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Impedance cardiography: A valuable method of evaluating haemodynamic parameters

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Abstract

This year marks 40 years since the technique was designed of measuring and monitoring the basic haemodynamic parameters in humans by means of impedance cardiography (ICG), also known as "impedance plethysmography of the chest", "electrical bioimpedance of the chest" or "reocardiography". The method makes it possible to denote stroke volume and cardiac output. It also enables the factors to be assessed that influence the following: preload (measurement of thoracic fluid content), afterload (measurement of systemic vascular resistance), the systemic vascular resistance index, contractibility (measurement of the acceleration index), the velocity index, the pre-ejection period, left ventricular ejection time, systolic time ratio and heart rate. Advances in hardware and software, including digital signal tooling and new algorithms, have certainly improved the quality of the results obtained. The accuracy and repeatability of the results have been confirmed in comparative studies with results obtained through invasive methods and echocardiography. Not only are haemodynamic changes monitored by means of ICG in intensive care units, in operating theatres and at haemodialysis stations, but repeated measurements also provide haemodynamic information during the treatment of patients with hypertension and heart failure and pregnant women with cardiological problems and gestosis. A single ICG investigation makes a great contribution to the basic information available about the circulatory system, which is helpful in the initial evaluation of patients in a severe general condition (for example in the admission room), and also makes it possible to make a swift diagnosis of the cause of complaints such as dyspnoea and hypotonia. A particular application of ICG is the assessment of haemodynamic parameters during the programming of atrioventricular and CRT pacemakers. Besides these uses, ICG is a valuable investigative tool. It is defect-free and does not have pulmonary artery pressure monitoring limitations. Moreover, it is not as time-consuming as echocardiography and the examination can be performed by trained technicians or nurses. (Cardiol J 2007; 14: 115–126)

Key words: impedance cardiography, electrical bioimpedance of the chest, reocardiography, cardiac output, haemodynamics, non-invasive diagnostics

Introduction

Evaluation of the haemodynamic state of a patient has always been a subject of interest to clinicians. Hitherto it has been somewhat difficult to obtain haemodynamic data and invasive techniques have usually been needed. These techniques are expensive, time-consuming, demand complicated

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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. The widespread increase in diseases of the circulatory system and progress in the diagnostics and the therapy of heart disease have made it necessary to introduce and propagate, on a greater scale than previously, cheap and non-invasive methods of measuring haemodynamic parameters. Non-invasive methods such as magnetic resonance imaging or echocardiography and methods such as radionuclide angiography which involve minimum invasiveness are unfortunately quite complicated and demand a separate laboratory, to which it may be difficult to transport severely ill patients. Thanks to these methods single measurements may be made which have an application in diagnosis and evaluation at a certain moment in the treatment but which are not suitable for the continuous monitoring of a patient's state. In this respect impedance cardiography offers a new standard of treatment and enables continuous bedside measurements to be made.

What is impedance cardiography?

Impedance cardiography (ICG) is a non-invasive method of evaluating haemodynamic parameters [1]. Other terms found in the literature to describe ICG are "impedance plethysmography of the chest", "electric bioimpedance of the chest" or "reocardiography" [2].

The haemodynamic parameters assessed by impedance cardiography

Through the use of ICG the state of the circulatory system and trends in changes in haemodynamic parameters can be assessed easily, quickly, cheaply and, most importantly, non-invasively. The method makes possible the denotation of stroke volume (SV) and stroke index (SI). It also enables the factors to be assessed that influence the following:

- preload — the measurement of thoracic fluid content (TFC);
- afterload — the measurement of systemic vascular resistance (SVR);
- the systemic vascular resistance index (SVRI);
- contractibility — the measurement of acceleration index (ACI);
- the velocity index (VI);
- the pre-ejection period (PEP);
- left ventricular ejection time (LVET);
- systolic time ratio (STR);
- heart rate (HR).

How impedance cardiography works?

The method is based on changes in the electrical resistance of the chest during heartbeat [1]. 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 [3]. 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 [2]. 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, 4]. These 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 (Z_0), 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 [1]. 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 [1, 5, 6], and changes in resistance associated with an outflow of blood are taken into consideration (ΔZ).

From the graph of the resistance changes of the chest (the impedance cardiogram graph: ΔZ) the next graph, that of its first derivative (ΔZ/Δt), is obtained, on which waves and points are visible which are used for further calculations. ECG tracing, obtained from the electrodes described above, is also needed. The curve is usually constructed in such a way that the fall in impedance causes an increase in the value on the Y-axis, a convention which reflects changes in conductivity. The polarity of the curve of the first derivative of the impedance is the same as the impedance curve [3].

On the graph of the first derivative of changes in impedance the following waves are distinguished: A, B, C, (ΔZ/Δt wave maximum), X, Y, O. The A wave appears between the beginning of the P wave and the beginning of the QRS complex and is linked to changes in volemia during atrial contraction. Next is the B wave, which appears simultaneously with the opening of the aortic valve. The next wave is known as ΔZ/Δt and corresponds to the peak of aortic flow, and this reflects the rapidity of changes in the blood flow through the aortic valve during left ventricle systole. It has been ascertained, however, that the ΔZ/Δt wave is also caused by changes in pulmonary artery flow during right ventricle systole [2].

According to Ito [7], the ΔZ/Δt wave reflects changes in the volume both in the ascending aorta and in the pulmonary trunk. The aorta has a several times greater influence on the value of the ΔZ/Δt wave than the pulmonary trunk. According to Thomsen et al. [8], changes in impedance are caused in 80% of cases by the aorta. The ΔZ/Δt wave ends with the X wave, which is convergent with the aortal component of the II tone and with aortic valve closure.

In the diastole a round, flat O wave appears in some patients [2]. Lababidi et al. [9] stated that this wave appeared in cases of mitral stenosis within the mitral valve opening. In other research the O wave was observed in patients with left ventricle dysfunction, especially diastolic. This wave was diminished after a change in body position or after treatment which diminished preload. The O wave in patients with severe heart failure is less susceptible to the above-mentioned procedure. It is suggested that the presence of the O wave has a prognostic value, and its changes can be used as an indicator of the effectiveness of the therapy [10–12].

One of three points of the impedance cardiogram is accepted as the beginning of the cardiac outflow: 1) the end of the B wave, 2) the crossing point of the ΔZ/Δt wave and the zero line, 3) the point where the dZ/dt signal is increased by 15% of the ΔZ/Δt wave maximum of the impedance cardiogram. The end of the outflow is usually defined as point X of the ΔZ/Δt signal [2]. The parameters of the outflow listed are continuously displayed on the screen of the device, so that it is possible to monitor the haemodynamic parameters from beat to beat.

Stroke volume: the key-parameter assessed by means of impedance cardiography

The notion of non-invasive monitoring of haemodynamic parameters appeared in 1940s [13], when Nyboer et al. [13] found a relationship between changes in impedance (ΔZ), basic impedance (Z_0) and the volume of the area investigated (ΔV), which they represented with the example:

$$\Delta V = \rho \times \frac{L^2}{Z_0^2} \times \Delta Z$$

where ρ is the specific resistance of blood and L is the length of the chest. Nyboer et al. used the method of impedance cardiography to evaluate the flow of blood in limbs [2].

In the 1960s Kubicek et al. [14] received a commission from NASA to work out a non-invasive method of assessing cardiac output (CO). The result of the team's work was the construction of the impedance cardiograph and the definition of a new equation determining SV. The equation included the maximum value of the first derivative of the impedance curve (ΔZ/Δtmax) and the time of the outflow from the left ventricle (LVET, left ventricular ejection time):

$$SV = \rho \times \frac{L^2}{Z_0^2} \times \left(\frac{\Delta Z}{\Delta t}\right)_{max} \times LVET$$

In the 1980s, Sramek [15] worked out a new equation for counting the SV using the model of the truncated cone of the chest instead of the cylindrical model used by Kubicek et al. Simultaneously, it was proposed to accept as value L (the length of the chest) 17% of the height of the patient (H). The new equation was as follows:

$$SV = \left(\frac{(0.17 \times H)^3}{4.2}\right) \times \frac{\left(\frac{\Delta Z}{\Delta t}\right)_{max}}{Z_0} \times LVET$$

In 1986 Bernstein [16] modified the Sramek equation, introducing the term δ (the relation of the actual weight to the so-called ideal weight). The aim of the modification was a more exact definition

of the volume of the chest. The new equation was presented as follows:

$$SV = \delta \times \left(\frac{(0.17 \times H)^3}{4.2} \right) \times \frac{\left(\frac{\Delta Z}{\Delta t} \right)_{max}}{Z_0} \times LVET$$

In spite of the improvements made by Sramek [15] and Bernstein [16], the manner of obtaining and converting the impedance signal and simplifications accepted in the algorithms led to results which were not uniform, variable and weakly correlated with invasive methods (thermodilution and the Fick method) [17]. It seemed that the ICG method, considered not very reliable, would not find application in clinical practice [18, 19]. However, progress in obtaining and converting the signal and new algorithms of calculating the outflow of the heart led to impedance cardiography becoming a new and valuable investigative tool.

Progress in hardware and software, such as the formulation of the CardioDynamics digital tooling of the signal (the DISQ digital impedance signal quantifier and the creation of that company's own patented modification of the Sramek and Bernstein equation, known as the ZMARC algorithm: Modulating AoRtic Compliance), did indeed improve the quality of the results obtained. The latest types of device, such as the CardioDynamics BioZ, are characterised by their precision and the repeatability of their results, as confirmed in clinical research. Moreover, the results are comparable to those obtained with invasive methods [1, 5, 19, 20–23]. The CO evaluated by means of impedance cardiography (BioZ ICG monitor, CardioDynamics, San Diego, California) was closely correlated with measurements using thermodilution in patients with both benign and severe heart failure [5].

Van Da Water et al. [20] showed that CO calculated with the use of the ZMARC equation had the greatest compatibility with that qualified in the use of thermodilution. In other clinical research in which this algorithm was used a lineal dependence and an acceptable degree of deviation between ICG and thermodilution was determined [22, 23].

Beside devices made by BioZ System, CardioDynamics, San Diego, impedance cardiographs made by other companies, such as the IQ™ System, Wantagh Incorporated, Bristol and SORBA Medical Systems, Inc., Brookfield are available on the market.

Advantages of impedance cardiography

The advantages of ICG include its non-invasiveness, relief of burden to the patient, speed in obtaining results (a "result at the bedside") and the low cost of the testing [24]. ICG can replace invasive methods of evaluating haemodynamic parameters and this can be done in all circumstances, including ambulatory treatment [25, 26]. Currently ambulatory assessment is possible, for example at a patient's home, when, earlier, hospitalisation would have been required. The data obtained enable intervention to take place quickly, such as initiating suitable pharmacotherapy and making appropriate modifications to the medicaments and doses already instituted. Verhoeve et al. [27] showed a high degree of repeatability of measurements obtained by means of ICG during the same day.

The aggravation of heart failure is linked to a fall in basic chest resistance because of pulmonary compensation, which can easily be detected by means of ICG. It has been demonstrated that the basic resistance of the chest (Z_0) is closely correlated with radiographic changes [28–30]. Milzman et al. [31] proved that $Z_0 < 19\ \Omega$ has a sensitivity of 90% and a specificity of 94% in recognising radiological pneumono-oedema; Z_0 below 18.5 Ω indicates interstitial pulmonary oedema and below 14.8 Ω pulmonary oedema. The efficiency of pulmonary haemostasis therapy can be assessed on the basis of an increase in the value of Z_0 [32].

Clinical application of impedance cardiography

Impedance cardiography in hypertension

ICG is used in the diagnostics and treatment of hypertensive patients [1, 32–38]. Although arterial hypertension is defined as elevated values of arterial blood pressure, it is also associated with abnormal CO, resistance, and susceptibility of the arteries. Arterial susceptibility can be calculated as the relation of SV to pulse pressure (i.e. the difference between systolic and diastolic arterial pressure) [39, 40].

These haemodynamic aspects of arterial hypertension have an influence on the diagnosis, risk assessment and treatment. Measurements of haemodynamic parameters enable the circulatory system to be better assessed, offer a greater possibility of recognising high-risk patients and enable treatment to be selected more appropriately.

Arterial blood pressure is not an indicator which characterises the whole circulatory system. Mean arterial pressure (MAP) is a product of two components: CO and SVR. Arterial hypertension can be a result of an increase in CO, SVR or both. Haemodynamic measurements allow patients with elevated CO to be distinguished from those with

elevated SVR as a cause of the arterial hypertension [41].

Linb and Eisenberg [42], using non-invasive evaluation of the circulatory system by means of ICG in patients with arterial hypertension, reported a good reaction to a beta blocker (propranolol) in patients with raised CO and the efficiency of vasodilatators of the calcium blocker group (nifedipine) in patients with elevated SVR. In the course of time CO usually diminishes and SVR increases.

In young adults, hypertension is more often associated with increased CO, while in older people it is linked with increased SVR. ICG can be used for risk assessment of possible complications of arterial hypertension. Galarza et al. [43] examined patients with arterial hypertension after cerebral stroke and patients with arterial hypertension without a history of stroke. They showed that in the former group CO was diminished and SVR was increased. These differences appeared in spite of identical blood pressure in both groups and the same antihypertensive treatment.

ICG has been used to assess non-pharmacological treatment in patients with benign arterial hypertension. In patients on a low-sodium diet it was ascertained that a diminishing of SV, a decrease in diastolic arterial blood pressure and an increase in the impedance of the chest (decreased TFC) was consistent with a diminution in the volume of extracellular fluid [44]. Measurements of haemodynamic parameters can be useful in the choice of antihypertensive treatment, dose selection and evaluation of the efficiency of the treatment. Several pieces of research have shown that therapy applied on the basis of ICG data has improved arterial blood pressure control.

Taler et al. [45] examined 104 patients with insufficient blood pressure control, using two or more antihypertensives. The patients were randomised into two groups: a group which was treated according to ICG findings and a group where the standard treatment was used. Proper blood pressure control (defined as achieving blood pressure below 140/90 mm Hg) was obtained 70% more often in the group treated according to ICG findings. In these patients a greater reduction in SVR was obtained and more intensive diuretics were used in treatment based on the level of TFC.

In patients with refractory arterial hypertension defined as systolic blood pressure of over 140 mm Hg or diastolic blood pressure of over 90 mm Hg, Sharman et al., [46] through treatment with two antihypertensive medicines, obtained good blood pressure control in 57.1% of patients who had not been treated earlier according to ICG data. Sramek et al. [47] also reported that by ICG the optimum antihypertensive treatment [47] can be chosen more easily. Deviations in values from the haemodynamic parameters may indicate patients who have interrupted the treatment or the occurrence of complications such as a worsening of kidney function [35]. A deterioration in heart function obtained by ICG, through the VI or STR for instance, may be the first signal of development of left ventricle failure.

Other applications of impedance cardiography

ICG can be useful in diagnosis and making therapeutic decisions in such clinical situations as dyspnoea [1, 48], pulmonary hypertension [4], mechanical ventilation [49], care after by-pass surgery [20, 22, 50, 51] and other operations, in intensive care units [21, 52–57], in dialysed patients [21, 58–64] and with heart pacemakers for the purpose of evaluation of SV and the optimisation of pacing parameters [65–74].

Impedance cardiography in cardiosurgery

Studies have been performed which indicate the possibility of using ICG in patients with a mechanical left ventricle assist device [75]. ICG was used to monitor haemodynamics during surgical operations [76–78]. Appraisal for surgical intervention and the optimisation of circulatory system parameters before intervention, especially in the elderly, are also possible by means of ICG.

Several authors have reported using ICG and qualifying contractibility parameters in the diagnostics of coronary heart disease. Indeed, lower contractibility parameters (ACI, dZ/dt were observed both at rest and during effort in patients with coronary heart disease than in those without. The interesting point is that no differences in SV were found between these groups [79, 80].

Impedance cardiography during pregnancy

ICG has proved useful for monitoring changes in parameters of the circulatory system in pregnant women [81–83] and also in infants, babies and children, because this method can be used successfully with patients who are too small for pulmonary artery catheterisation and, most importantly, it is not associated with a risk of complications. ICG has been used with children receiving chemotherapy to evaluate cardiac dysfunction [84].

Impedance cardiography during cardiac pacemaker programming

Great hopes have been pinned on the use of ICG for obtaining the optimum atrioventricular setting

in DDD pacemakers [64–69] and ICG is becoming a method of optimising CRT pacemakers [70–74].

Impedance cardiography in differentiating the reasons for dyspnoea

Springfield et al. [48] indicated that ICG as a useful tool in the differential diagnostics of patients with dyspnoea. By ICG the authors obtained significant differences in the cardiac index (CI) (2.2 *vs.* 3.1; $p < 0.0001$), STR (0.52 *vs.* 0.37; $p < 0.01$) and VI (32.9 *vs.* 42.7; $p < 0.01$) between patients with cardiogenic and those with non-cardiogenic dyspnoea.

Therapy monitored by impedance cardiography

Albert et al. [85] emphasised that the availability of haemodynamic data influences the manner of treatment. In a study conducted on patients with low CO, continuous cardiac performance monitoring increased the number of therapeutic decisions and shortened the time of hospitalisation by an average of two days.

ED-IMPACT study results (the Emergency Department IMPedance Cardiography-aided Assessment Changes Therapy) indicate that haemodynamic data obtained by ICG caused a change in the treatment in 24% of the patients with dyspnoea, while the brain natriuretic peptide caused a change in the treatment in 11% of similar patients [86]. Taler et al. [87] point to the usefulness of ICG in the effective choice of antihypertensive medicines in refractory arterial hypertension. Yung et al. [26] confirmed the precision of ICG evaluation of CO in patients with pulmonary hypertension in a comparison between ICG, thermodilution (TD) and the Fick method (F). The following correlation was obtained: ICG *vs.* F 0.84, TD *vs.* F 0.89, ICG *vs.* TD 0.80.

Impedance cardiography as a means of pulmonary congestion assessment

ICG can be applied in haemodynamic monitoring during diuretic therapy, as well as in the monitoring of patients during pleurocentesis and pericardiocentesis [88]. TFC, the reverse of the chest impedance, correlates closely with the amount of fluid, both intravascular and extravascular, in the chest. In patients after pleurocentesis Petersen et al. showed a high degree of correlation between the amount of fluid obtained and the change in chest impedance [89]. Ebert et al. [90] showed a nearly ideal linear correlation between changes in central venous pressure and chest impedance.

Impedance cardiography after orthotopic heart transplantation

A use for ICG is also found in the assessment of patients after heart transplantation. According to Nollerta, a diminution of 20% in ACI, the contractibility parameter obtained by means of ICG, has a sensitivity of 71% and a specificity of 100% in the diagnosis of graft rejection. The number of heart biopsies may also be reduced [24].

Impedance cardiography in heart failure

Data on haemodynamic parameters obtained by means of ICG can be very helpful in the diagnosis and treatment of heart failure patients [1, 23, 57, 91, 92, 94]. Albert et al. [85] have indicated the usefulness of ICG in cases of decompensated heart failure. Thanks to ICG the risks associated with catheterisation of the pulmonary artery (infection, pulmonary artery perforation and arrhythmia) may be avoided. The low cost of this non-invasive mode of measurement and the saving made on doctors' and nurses' time are also relevant factors. A non-invasive method of SV measurement has special significance for patients requiring intravenous medications, including inotropics.

Vijayaraghavan et al. [92] showed the prognostic role of haemodynamic parameters obtained by means of ICG in patients with chronic heart failure and the strong dependence of changes in these parameters on functional class and quality of life. Thanks to the ICG it is possible to investigate the influence of medicines on haemodynamic parameters, to assess the stability of the circulatory system and to choose the best moment to start the therapy (for instance beta-blocker or ACE-inhibitor therapies) and to make a decision about the moment of initiating catecholamines, determining the proper dose and monitoring the efficiency of the treatment in the case of decompensated heart failure [92, 94].

In many clinical studies ICG has been compared to invasive methods (thermodilution and the Fick method) [5, 19, 20, 23, 85] and non-invasive methods (echocardiography) [19, 75, 95]. A close correlation was obtained between results obtained by ICG and invasive and non-invasive methods.

In a study of severe heart failure patients who underwent pulmonary artery catheterisation Draznner et al. [23] compared ICG with invasive methods. In this study the correlation and the agreement between SV as assessed by ICG and the Fick method were the same as between thermodilution and the Fick method. They also showed that the Pearson correlation between ICG and thermodilution was 0.76 for CO and 0.64 for CI. In the study by

Albert et al. [85] the analogous correlations were 0.89 and 0.82 respectively. Thus the authors were able to claim that the results obtained demonstrated the clinical usefulness of ICG in decompensated heart failure patients.

Impedance cardiography *versus* other methods of measuring haemodynamic parameters

There are, however, studies which do not confirm this close correlation between ICG and invasive methods. Engoren and Barbee [6] state that measurement of SV by means of ICG, thermodilution and the Fick method are not comparable in a heterogeneous group of the most seriously ill patients. In this study it was confirmed that in critically ill patients SV measurement by means of ICG was not precise enough to replace thermodilution.

SV measurement can be determined by echocardiography, which has shown a good correlation with invasive methods [96, 97]. However, in comparison with ICG echocardiography is considerably more time-consuming and demands suitably prepared staff [97]. Parrot et al. [95] compared ICG with echocardiography, claiming that ICG determined changes in heart performance both easily and cheaply. The authors showed a high degree of correlation between changes in ICG parameters (CI and STR) and ejection fraction (EF): CI *vs.* EF 0.85, STR *vs.* EF –0.73.

CO evaluation by means of the direct Fick method is considered the most precise method, although it is very time-consuming and involves the necessity of receiving blood samples from the pulmonary artery and arterial blood [19, 26]. The indirect Fick method uses pulsoxymetry instead of this [19], although it is still associated with the inconveniences of pulmonary artery catheterisation. The Fick method is useless in patients with lung disease. The method most often used is thermodilution [20], but this has its own limitations; the variability of CO measurements by thermodilution fluctuates between 5% and 20% and so, in order to proceed, the three following measurements are necessary. These measurements are averaged and cannot differ between themselves by more than 10% [19]. Thermodilution and the Fick method are expensive and can involve the complications associated with pulmonary artery catheterisation [20, 26, 98].

It is easier to measure SV by means of ICG than by thermodilution, because it can be carried out more quickly and without the risk of infection or the other complications of pulmonary artery catheterisation. Additionally, ICG enables SV to be monitored in a continuous mode, unlike thermodilution, in which single measurements are made with injections of fluids, which also add to the patient's burdens [99].

In literature we can find data showing better results in the treatment of heart failure patients on the basis of findings obtained from pulmonary artery catheterisation and also research which questions the usefulness, safety and the profitability of the procedure, suggesting that it does not improve the results of treatment and increases the complication rate and costs [57]. Silver et al. [57] point out the high cost of pulmonary artery catheterisation, claiming that it can be replaced by ICG; similar suggestions emerge from the report by Hendrickson [98].

The economic aspects of impedance cardiography

The cost of ICG is the expense of a single purchase of the device and the cost of the electrodes, which is low. There are no additional hidden costs, no risks involved in the measurement and no possibility of complications during research. Additionally, the results are obtained very quickly, it only being necessary to stick on the electrodes, which is undoubtedly beneficial for the patient and reduces costs, speeding up the correct diagnosis and initiation of treatment and thus shortening the length of hospitalisation [98]. According to Clancy et al. [100] the saving from using ICG exceeds 600 dollars per patient in initial assessment, if the non-invasive method is used instead of pulmonary artery catheterisation. An additional saving is that of the time of medical personnel [101]. The cost of treatment of possible complications from pulmonary artery catheterisation also enters into the equation.

Should pulmonary artery catheterisation be given up?

The high risk of using invasive methods is a matter raised increasingly often [1]. There are studies which show [102, 103] that the routine usage of pulmonary artery catheters in critically ill patients can be linked to increased mortality and raise the costs of treatment. In a study by Chittock et al. [104] the use of a pulmonary artery catheter was shown to be associated with a reduction in mortality among the most seriously ill patients, while in the remaining patients pulmonary artery catheterisation increased mortality. In the year 1997 the Society of Critical Care Medicine expressed the opinion that the usage of pulmonary

artery catheterisation in patients with heart failure was of doubtful value and that randomised studies are necessary to decide whether the advantages of catheterising outweigh the risk [105]. This was why the multicentre randomised study ESCAPE (Evaluation Study of Congestive Heart Failure and Pulmonary Artery Catheterisation Effectiveness) was designed. In the bioimpedance subgroup of the ESCAPE study the usefulness of ICG in advanced heart failure patients will be assessed [106].

The following are cited as complications of pulmonary artery catheterisation: damage to the wall of the pulmonary artery, pneumothorax, aeroembolism, septicaemia, thrombophlebitis, phlebothrombosis, pulmonary infarction, endocarditis, arrhythmia and even an increase in mortality [98]. Because of the lack prospective studies demonstrating the advantages of pulmonary artery catheterisation, many doctors have given up this method. Furthermore, not all patients hospitalised because of aggravated heart failure are treated in an intensive care unit where pulmonary artery catheterisation would be possible. In such situations ICG can provide the requisite haemodynamic data in a general department [57].

The above findings point to ICG as a method which is simpler, quicker and, most importantly, safer to use, as it is non-invasive and does not burden the patient, while still being reliable.

In the last year two multicentre studies concerning ICG use with patients with chronic heart failure have been completed: the PREDICT study (Prospective Evaluation and identification of Decompensation by Impedance Cardiography Test) and the BIG study (BioImpedance cardioGraphy). The BIG study is part of the ESCAPE study and their initial results have already been published [107]. The data obtained from this research will help to determine the role of ICG in the management of heart failure patients.

Limitations of impedance cardiography

The results obtained may be inaccurate under the following circumstances: when there is a considerable degree of aortic insufficiency and septic shock, when there is a considerable degree of arterial hypertension (MAP > 130 mm Hg), when the height of the patient is less than 120 cm or over 230 cm, when the weight is less than 30 kg or over 155 kg and when intra aortic balloon pump (IABP) counterpulsation is employed [4, 26]. ICG is contraindicated in patients with pacemakers with a sensor responsible for minute ventilation rate switched on as the pacemaker rate in these patients can increase because of the ICG signal. These patients must therefore have this function switched off before measurement [108]. In patients with atrial fibrillation or with numerous premature beats a considerable arrhythmia can influence the ICG signal and make the investigation impossible [41].

Summary

Over 40 years have passed since the technique of measuring and monitoring the basic haemodynamic parameters in humans by means of ICG was formulated.

The progress of hardware and software, including digital signal tooling and new algorithms, has certainly improved the quality of the results obtained.

The accuracy and repeatability of the results have been confirmed in comparative studies with results obtained through invasive methods and echocardiography. Not only are haemodynamic changes monitored by means of ICG in intensive care units, in operating theatres and at haemodialysis stations, but repeated measurements also provide haemodynamic information during the treatment of patients with hypertension and heart failure and pregnant women with cardiological problems and gestosis. A single ICG investigation makes a great contribution to the basic information available about the circulatory system, which is helpful in the initial evaluation of patients in a severe general condition (for example in the admission room), and also makes it possible to make a swift diagnosis of the cause of complaints such as dyspnoea and hypotonia.

A particular application of ICG is the assessment of haemodynamic parameters during the programming of atrioventricular and CRT pacemakers. Besides these uses, ICG is a valuable investigative tool. It is defect-free and does not have pulmonary artery pressure monitoring limitations. Moreover, it is not as time-consuming as echocardiography and the examination can be performed by trained technicians or nurses.

The main limitation on the widespread use of this diagnostic and investigative method is the relatively high price of the equipment. The appearance on the market of new producers of such devices, however, suggests that this method will become widely used.

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