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Evaluation of Intra-aortic Balloon Counterpulsation Impact on Stroke Volume using a Non-invasive Technique: Impedance Cardiography

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Introduction

Evaluation of the haemodynamic state of patients with acute myocardial infarction (AMI) has always been a subject of interest for clinicians. The search of optimal methods and grounding of the indications for the monitoring of central hemodynamics conditioned the introduction of invasive methods for evaluation of hemodynamics into clinical practice in 1970. The method of intermittent thermodilution (ITD), using Swan–Ganz catheters, became a "gold standard" for the evaluation of hemodynamic changes. Until now it has been somewhat difficult to obtain haemodynamic data and invasive techniques have usually been needed. However, these techniques are expensive, time-consuming, demand complicated equipment and trained staff, and are not always possible to use because of the condition of the patient, which may be either too severe or else too good to run the risks associated with invasive techniques [1]. These circumstances conditioned the necessity for the introduction of non-invasive methods into clinical practice for the evaluation of patient's hemodynamic state.

Noninvasive impedance cardiography (ICG) has been introduced by W.G. Kubicek et al. in the 1960s as a simple and non-invasive measurement of cardiac output which is used till nowadays [1]. The notion of non-invasive monitoring of haemodynamic parameters appeared in 1940s [1], when J. Nyboer et al. [2] found a relationship between basic impedance, its changes, and the volume of the area investigated. J. Nyboer et al. used the method of impedance cardiography to evaluate the flow of blood in limbs [2]. In the 1960s, W.G. Kubicek et al. received a commission from NASA to work out a non-invasive method of assessing cardiac output. The result of the team's work was the construction of the impedance cardiograph and the definition of a new equation determining stroke volume [1].

Some subsequent modifications of ICG calculation formula for cardiac output and stroke volume estimation improving accuracy of measurements were suggested [3,4,5]. ICG gives a possibility to measure stroke volume directly. This is especially important in critically ill patients (patients with complicated AMI by acute failure of the left ventricle) when different cardiac assist devices are applied for the evaluation of their impact on hemodynamic profile of the patient.

Another important challenge is that methods used in clinical practice and needed for the evaluation of the impact on the hemodynamic profile applying different therapeutic measures (cardiac assist devices, intra-aortic balloon counterpulsation) usually give us parameters "per minute", such as cardiac output (blood volume ejected by the heart per minute) or cardiac index, while stroke volume (blood volume ejected during each contraction) or stroke index are only estimated.

Genesis of impedance cardiography signal

The genesis of ICG signal is explained as impedance variations determined by varying blood volume in main chest vessels during various phases of heart cycles. The method is based on changes in the electrical resistance of the chest during heartbeat [1,6]. The following changes occur during the outflow of blood from the heart and influence the impedance signal registered: enlargement of the volume of the aorta, enlargement of the volume of the blood in the pulmonary circulation and laminar blood flow in the large vessels [1,7]. With the electrical current frequencies used in ICG (10 kHz to 100 kHz), erythrocytes, in general, do not conduct an electrical current.

When at rest, Brownian motions hold their accidental orientation. The electrical current which is flowing along the vessel must flow around the red blood cells, which causes low electrical conductivity. The laminar flow causes an erythrocyte arrangement parallel to the flow direction and the electrical current then meets smaller cross-section surfaces, which results in higher conductivity [1]. In modern ICG systems, eight electrodes are used (four electrodes delivering the electrical current, known as "the current electrodes", and four electrodes registering the voltage changes, "the voltage electrodes"). The electrodes are positioned symmetrically on both sides of the patient's neck (on the neck, the current electrodes lie above the voltage electrodes), and on both sides of the chest on the mid-axillary line on a level with the xiphoid process (on the chest, the current electrodes lie below the voltage electrodes). An alternating current of low intensity (4 mA, 60 kHz) flows along the four current electrodes, while the next four electrodes - the voltage electrodes - which are situated internally to the current electrodes, register temporary changes in voltage [1]. Additional 5 electrodes are also used for ECG registration. As a result of Ohm's law, when the current of constant intensity flows through the chest, the changes in voltage are directly proportional to the changes in resistance. The entire resistance of the chest, known as the basic resistance, is the sum of the resistance of each of the components of the chest: the adipose tissue, the heart and skeletal muscles, the lungs, vessels, bones and air [6]. Changes in the resistance of the chest result from changes in the volume of the lungs during respiration and from changes in the volume and blood velocity in the large vessels during systole and diastole. Changes in resistance caused by breathing are eliminated by the use of electronic filters [6,8,9], and changes in resistance associated with an outflow of blood are taken into consideration [1].

Difficulties of stroke volume as primary index determination among other hemodynamic indices

Few methods for assessment of hemodynamic profile of the patients are approved for application in clinical practice. Among these methods, invasive techniques (intermittent thermodilution, dye dilution, transpulmonary thermodilution) dominate, requiring invasive approach (puncture of main veins and arteries). Only few methods used in clinical practice are noninvasive (impedance cardiography, echocardiography) [10]. On the other hand, all invasive techniques measure cardiac output, and other parameters are obtained as derivatives using a formula. This aggravates the evaluation of hemodynamcs of each cardiac cycle – stroke volume and stroke index. Only continuous techniques (usually described as "beat to beat" techniques) allow primary measurement of stroke volume and its changes [10]. Noninvasive ICG technique is one of such methods.

Intra-aortic balloon counterpulsation in acute myocardial infarction

Intra-aortic balloon counterpulsation (IABC) is a widely accepted therapeutic method of temporary support of patients with impaired left ventricular function. Impaired left ventricular function causes low cardiac output and inadequate coronary perfusion. Counterpulsation helps to balance the myocardial oxygen supply and demand in these patients. The hemodynamic effects of IABC are immediate, predictable, and most importantly, decrease morbidity and mortality [11].

Balloon for IABC is placed in the descending aorta and inflates during the diastolic phase of the cardiac cycle, enhancing blood flow to the coronary and systemic circulation, and deflates during systole, reducing afterload. Overall, this should increase stroke volume and decrease myocardial oxygen demand [12].

There is a wide range of indications for IABC application, but one of the most common ones is management of complicated AMI, irrespectively of the complication type – be it a cardiogenic shock, low-cardiac output state, hypotension, refractory pulmonary congestion, or refractory polymorphic ventricular tachycardia [13].

Aim

The aim of the study was to analyse the possibility of ICG application for the assessment of stroke volume increment during IABC.

Materials and Methods

All patients with AMI and managed by IABC (Arrow "UltraFlex"™ balloon) were monitored by ITD (as a reference method) and ICG techniques. All measurements were taken in Cardiology intensive care unit, using the same two instruments. Routine hemodynamic variables – cardiac output (CO), stroke volume (SV), cardiac and stroke indexes as well as systemic vascular resistance were recorded.

The instrumentations included a pulmonary artery catheter (7 F, Baxter™), the software for ITD measurement was Datex® CS/3 by Datex-Engstrom®, and original recording system Heartlab™ (K. Dregunas, E. Pavilonis [14]; certificate No: LS.08.02.1957) was used for ICG signal acquisition and primary analysis.

According to the protocol, hemodynamic calculations were performed twice – the first measurement was performed at the initiation of hemodynamic monitoring within first 6 hours after admission, while the second measurement was performed after 24 hours (usually associated with improvement or stabilization of clinical status, irrespectively of whether they were temporary or permanent).

Swan-Ganz flow-directed triplelumened catheter was inserted through either subclavian, or internal jugular vein with continuous pressure and electrocardiographic monitoring. Selected measurements of the right atrial, pulmonary artery, and pulmonary capillary wedge pressures and CO were obtained. ITD measurements were performed by standard procedure flushing 10 ml of sodium saline injectate via proximal lumen of pulmonary artery catheter.

ICG signal was recorded using standard technique of 8 electrodes [1,4,5]. SV and CO was calculated using a modified formula suggested by W.G. Kubicek with co-authors, which was modified by D.P. Bernstein [4] and B.B. Sramek [5] with co-authors:

$$SV = \frac{(0.17H)^3}{4.2} \times \frac{(dZ/dt)_{\max} \times T_{Lve}}{Z_0} \qquad (1)$$

$$CO = SV\,x\,HR \qquad (2)$$

where SV – stroke volume; CO – cardiac output; HR – heart rate; Z_0 – baseline impedance between recording electrodes; H – patient's height; dZ/dt_{max} – the maximum of the first derivative of impedance; T_{Lve} – left ventricle ejection time.

ITD and ICG measurements for all patients were made simultaneously. Received CO values were used for ITD and ICG correlation assessment during intra-aortic balloon counterpulsation.

Morphological analysis of counterpulsated and non-counterpulsated ICG curves was performed after 24 hours following the initiation of IABC (after stabilisation of the patient's status). For extraction of separate impedance curves, we used original program designed by scientists of Institute for Biomedical Research of Kaunas University of Medicine (A. Krisciukaitis et al.) [15]. The window of the program is presented in Fig.1. Extracted curves were transferred to MS Excel software in order to figure them as well as to evaluate the plot area under the curve for further quantitative comparison of counterpulsated and non-counterpulsated curves.

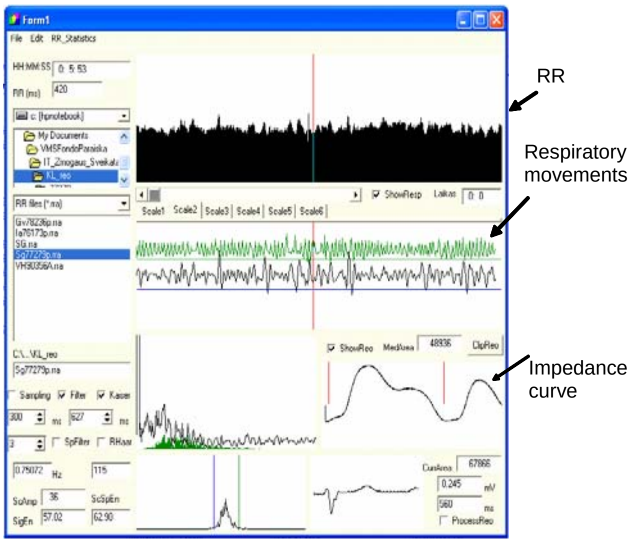


Fig. 1. The window of the original program used for ICG signal acquisition

Statistical analysis: SPSS and MS Excel software were used for data analysis. Correlation between the ITD and ICG techniques was determined using linear regression. Statistical calculations are presented as mean values and standard deviation (SD).

Approval from Kaunas Regional Biomedical Research Ethics Committee for the study was received (protocol number: 169/2004).

Patients

35 patients were investigated according to the study protocol in Kaunas Medical University Hospital. 19 (54.3%) men and 16 (45.7%) women. Average age was 69.9±9.4 years, body mass index – 27.3±3.8.

Anterior AMI diagnosed in 22 (62.9%) patients, inferior – in 12 (34.3%), and circular – in 1 (2.8%) patient. 6 (17.1%) patients were recognised as second class according to Killip, 5 (14.3%) - as third, and 24 (68.6%) – as fourth class.

All patients underwent coronary angiography. One-vessel disease was diagnosed in 5 patients (14.3%), two-vessel disease – in 9 (25.7%), while three-vessel disease – in 21 (60%) patients. The ejection fraction on admission was 24.3±12.5%. The duration from the onset of pain prior to hospitalization was 7.0±5.2 hours, while the time to primary coronary angiography was 9.3±4.8 hours.

The analysis of ICG data was performed in subsequent 32 patients' records due to poor ICG signal in 4 patients, which was conditioned by continuous movement of the patients, and insufficient amplitude of ICG signal due to extremely low cardiac output (<0.9 l/min) .

Results

We analysed 64 paired measurements, carried out in 34 patients (haemodynamic data were not recorded due to failure to place thermodilution catheter: the first measurement (34 paired CO measurements) was performed upon initiation of hemodynamic monitoring within 6 hours after admission to Cardiology intensive care unit, and the second measurement - after 24 hours (30 paired CO measurements, as four patients have died within 24 hours due to refractory to treatment cardiogenic shock). CO values according to the method of hemodynamic monitoring are presented in the Table 1.

Table 1. Cardiac output values according to the monitoring method

	First measurement		Second measurement	
Variable	**ITD**	**ICG**	**ITD**	**ICG**
CO, l/min	3.9	5.9	4.7	4.9
Maximum value, l/min	7.8	8.8	8.9	9.4
Minimal value, l/min	0.4	2.1	1.9	1.8
SD, l/min	1.7	2.2	1.9	2.4
Correlation coefficient*	0.37		0.98	

* - estimated comparing cardiac output obtained by impedance cardiography and intermittent thermodilution

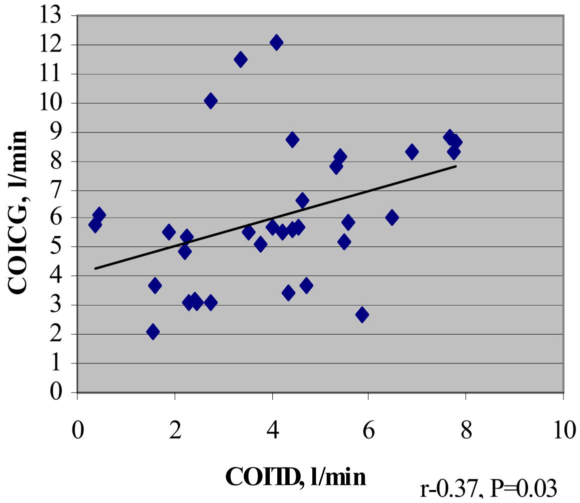
We observed very strong positive linear correlation (r-0.98) during the second measurement (p<0.0001), while during the first measurement weak positive linear correlation (r-0.37) was observed – statistically significant as well (p=0.03).

Higher CO values, as was expected, were received during the second measurement after improvement or at least stabilization of patients' status.

Regression analysis plots of the first (the initial measurement at the beginning of hemodynamic monitoring – the status of the patients compromised by cardiogenic shock, pulmonary oedema, managed by high doses of dopamine) and the second (carried out after 24 hours usually associated with stabilization of the patient status) measurements are presented in Fig. 2 and 3.

Higher dispersion was observed during the first measurement, and lower - during the second one.

Counterpulsated and non-counterpulsated ICG curves were extracted, and significant changes in the shape of pulse waveform were observed. Shapes of counterpulsated and non-counterpulsated ICG curves are presented in Fig.4 and 5.



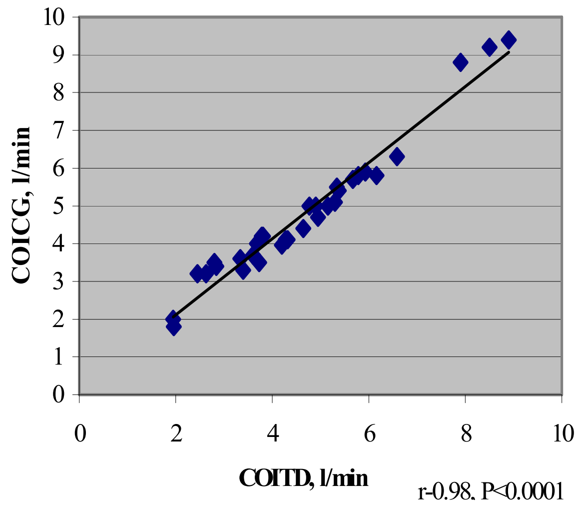


Fig. 2, 3. Regression analysis: correlation of CO_{ITD} and CO_{ICG} (the first measurement and the second measurement). Where COITD - cardiac output measured by intermittent thermodilution; COICG - cardiac output measured by impedance cardiography.

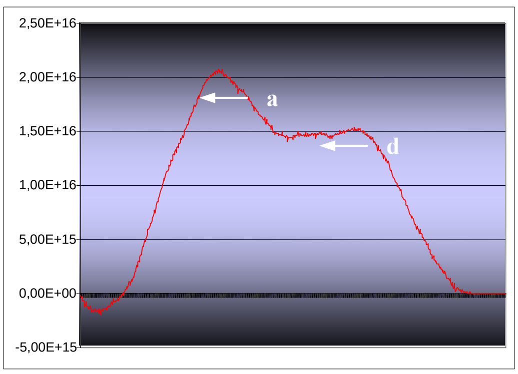


Fig. 4. Non-counterpulsated ICG curve, where **a** indicates anacrotic notch, and **d**- dicrotic wave.

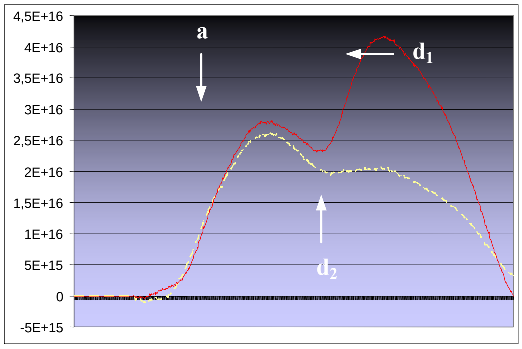


Fig. 5. Counterpulsated ICG curve, where **a** indicates anacrotic wave, $\mathbf{d_1}$ - dicrotic wave of counterpulsated cardiac cycle, and $\mathbf{d_2}$ – dicrotic wave of non-counterpulsated cardiac cycle.

We performed a comparison of the counterpulsated and non-counterpulsated cardiac cycle ICG curves. A significant augmentation of the pulse waveform is clearly seen in the region of dicrotic wave, while the anacrotic part remains almost unaffected. The difference between the counterpulsated and the non-counterpulsated ICG curves is presented in Fig. 6.

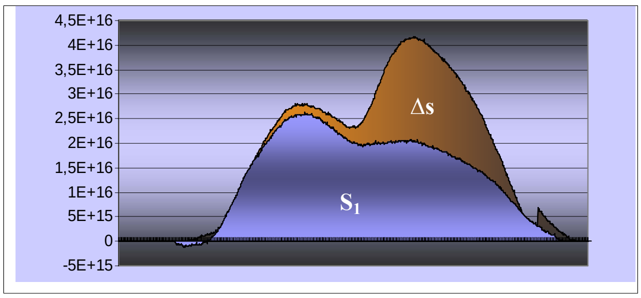


Fig. 6. Comparison of counterpulsated and non-counterpulsated ICG curves; the area indicated as **Δs** represents the impact (augmentation) of counterpulsation on the shape of ICG curve, while $\mathbf{S_1}$ indicates the area of non-counterpulsated curve.

An increment of the stroke volume up to 27.63% (minimal – 5.53%, maximal – 44.18%) was observed when comparing the plot area of the counterpulsated and non-counterpulsated ICG curves. The difference was statistically significant ($p<0.05$). The variation in the registered ICG curves (as an example, the data of one patient's record) is presented in Fig. 7 and 8.

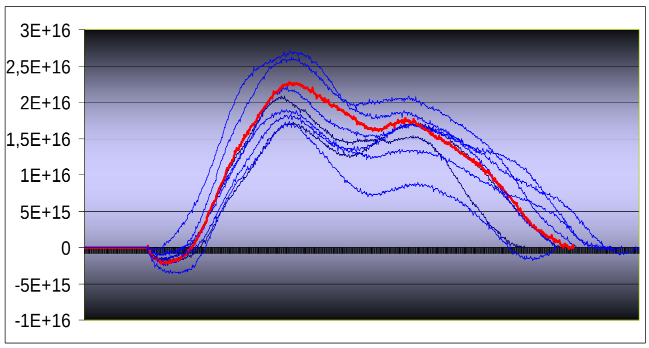


Fig. 7. View of non-counterpulsated ICG curves

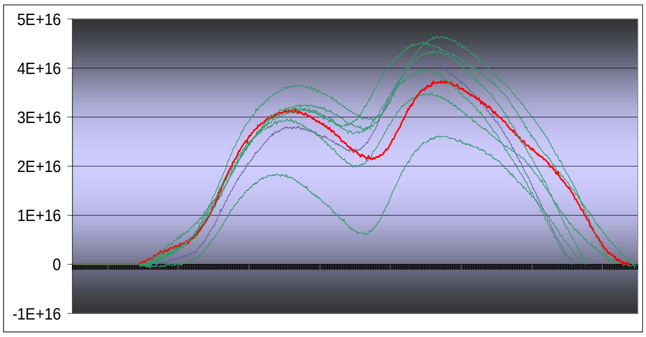


Fig. 8. View of counterpulsated ICG curves

Discussion

The evaluation of hemodynamic state in patients with complicated AMI managed by IABC is accomplished mainly and most commonly by invasive methods [16], although, as we observed in our study, non-invasive methods might be successfully applied in clinical practice [17]. The possibility of complications during ITD application, and their influence on the patient outcome triggered a new wave of investigations aimed to improving the accuracy of non-invasive methods for the evaluation of SV like ICG [3].

The exceptional feature of ICG is the possibility to measure SV as a basic variable, while widely used thermodilution technique gives us CO as the basic variable, and stroke volume is only a derivative. Thermodilution technique does not allow for the assessment of hemodynamics of each cardiac cycle, which in our opinion is extremely important in patients managed by IABC.

In our study, we presented the possibility of the application of ICG for the assessment of hemodynamic impact on hemodynamic profile in patients when measuring changes in SV. Clinicians often deal with problems related to the choice of a proper regimen for IABC. We performed our measurements on the regimen "1 to 4" - this means that every fourth cardiac cycle was assisted by inflation of the aortic balloon, but in some cases we observed better improvement in the clinical status when applying "1 to 1" or "1 to 2" regimens where all cardiac cycles or every second cardiac cycle were assisted. ICG could be an appropriate method for the quantitative estimation of the selection of optimal IABC regimen via measurement of its impact on SV augmentation.

On the other hand, there are some unsolved questions for wide application of ICG – the evaluation of breathing cycles and their influence on impedance changes, some recorded data might be unusable due to poor quality of the ICG signal, and this might be due to continuous patient movement, as well as in cases of severe condition of the patient – low cardiac output state, managed by high doses of inotropes. Because of these reasons, we analysed ICG curves after relative stabilization of the patient status, i.e. 24 hours after the initiation of IABC.

Conclusions

1. Impedance cardiograph is a reliable method for the evaluation of hemodynamic state in patients with acute myocardial infarction managed by intra-aortic balloon counterpulsation. However, the application of impedance cardiography is compromised in patients with severe cardiogenic shock who are dependent on high doses of inotropic agents (dopamine).
2. The application of impedance cardiography allows for a quantitative estimation of the influence of intra-aortic counterpulsation on hemodynamics via the measurement of stroke volume and its increase during counterpulsated systole.

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In clinical practice, hemodynamic methods usually yield cardiac output values, while stroke volume (blood volume ejected during each contraction) is only estimated. Impedance cardiography gives a possibility for a direct measurement of stroke volume. Our aim was to analyse the possibility for the application of impedance cardiography for the assessment of an increase in stroke volume during intraaortic counterpulsation. This paper presents the possibilities for the application of impedance cardiography for the quantitative estimation of the influence of aortic counterpulsation on hemodynamics via the measurement of stroke volume. 35 patients were investigated during the study. In the comparison of intermittent thermodilution and impedance cardiography, the correlation coefficient ranged between 0.37 and 0.98. The comparison of the plot area of the extracted impedance cardiography curves of counterpulsated and non-counterpulsated cardiac cycles showed an increment of the stroke volume of up to 27.63% ($p<0.05$). Ill. 8, bibl. 17 (in English; summaries in English, Russian and Lithuanian).

Ю. Бражджёните, А. Мацас, Р. Жалюнас. Оценка влияния контрапульсации аорты на изменение систолического объёма методом неинвазной кардиографии импеданса // Электроника и электротехника. – Каунас: Технология, 2007. – № 7(79). – С. 53–58.

В клинической практике чаще всего используемые методы исследования гемодинамики позволяют непосредственно оценить минутный объём сердца, в то время как систолический объём надо рассчитывать. Методом кардиографии импеданса можно непосредственно оценить систолический объём. Это особо важно применяя дополнительные приспособления для поддержки кровообращения (контрапульсация аорты) тех больных, у которых наблюдается острый инфаркт миокарда с осложнениями. В работе анализируются возможности применения кардиографии импеданса для оценки изменений систолического объёма во время контрапульсации аорты. К исследованию привлечены 35 больных. Корреляционный коэффициент между значениями минутного объёма сердца, зарегистрированными методом кардиографии импеданса и интромитирующей термоделюцией колебался от 0,37 до 0,98. Оценивая площадь контрапульсированных и неконтрапульсированных кривых кардиографии импеданса, наблюдалось увеличение систолического объёма до 27,63 % (п<0,05). Ил. 8, библ. 17 (на английском языке; рефераты на английском, русском и литовском яз.).

J. Braždžionytė, A. Macas, R. Žaliūnas. Aortos kontrapulsacijos įtakos sistolinio tūrio pokyčiams vertinimas neinvaziniu impedanso kardiografijos metodu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 7(79). – P. 53–58.

Klinikinėje praktikoje dažniausiai naudojami hemodinamikos tyrimo metodai leidžia tiesiogiai nustatyti minutinį širdies tūrį, o sistolinis tūris yra apskaičiuojamas. Impedanso kardiografijos metodu galima tiesiogiai nustatyti sistolinį tūrį. Tai ypač aktualu taikant pagalbines kraujotakos palaikymo priemones (aortos kontrapulsaciją) ligoniams, sergantiems komplikuotos eigos ūminiu miokardo infarktu. Darbe analizuojamos impedanso kardiografijos taikymo galimybės sistolinio tūrio pokyčiams vertinti aortos kontrapulsacijos metu. Į tyrimą įtraukti 35 ligoniai. Koreliacijos tarp širdies minutinio tūrio verčių, registruotų impendanso kardiografijos ir intermituojančiosios termodiliucijos metodais, koeficientas svyravo nuo 0,37 iki 0,98. Vertinant impedanso kardiografijos kontrapulsuotų ir nekontrapulsuotų kreivių plotą, nustatyta, kad sistolinis tūris padidėjo iki 27,63% ($p<0,05$). Il. 8, bibl 17 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).

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