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Non-Invasive Methods of Haemodynamic Monitoring

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Abstract

Diseases of the cardiovascular system are one of the most common causes of death in Poland and in the world. Along with the progress of medicine and development of diagnostic methods, there are a growing number of useful procedures allowing for better monitoring of patient's cardiovascular parameters and thereby more effective treatment. Monitoring of haemodynamic parameters of the circulatory system is necessary in patients hospitalised in anaesthesiology departments and in most intensive cardiac care units. The methods employed to evaluate the work of the heart can be divided into invasive and non-invasive, depending on whether they require a disruption of the continuity of the patient's tissues. In view of the ease of implementation of non-invasive methods, their costs and their implementability in practically every patient, these methods are used with increased frequency, both in patient care, as well as in measurements taken for scientific purposes. In recent years, several new methods have been developed which in many aspects are by no means inferior to the "golden standard" constituted by the invasive methods. When supported by medical knowledge and experience of health care professionals, they become particularly useful and valuable for improving medical care. This paper presents the latest of the currently available methods of haemodynamic monitoring. The mechanism of action of each of them has been explained, as well as the possibilities they present, the limitations they hold and the examples of their use in patient care.

Key words: haemodynamic monitoring, bioimpedance, electrocardiography

1. Introduction

Diseases of the cardiovascular system are one of the most common causes of death in Poland and in the world. Owing to the progress of medicine, and the ever increasing number of cutting-edge diagnostic methods, as well as thanks to the enhancement of monitoring methods, patient treatment has been rendered more effective. The assessment of individual haemodynamic parameters of the circulatory system is a basic element of highly specialised medical care in anaesthesiology and intensive care units, as well as in intensive cardiac care departments. The methods used for assessing cardiovascular capacity can be divided into invasive and non-invasive. The first group includes all those methods that in any way disrupt the continuity of the patient's tissues: ventriculography, the method of continuous cardiac output measurement (PAC-CCO), Fick's method, thermodilution method (PATD, PAC-CO), dye dilution method, methods for analysing the wave heart rate, such as pulse heart rate (LIDCO) analysis and the use of APCO algorithm (Vigileo), together with pulse contour analysis (PICCO). Non-invasive methods encompass the following: non-invasive cardiac output monitoring (ICON), bioreactance (NICOM), impedance cardiography (ICG), electrical cardiometry (EV), CNAP monitor, methods based on the use of a cuff wrapped around the finger, transthoracic echocardiography with a measurement of the cardiac output per minute at the level of the left arterial outlet and magnetic resonance. There are advantages and disadvantages to each of the above-listed methods. Although widely used, invasive methods are expensive, they require trained medical personnel, and are also time-consuming and complicated. In addition, they require a disruption of tissue continuity, which is associated with an increased risk of infection. Recently, non-invasive methods have been recurred to more often, as they are safe for the patient and significantly less costly. They allow for continuous monitoring of the patient's condition, but one should bear in mind their limitations and the lack of implementation possibility in all patients.

2. Aim of the Study, Materials and Methods

This paper presents the latest of the currently available methods of haemodynamic monitoring. The mechanism of action of each of them has been explained, as well as the possibilities they present, the limitations they hold and the examples of their use in patient care.

3. Discussion of Individual Methods

3.1. NICOM (non-invasive cardiac output measurement)

It is a method based on processing of the chest signal bioimpedance. Bioreactance consists in conducting an analysis of the AC current flow through the chest. Bioreactance technology was developed by Cheetah Medical researchers after many years of intensive research, testing and validation. Bioreactance uses the analysis of time delay and phase shifts of the alternating electric current flowing through the patient's chest. Pulsatile blood flow in large vessels of the chest causes a change in the amplitude (due to phase shift or time delay) of the AC voltage applied to the chest. The main role in pulsatile blood flow within the chest is played by the aortic blood flow, hence the NICOM signal almost perfectly correlates with the aortic flow. In addition, other fluids located within the chest have a relatively static level, and, therefore, they do not affect changes in phase shifts that could in turn impact the NICOM signal [1]. As a result of the conducted research, it was observed that the obtained phase shift is closely correlated with the ejection fraction of the heart. The NICOM system consists of a high-frequency alternating current generator (75kHz), four pairs of sensors (transmitters and receivers) placed on the chest skins surface around the heart and a CHEETAH NICOM monitor for the recording. Double sensors are located on both sides of the chest - two on the right and two on the left. In each pair of sensors, there is one transmitter sensor which supplies high-frequency alternating current to the chest surface while the other one - which acts as the receiver - receives the received voltage. The NICOM monitor is equipped with a highly sensitive phase detector that continuously records phase shifts generated by the aortic flow within the chest. As a result, a NICOM signal is generated, which is recorded separately on the right and on the left side of the chest, and then it is subjected to digital processing, so that an average result defining the ejection fraction of the heart is obtained [2-4]. During the diastole, the phase shift (ϕ) increases rapidly until the maximum value is reached at the end of the contraction. It is an expression of the increase in blood volume in the aortic lumen. During the diastole, the blood capacity in the aorta decreases, which is displayed in the graph as a reduction in the phase shift. Phase shift changes ($d\phi/dtmax_{)}$ are a reflection of changes in the blood volume within the chest - and, more accurately, they are proportional to changes in aortic blood flow during one heart cycle. Maximum flow ($d\phi/dtmax_{)}$ is measured at the point of the maximum CHEETAH signal, while the ventricle ejection time (VET) is measured from the beginning of the contraction phase to the end of the diastole. The stroke volume (SV) is calculated according to the following formula: $SV = C \times VET \times d\phi/dtmax$, where C is a constant value, taking into account the age, sex and body surface of the patient. Cardiac output (CO) can then be calculated by multiplying the stroke volume (SV) by the heart rate (HR): $CO = SV \times HR$ [2-4].

Studies on the accuracy of cardiac output measurement using bioreactance technology have been conducted since 2007. It has been shown that the cardiac output measured using bioreactance is highly correlated with the values obtained when employing thermodilution or pulse contour analysis. Squara et al. analysed the accuracy of the bioreactance method as compared to the markings when using thermodilution while observing 110 patients immediately following a cardiac surgery. The measurements obtained during the application of both methods did not differ significantly from each other. In addition, it was found that the markings obtained using the NICOM device were made with greater precision and, in case of occurrence of haemodynamic changes, they were recorded faster with NICOM [5]. As part of another multicentre study, 111 patients who required an assessment of the cardiac output were observed. Measurements were taken simultaneously using bioreactance and thermodilution. As before, cardiac output measurements performed with the two methods did not differ significantly from one another, however, the bioreactance method did not involve any patient's exposure to complications owing to its non-invasive nature [2].

Despite its many advantages, the bioreactance method also has some limitations. Any electrical disturbances interfere with the signal generated. For example, electrocoagulation used during surgical procedures prevents accurate recording. It should also be remembered that when using this method, averaged measurements are obtained within 60 s, hence, sudden short-term cardiac abnormalities may not be detected.

3.2. Impendance Cardiography, ICG

Impedance cardiography (ICG) is a safe and non-invasive method of haemodynamic monitoring. It was discovered in the 1930s, and it was first used in practice in the 1960s by astronauts during spaceflights [6]. This method uses the phenomenon of variation of electrical resistance of the alternating current (impedance), resulting from the blood flow in large arteries in a specific part of the body. Each tissue type has its own specific electrical resistance. The muscles, lungs, adipose tissue and bones found in the chest area are characterised by high electrical resistance and, therefore, they do not conduct the electrical current supplied during the test. In contrast, the blood flowing through the arteries of the chest is characterised by a relatively low impedance, hence, it most definitely act as a better conductor of electric current. Bearing in mind the rhythmic repetition of blood flow from the heart cavities to large arteries and the resulting small yet synchronous changes in electrical resistance, it is possible to record them for the assessment of basic haemodynamic parameters [7]. Impedance changes in the chest area are affected by changes in lung volume, however, the resulting changes in electrical resistance are subject to electronic filtering, so that a selective assessment of the cardiovascular system function is possible [8]. The test consists in placing 8 electrodes (4 delivering current and 4 receivers) on the patient's skin symmetrically on both sides of the neck and the chest. On the neck, the electrodes supplying the current are located above the receiving electrodes, while on the chest, they are placed in the opposite direction. The alternating current of low intensity (2-4mA) and high frequency (60-100kHz) used during the study is safe for the patient and is completely unnoticeable to them. Receptive electrodes record voltage changes and are used to record the ECG [9-12].

The Ohm's law, used during the use of impedance cardiography, says that the constant current flowing through a given area causes voltage changes which are directly proportional to the changes in resistance. The observed change of bioimpedance in time allows for a creation of a graph reflecting the changes in the volume of the blood flowing through the aorta. On the basis of this record, it is possible to determine the stroke volume (SV) and the cardiac output (CO). In addition, the simultaneous combination of bioimpedance curve and ECG recording allows the assessment of many haemodynamic parameters, such as: pre-ejection period of the left ventricle (PEP), left ventricular ejection time (LVET) andthe systolic time ratio (STR). The use of impedance cardiography also allows to determine the following: velocity index (VI), acceleration index (ACI), Heather index (HI), systemic vascular resistance (SVR), pulse pressure (PP), total artery compliance (TAC) [13].

Since the detection of impedance cardiography, many studies have been carried out to assess the effectiveness, accuracy and reliability of the method in comparison with other invasive and non-invasive methods. Numerous studies have confirmed a statistically significant correlation between haemodynamic parameters determined by thermodilution and ICG as well as by the Fick and ICG methods [14-19].

Like any other method, impendance cardiography is not without its limitations. It should not be used to assess haemodynamic parameters in patients with a septic shock, severe arterial hypertension, with a high degree of aortic regurgitation, and in patients with intra-aortic balloon counterpulsation. ICG is also contraindicated by significant arrhythmias, such as atrial fibrillation, tachycardia (> 250 / min) and frequent additional contractions. In addition, significant deviations in the body structure of the subject also constitute a contraindication for the use of ICG (very high or very low growth, significant obesity, significant malnutrition or condition following sternotomy). A properly conducted examination requires the patient to remain motionless, hence the markings will be impossible to obtain from patients who are agitated, non-cooperative, those suffering from seizures or in small children [13,20]. The study should not be performed in people with an implanted cardiac pacing system, which is equipped with the function of changing the rhythm frequency depending on the minute ventilation, as this would create a risk of impairing the functioning of the pacemaker [8].

3.3. Electrical Velocimetry, EV

It is a method developed in 2001 by Bernstein and Osypek, and it entails the modification of the measurement obtained during the use of impedance cardiography [21]. Electrical cardiometry is based on the electric measurement of the speed of blood flow resulting from changes in blood conduction in the aorta. During rest, owing to the Brownian motion, the erythrocytes are arranged chaotically in the vessel, while after opening the aortic valve, they line up in parallel to the flow direction (laminar flow). This model uses the phenomenon of changing the flow of erythrocytes from chaotic to laminar after opening the aortic valve [22]. The effect of changing the erythrocyte setting is the decrease in impedance, and thus the increase in the conductivity of the electric current. The test consists in placing 4 ECG electrodes on the patient's skin - two on the left side of the neck and two along the central left axillary line at the level of the xiphoid process. The EC method, by means of analysing the rate of changes in the flow conductivity, calculates the peak of the blood acceleration in the aorta and the flow time (the ejection time of the left ventricle). To calculate the relevant haemodynamic parameters, such as cardiac output, it is necessary to use a special algorithm. Thanks to the cardiometry method, it is possible to determine the following: cardiac output, stroke volume, cardiac index, cardiac output index, peripheral vascular resistance, index of cardiac contractility, left ventricular ejection [22].

A study conducted by Schmidt et al. compared the use of electrical cardiometry and transesophageal echocardiography in patients qualified for CABG (coronary artery bypass grafting). The results obtained using these two methods were significantly similar to each other [23.24]. Other researchers also did not observe significant differences in the comparison of the method of electrical cardiometry with thermodilution or with the Fick method [25-27].

3.4. CNAP Monitor

The routine medical examination includes a non-invasive blood pressure measurement using the Korotkov method, which was developed in 1905 [28]. Korotkov pressure measurement using a mercurial sphygmomanometer is recommended by many scientific societies. It is simple, inexpensive and non-invasive, but despite the ease of its implementation, it is associated with the risk of numerous errors in the measurement. In addition, it does not allow for continuous recording of changes in BP (blood pressure), and thus, it has numerous limitations of use during surgery or in patients who are in severe medical condition. Therefore, in patients requiring continuous monitoring of blood pressure, it is necessary to use an invasive method of blood pressure assessment, or so-called Blood pressure measurement, which involves placing a catheter inside the arterial blood vessel, which most often, owing to its easy accessibility, is a radial artery. The method of bloody BP measurement is associated with the risk of many dangerous complications, such as haemorrhage, haematomas and infections [29, 30].

Constituting an alternative to blood pressure measurement in patients requiring continuous monitoring of this parameter is the use of the CNAP Monitor. It is a device enabling non-invasive, continuous blood pressure and pulse measurement - in the beat-to-beat mode - owing to the use of sensors with cuffs that are placed on the patient's fingers. The CNAP Monitor is a measurement system built from plethysmographic sensors (light-emitting diode and detector) located in the cuff of the measurement sensor placed on the patient's fingers. The principle of operation is based on the measurement of perivascular environment pressure around the phalanx bone. The change in blood volume in the finger is detected by a detector that records the change in the light beam. Then the signal is sent to the cuff pump, causing the pressure to change. It reflects the pressure changes in the arteries of the finger. The pressure measurement in the cuff placed on the finger corresponds to the change in the pressure occurring during each heartbeat. The obtained values are registered continuously in the form of an arterial blood pressure graph and they are then properly calibrated using the oscillometric method. Owing to the technology using the automatic function of calibration performed in the background, the obtained measurements are displayed on the patient's monitor in real time. This method serves to determine the values of systolic, diastolic and mean pressure, as well as the pulse rate for each heartbeat (beat-to-beat). Additionally, the device makes it also possible to determine the minute cardiac output, cardiac output volume, cardiac index, cardiac systolic index and peripheral vascular resistance [31.32]. Despite its many advantages, this method is not without some limitations. First of all, it cannot be used in patients with poor peripheral blood perfusion, with Reynaud's syndrome, with body weight

<40kg or> 180kg, with BMI> 35kg/m2, cardiac arrhythmias in the form of tachyarrhythmia, or in patients with implants located in upper limb vessels or with tremors [33].

The tests carried out on various groups of patients confirmed the satisfactory accuracy of the measurements performed using the CNAP monitor. In comparison to the measurements obtained by means of the blood method, these results did not significantly differ from each other [34, 35].

3.5. Transthoracic echocardiography with the measurement of the minute cardiac output at the level of the left arterial outlet

The echocardiography employing a 5-cavity apical view is quite the labour-intensive method of the assessment of cardiac output, and one which additionally requiring a lot of experience and skill. Slight deviation of the head towards the back from the 4-cavity apical projection allows for an obtaining a 5-cavity image with regard to the left arterial outlet. The Doppler gate below the aortic valve leaflets allows the imaginig of blood flow through the left arterial outlet. Then, by making several measurements, the device automatically measures and estimates the volume of the cardiac output [36].

4. Summary

Constant control of haemodynamic parameters is essential when caring for patients remaining in severe general condition, undergoing surgery, and in those admitted to Intensive Care or Intensive Cardiac Care Units. The clinical experience and expertise of the physician play a huge role in the diagnostic and therapeutic process. However, at the present time, when various diagnostic devices are widely available and newer medical technologies are being created, the effectiveness of diagnostic and therapeutic measures taken is also largely dependent on the knowledge of appropriate diagnostic equipment for its use and interpretation of the results obtained. The invasive methods still constitute the golden standard for assessment of the haemodynamic parameters, which require suitably qualified medical personnel on top of being costly and involving an increased risk to the patient's health and life. The conducted validation studies prove that many new non-invasive methods are by no means inferior to the effectiveness and accuracy of the measurements performed using invasive methods. In addition, they are sometimes less costly and much simpler to implement than invasive tests, and, above all, what can be considered their most important advantage - they usually do not involve any risk to the patient's health and life. Perhaps with the development of technology, they will be able to fully replace the invasive monitoring methods.

References

1. Marik PE. Noninvasive cardiac output monitors: a state-of the-art. review. *Journal of Cardiothoracic and Vascular Anesthesia*. 2013; 27: 121–34.

2. Raval NY, Squara P, Cleman M, Yalamanchili K, Winklmaier M, Burkhoff D. Multicenter evaluation of noninvasive cardiac output measurement by bioreactance technique. *Journal of Clinical Monitoring and Computing*. 2008; 22: 113–119.

3. Keren H, Burkhoff D, Squara P. Evaluation of a noninvasivecontinuous cardiac output monitoring system based on thoracic bioreactance. *American Journal of Physiology*. 2007; 293: H583-H589.
4. https://www.cheetah-medical.com/how-it-works/bioreactance/ (accessed: 2017.11.24)
5. Squara P, Denjean D, Estagnasie P, Brusset A, Dib JC, Dubois C. Noninvasive cardiac output monitoring (NICOM): a clinical validation. *Intensive Care Medicine*. 2007; 33: 1191–1194.
6. Kubicek WG, Karnegis JN, Patterson RP, Witsoe DA, Mattson RH. Development and evaluation of an impedance cardiac output system. *Aerospace Medicine*. 1966; 37(12): 1208-1212.
7. Siebert J. Kardiografia impedancyjna. Via Medica, Gdańsk 2006.
8. Sodolski T, Kutarski A. Impedance cardiography: A valuable method of evaluating haemodynamic parameters. *Cardiology Journal*. 2007; 14(2): 115-126.
9. Kim DW. Detection of physiological events by impedance. *Yonsei Medical Journal*. 1989; 30: 1-11.
10. Woltjer HH, Bogaard HJ, de Vries PM. The technique of impedance cardiography. *European Heart Journal*. 1997; 18: 1396-1403.
11. Summers RL, Shoemaker WC, Peacock WF, Ander DS, Coleman TG. Bench to bedside: electrophysiologic and clinical principles of noninvasive hemodynamic monitoring using impedance cardiography. *Academic Emergency Medicine*. 2003; 10: 669-680.
12. Strobeck J, Silver M. Beyond the four quadrants: the critical and emerging role of impedance cardiography in heart failure. *Congestive Heart Failure*. 2004; 10 (supl. 2): 1–6.
13. Krzesiński P, Gielerak G, Kowal J. Kardiografia impedancyjna – nowoczesne narzędzie terapii monitorowanej chorób układu krążenia. *Kardiologia Polska*. 2009; 67: 65–71.
14. Castor G, Molter G, Helms J, Niedermark I, Altmayer P. Determination of cardiac output during positive end-expiratory pressure--noninvasive electrical bioimpedance compared with standard thermodilution. *Critical Care Medicine*. 1990; 18(5): 544-546.
15. Spiess BD, Patel MA, Soltow LO, Wright IH. Comparison of bioimpedance versus thermodilution cardiac output during cardiac surgery: evaluation of a second-generation bioimpedance device. *Journal of Cardiothoracic and Vascular Anesthesia*. 2001; 15(5): 567-573.
16. Yung GL, Fletcher CC, Fedullo PF, Johnson FW, Kinninger K, Knowlton KU. Noninvasive cardiac index using bioimpedance in comparison to direct Fick and thermodilution methods in patients with pulmmonary hypertension. *Chest*. 1999; 116 (Suppl. 2): 281S.
17. Verhoeve PE, Cadwell CA, Tsadok S. Reproducibility of noninvasive bioimpedance measurements of cardiac function. *Journal of Cardiac Failure*. 1998; 4 (supl.): S3 (streszczenie).
18. Van De Water JM, Miller TW, Vogel RL, Mount BE, Dalton ML. Impedance cardiography: the next vital sign technology? *Chest*. 2003; 123: 2028-2033.
19. Yancy C, Abraham WT. Noninvasive hemodynamic monitoring in heart failure: utilization of impedance cardiography. *Congestive Heart Failure*. 2003; 9: 241-250.
20. Żuchowski B, Guzik P. Elektryczna bioimpedancja klatki piersiowej. *Anesteziologia i Ratownictwo*. 2008; 2: 434-442.

21. Zoremba N, Bickenbach J, Krauss B, Rossaint R, Kuhlen R, Schälte G. Comparison of electrical velocimetry and thermodilution techniques for the measurement of cardiac output. *Acta Anaesthesiologica Scandinavica*. 2007; 51: 1314-1319.
22. Chutkowski R, Malec-Milewska M. Kardiometria elektryczna – nowa metoda nieinwazyjnego monitorowania hemodynamicznego. *Borgis - Postępy Nauk Medycznych*. 2014; 5: 346-351.
23. Grollmuss O, Demontoux S, Capderou A, Serraf A, Belli E. Electrical velocimetry as a tool for measuring cardiac output in small infants after heart surgery. *Intensive Care Medicine*. 2012; 38(6): 1032-1039.
24. Schmidt C, Theilmeier G, Van Aken H, Korsmeier P, Wirtz SP, Berendes E et al. Comparison of electrical velocimetry and transoesophageal doppler echocardiography for measuring stroke volume and cardiac output. *British Journal of Anaesthesia*. 2005; 95(5): 603-610.
25. Osthaus WA, Hubert D, Beck C, Winterhalter M, Boethig D, Wessel A et al. Comparison of electrical velocimetry and transpulmonary thermodilution for measuring cardiac output in piglets. *Pediatric Anesthesia*. 2007; 17(8): 749-755.
26. Norozi K, Beck C, Osthaus WA, Wille I, Wessel A, Bertram H. Electrical velocimetry for measuring cardiac output in children with congenital heart disease. *British Journal of Anaesthesia*. 2008; 100(1): 88-94.
27. Raue W, Swierzy M, Koplin G, Schwenk W. Comparison of electrical velocimetry and transthoracic thermodilution technique for cardiac output assessment in critically ill patients. *European Journal of Anaesthesiology*. 2009; 26: 1067-1071.
28. O'Rourke MF, Seward JB. Centralne ciśnienie tętnicze i ciśnienie tętna sto lat po odkryciu Korotkowa. *Medycyna po Dyplomie*. 2007; 16: 99-110.
29. Kucewicz E, Czech B, Juszczyk G, Pawlak S, Szapiel G, Czaban S et al. Bezpośredni pomiar ciśnienia tętniczego krwi w tętnicy promieniowej – wiarygodność pomiaru w wybranych stanach klinicznych. *Anestestezjologia i Intensywna Terapia*. 2002; 2: 131-134.
30. Kaplan JA, Reich DL, Konstandt SN. Kaplan's Cardiac Anesthesia, Elsevier Inc. 2006.
31. http://www.medipment.pl/produkt/CNSYSTEMS-CNAP-Monitor-65305 (accessed: 2017.11.26).
32. https://www.draeger.com/Products/Content/infinity-cnap-smartpod-pi-9068562-pl.pdf (accessed: 2017.12.05).
33. Pawlak J, Zalewski P, Klawe JJ, Tafil-Klawe M. Nowoczesna metoda nieinwazyjnego ciągłego pomiaru ciśnienia krwi za pomocą urządzenia CNAP® Monitor 500 – praca przeglądowa. *Acta Bio-Optica et Informatica Medica*. 2012; 18: 202-205.
34. Dewhirst E, Corridore M, Klamar J, Beebe A, Rice J, Barry N et al. Accuracy of the CNAP monitor, a noninvasive continuous blood pressure device, in providing beat-to-beat blood pressure readings in the prone position. *Journal of Clinical Anesthesia*. 2013; 25(4): 309-313.
35. Ilies C, Kiskalt H, Siedenhans D, Meybohm P, Steinfath M, Bein B et al. Detection of hypotension during Caesarean section with continuous non-invasive arterial pressure device or intermittent oscillometric arterial pressure measurement. *British Journal of Anaesthesia*. 2012; 109(3): 413–419.

36. Piechota M. Monitorowanie czynności i dynamiki układu krążenia. MakMed. Lublin 2016.