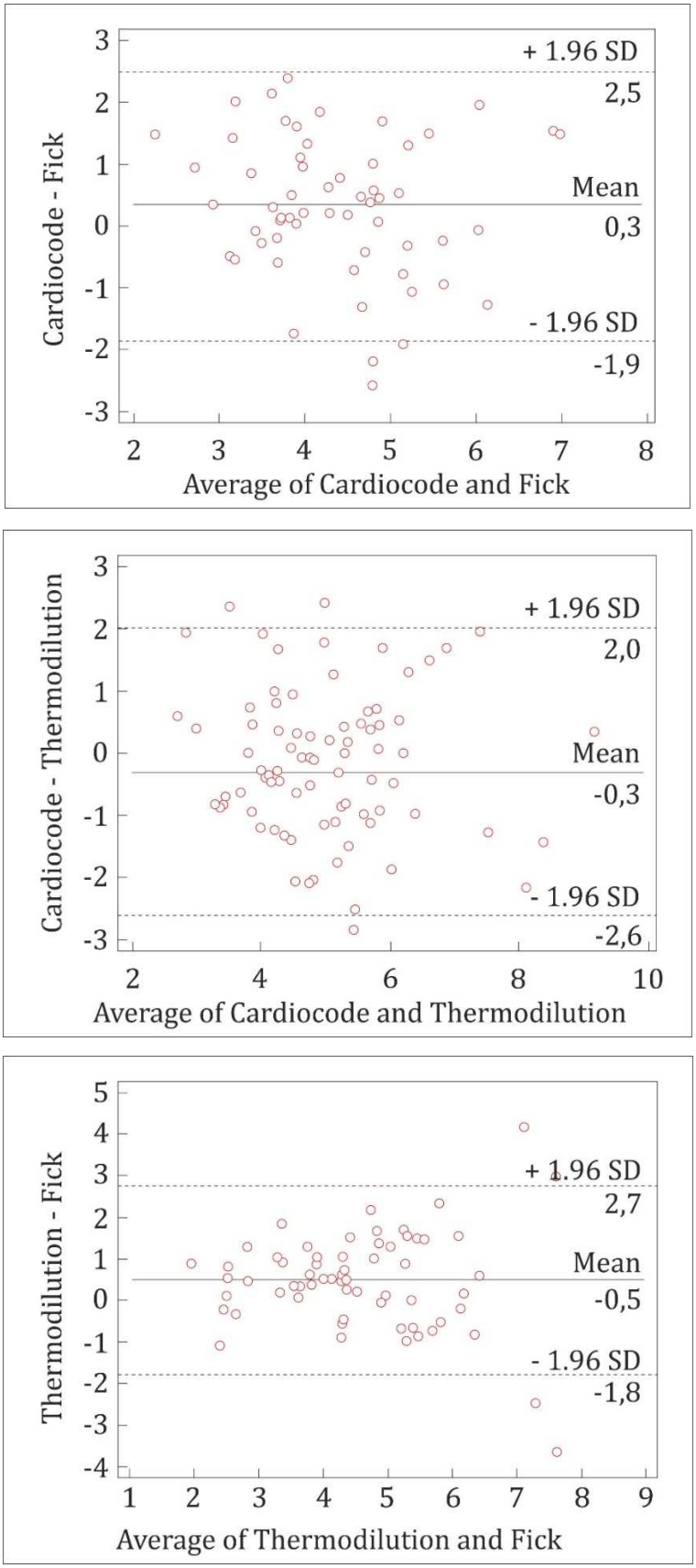


Figure 1. Comparative analysis of results for the three methods: Cardiocode vs. thermodilution, and Fick method vs.thermodilution.

This is decisive evidence that the Cardiocode technology demonstrates its indisputable advantages. However, unfortunately the unique capabilities of this advanced technology have not found a wide application in practice yet. Therefore, our idea is to summarize herein the basics of the novel technology and the hemodynamic data interpretation concept.

Practical informative value of the hemodynamic phase-related parameters: phase-related volumes SV, MV, PV1, PV2, PV3, PV4, and PV5

The significance of each of the cardiac cycle phases was presented herein above. Let us discuss how to interpret them basically.

SV is stroke volume of blood (ml). It is a sum of two volumes: PV1 and PV2. Parameter PV1 is the blood volume which is supplied to the ventricle in the phase of early diastole, and it is an indicator of the suction function of the ventricle (ml). PV2 is the blood volume which is delivered to the left ventricle of the heart during the phase of atrial systole, and it is an indicator of the atrial contractility performance (ml). The stroke volume SV is always equal to the sum of two diastolic blood volumes PV3 and PV4. It corresponds to the energy conservation law, i.e. the volume at inlet of the circulation system should be equal to that at outlet thereof. It is an axiomatic statement. Therefore, the stroke volume SV should be interpreted as the total result indicating the performance of all other cardiac cycle phases in integrative manner. The volume in question is generated during two phases: within the rapid and slow ejection phase. The normal value of this parameter is 55 ml. Some changes in the parametric value can be observed during orthostatic test. But in well-conditioned athletes no changes in the stroke volume under orthostatic test conditions are reported. It is important to take into account that the said normal value may show acceptable deviations with increase in body weight and age. The more the weight, the higher is the stroke volume, and vice versa. The same is applicable to the age of patients: the less it is, the less is the stroke volume. The Cardiocode technique provides for such age and BMI corrections when digitally processing the data. These relationships are presented in Fig. 2 and 3 below.

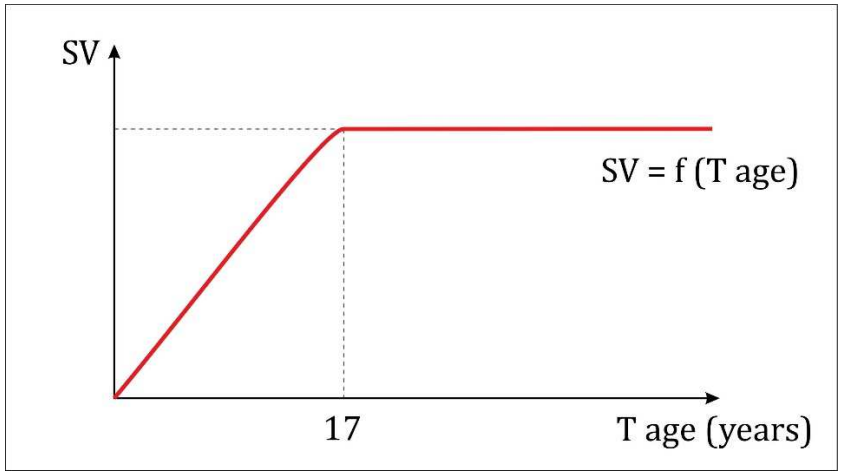


Figure 2. Relationship between stroke volume SV and age

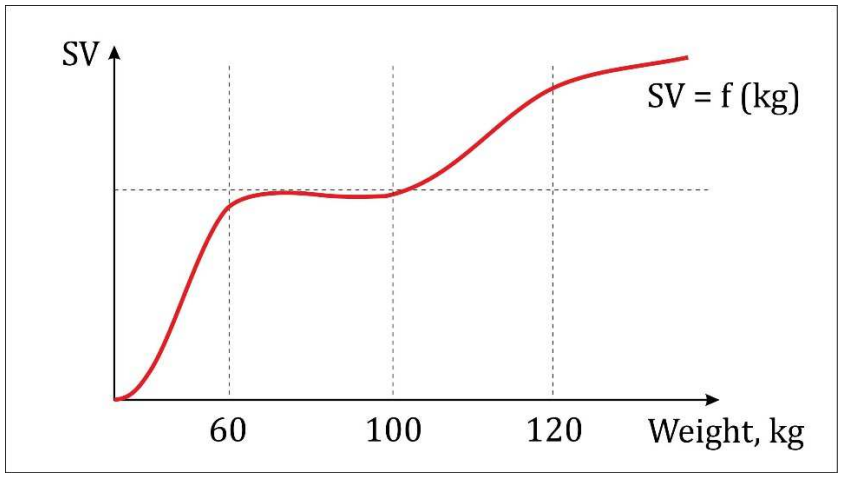


Figure 3. Relationship between stroke volume SV and body weight

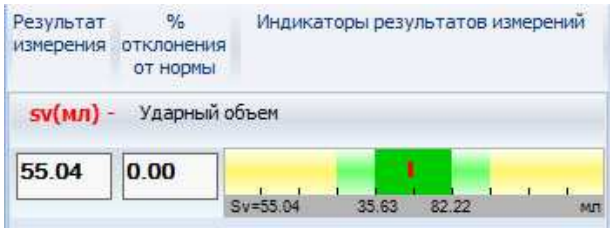
But what values of parameters SV and MV are considered to be normal? In order to answer this question, a number of factors should be taken into account, not only age and BMI of a patient. The Cardiocode technology takes into consideration the multitude of factors which might influence the final parameter value which is accepted to be the normal one. For the purpose of application of the Cardiocode technique, the following normal values have been taken as the norms for a middle-aged person with an average BMI: SV=55 ml and MV= 3,7l/min. But these values might show some changes during the orthostatic test. Another important issue should be addressed in this connection: the norm should be taken lower in patients aged under 15. The normal value may have differences from the above norm in some patients who show some specific physiological parameters. So, it is a must for a physician to properly interpret the actual measured value and deviations thereof considering influence of all factors involved. It is essential to know the actual range of the norm for a given patient to make effective diagnostics. Theoretical calculations and clinical studies have shown that the deviations +30 % are judged to be within the norm. If the said deviation is exceeded by 50%, such

measured value within the transition area between the norm and pathology is considered to be still acceptable.

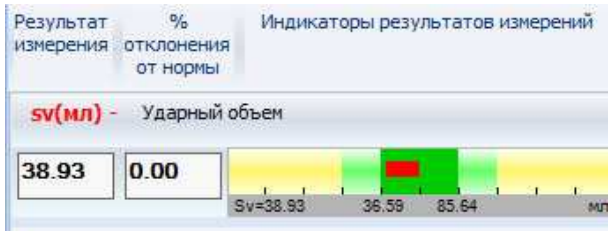
The Cardiocode device displays these ranges in the form of dark and light green fields on the monitor (Fig.4). To be more precise, the calculation of the boundary values located in the green field is always a more complicated thing. We can say that the deviation of +30 % is an approximate acceptable value. In fact, it is computed more accurately with complex mathematical equations of hemodynamics taking into account actual durations of the phases in each cardiac cycle [13-17].

Minute volume MV is computed by multiplication of the actual SV parameter by the HR. The MV parameter is measured in liters per minute. The computation results are displayed by Cardiocode similarly to the SV indication. The MV is regulated by variable heart rate. For the purpose of the proper diagnostics, this feature should be taken into account, too.

Phase-related diastolic blood volumes PV1 and PV2 are significant markers of the relaxation of heart muscle fibers in the early diastole phase and their elasticity in the atrial systole. Interpreting the above hemodynamic parameters from the point of view of biophysics, we can say that PV1 (ml) is the volume of blood which enters the ventricle in the early diastole phase; the parameter in question characterizes the suction function of the ventricle. PV2 (ml) is the volume of blood which enters the left ventricle in the atrial systole, and itis an indicator of the contractility performance of the heart muscle fibers.



a)



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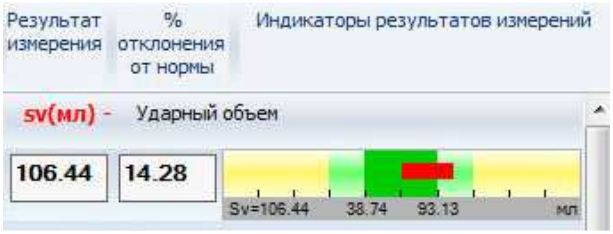

c)

Figure 4. Example: Stroke value SV: actual measured value displayed as red indicator bar in the dark green field,within the norm. Details: a)and b) red indicator bar shows the norm, 0.00% deviation from the norm; c) red indicator bar shows the actual measured value which is within the norm, but with an acceptable deviation of 14.28% (exceeding the norm)

Figure 5. Hemodynamic parameter PV2: the volume of blood entering the left ventricle in the atrial systole; the given data were obtained during monitoring of a patient. Measurements were taken every hour. Observed is a growth of the PV2 parameter with increasing deviation from the norm from 32.64% to 73.62%. It is a marker of increased atrial preloading and reduced elasticity of heart muscle fibers

Hemodynamic parameter PV3 (ml) showing the volume of blood ejected by the ventricle in the rapid ejection phase and another hemodynamic parameter PV4 (ml) demonstrating the volume of blood ejected by the ventricle in the slow ejection phase are displayed by Cardiocode in the same way as it is the case with the other hemodynamic parameters.

For the purpose of computations, the following simple rule is applicable: the sum of the diastolic blood volumes must always be equal to that of the systolic volumes, and any of the sums must be equal to stroke volume SV as given below:

$$SV=PV1+PV2=PV3+PV4$$

The Cardiocode device software is capable of digitally processing the ECG based on the above mathematics and deriving the complete set of the hemodynamic parameters for each cardiac cycle which may be effectively used for diagnostics.

Hemodynamic parameter PV5 is the volume of blood (a fraction of SV) which is pumped by the ascending aorta operating as peristaltic pump. It characterizes the aortic tonus and is measured in ml, too. But actually, under the real conditions, only a certain fraction of the total blood volume circulates in our organism. The PV5 parameter corresponds just to the circulating ("moving") fraction of blood. Functionally, it depends on energy of the blood volume supplied to the aorta. If the blood volume is high, the aorta is additionally loaded in order to support blood circulation in the blood vessels.

Conclusions

1. Blood volumes non-invasively measured on the basis of the cardiac cycle phase analysis by digital processing of ECG are true circulation volumetric parameters.

2. The informative value of the obtained phase-related blood volume parameters as indicators of the performance of the cardiovascular system is considerably higher as compared to the informative value of parameters produced by any other existing hemodynamic data equipment.

3. Cost-effectiveness of the new non-invasive technology capable of obtaining a huge volume of new information about the performance of the cardiovascular system in accordance with the novel cardiac cycle phase analysis concept outperforms all conventional measuring methods applied now in cardiology diagnostics.

Statement on ethical issues

Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest

None declared.

Author contributions

All authors participated in the manuscript preparation and data analysis. N.E.S. drafted the manuscript. All authors read the ICMJE criteria for authorship and approved the final manuscript.

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