CONSIDERATIONS ON IMPEDANCE CARDIOGRAPHY

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ABSTRACT

Impedance cardiography is an electronic plethysmographic technique which provides information on cardiac stroke index, myocardial performance, thoracic fluid content and peripheral circulation. The method has gained popularity in recent years because it is not invasive. While less precise in absolute terms than invasive methods the results are reproducible, and the technique accurately assesses variations in measurements. It may be used in most anaesthetized patients without the possibility of any of the complications which sometimes accompany the use of more precise invasive methods.

This paper describes impedance cardiography and methods for its use.

Description

IMPEDANCE CARDIOGRAPHY is an electronic plethysmographic technique which provides information on cardiac stroke index, myocardial performance, thoracic fluid content, and peripheral circulation. The method has gained popularity in recent years because it is not invasive. Although the technique was introduced as early as 1930^{1,2} it was only perfected in the late sixties to meet the requirements of the Apollo space flights. In 1966, Kubicek, *et al.*³ had derived a formula to calculate cardiac stroke volume through changes in thoracic impedance.

The impedance (z) offered by mammalian tissue to an alternating electric current of 100 kHz and 4 ma is resistive in nature. The waves derived from impedance variations, occurring during the cardiac cycle, form the Impedance Cardiogram or ZCG (Figure 1). Kubicek, *et al.*³ investigated the origin of the impedance wave in dogs with electromagnetic flowmeters during the selective obstruction of right and left ventricular outflows. They found that the major component of the pulsatile z wave was related to aortic outflow and a minor fraction to right ventricular outflow. Respiratory impedance variations are electrically damped.

A typical ZCG (Figure 1) consists of 3 segments:^{2,4,5} (1) wave A corresponds to the P wave and the PR interval of the ECG, (2) wave C to the QRS complex and, thus, ventricular ejection, and (3) wave V is synchronous with the protodiastolic

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FIGURE 1 Simultaneous tracings of first derivative of the impedance cardiogram, impedance cardiogram, ECG and phonocardiogram. The first derivative tracing and the impedance cardiogram show recordings of calibration signals on the right. Points A, B, X, Y, O and Z of the dz/dt wave and A, C and V of the ZCG are explained in the text. The phonocardiogram displays the first and second heart sounds. Note that the point X of the dz/dt wave occurs at the same time as the second heart sound.

period. The first derivative of the impedance cycle (ZCG) includes points A, B, X, Y, O and Z (Figure 1).⁶ They are respectively related to atrial contraction, maximal first sound vibration, aortic and pulmonary valve closure, mitral valve opening, and the onset of the third sound. At the beginning of left ventricular ejection is a point (J) which follows B and is well defined in Figure 2. The differential at the peak between B and X ($(dz/dt)_{min}$) denotes maximal ventricular ejection.

Utilization

Impedance cardiography is used to calculate stroke volume. One approximates the thorax to a cylinder containing a homogeneous conduction

FIGURE 2 First derivative impedance cardiogram recorded from an adult patient. Points A, B, J, X, Y, O and Z are explained in the text. Point J corresponds to onset of rapid ejection from the left ventricle. Ventricular ejection time T (in seconds) is the time interval between the points J and X. T is 0.32 seconds in this recording.

medium.¹ Human chest anatomy introduces errors which vary among individuals. Therefore, the technique is more useful in following trends than in calculating absolute values.

According to Scott,¹ Bonjer established a relationship between impedance changes (Z) and changes in volume (V) in a symmetrical homogeneous cylinder with a basic resistivity of f ohm/centimeters, which he expressed as:

$$\text{Formula A} \quad V = f(l/z)^2 Z$$

in which l was the length of the cylinder, z the impedance of the cylinder and Z impedance changes. The equation may be used to calculate stroke volume by substituting Z by peak ventricular ejection rate multiplied by ventricular ejection time in seconds (T), or:

$$\text{Formula B} \quad V = f(l/z)^2 (dz/dt)_{\min} XT$$

Both haematocrit and temperature affect body resistivity.⁷ An average resistivity value of 150 ohms/cm has thus been used to minimize these effects.⁸ If the haematocrit has been calculated, the resistivity becomes:

$$f = 56 \times 8e^{0.025H}$$

in which H is the haematocrit, and e the natural logarithm.

Most commercially available impedance cardiographs are portable units weighing around 8 kg. A facultative computer incorporating an oscilloscopic display may be used but is an unnecessary expense. It can be replaced by a two-channel recorder with sweeps of 25 and 50 mm/sec using timed chart paper.

Methodology

To obtain an impedance cardiogram, the patient wears a set of four adhesive aluminized

FIGURE 3 Electrode placement for using impedance cardiography. Exact locations are described in the text. Electrodes 1 and 4 are used to pass a constant current through the chest and also detect ECG signals. The impedance cardiogram, its first derivative and the basic thoracic impedance (Z_0) are detected by electrodes 2 and 3.

mylar strip electrodes 2.5 cm wide (Figure 3). Strips 2 and 3, respectively, encircle the root of the neck and the thorax at the level of the xiphoid process. Strips 1 and 4 are 3 cm above and below strips 2 and 3 respectively. Adequate tension ensures skin contact. Patient electrodes are numbered sequentially and securely clipped to corresponding leads. The system incorporates a basic circuit which sends a 4 ma and 100 kHz alternating current between electrodes 1 and 4. The product of this current (I) and the thoracic impedance (Z_0) generates a voltage (E) equal to $I \times Z_0$ during its passage between electrodes 2 and 3.⁶ Amplification of this signal produces the impedance cardiogram (ZCG). A phonocardiograph circuit and an ECG signal from electrodes 1 and 4 are included (Figure 1).⁹ ZCG, $(dz/dt)_{\min}$, ECG and basic thoracic impedance (Z_0) can be obtained through output jacks connected to a recorder.⁹ A warming up time of 20 minutes is required for efficient operation. The phonocardiograph identifies point X (or second heart sound); however, since this point is usually well defined, the addition of phonocardiography is often an unnecessary additional refinement. Patient movements (including breathing) are dampened by a trace stabilizing control which eliminates baseline shifts.

Optimal results are obtained by starting the tracing during voluntary apnoea. To simplify stroke volume calculations the cardiograph is switched to calibration and the gain adjusted to 1 cm for a signal of 1 ohm. The $(dz/dt)_{\min}$ is recorded during at least 6 heart beats. The Z_0 control is then adjusted to the "hold" position for recall. Each set of recordings is followed by a calibration tracing signal to estimate $(dz/dt)_{\min}$ amplitude and ventricular ejection time. The $(dz/dt)_{\min}$ and stroke volume calculation are shown in Figure 2. Vertical lines indicate 0.04 sec intervals. Ventricular ejection time is measured from J to X (0.32 secs). The amplitude of

$(dz/dt)_{\min}$ is 1.4 cm which, when divided by the amplitude of the calibration signal (1 cm), provides the first derivative of impedance during ventricular ejection. With a Z_0 of 22 ohms, a haematocrit of 44 per cent, resistivity factor of 150 ohm/cm, electrodes 2 and 3, 24 cm apart, and a heart rate of 65/min, the *stroke volume* can be calculated from *Formula B*, previously given; which becomes:

$$\text{Stroke Volume} = 150(24/22)^2 \times 1.4 \\ \times 0.32 = 80 \text{ ml}$$

and the cardiac output, $80 \times 65 = (5,200 \text{ ml/min, or } 5.2 \text{ l/min.})$

Many authors have investigated the reliability of the measurement of cardiac output by the impedance technique.¹⁰⁻¹⁸ The general opinion is that overestimations are frequent but reproducibility accurate (when compared with thermodilutional techniques). Results can be considerably improved by assessing blood resistivity rather than using a fixed mean value of 150 ohms/cm.¹⁰ However, in the very obese, resistivity must be raised to 175.¹² Pate, *et al.*,¹³ who compared impedance cardiac outputs against dye dilution technique, the radioisotope method, pulse contour assessments and electromagnetic flowmetry, confirmed that the plethysmographic technique erred towards overestimation but accurately assessed variations in measurements. Inaccuracies have been ascribed to right to left shunts, inequalities in velocity during left ventricular ejection, pectoral asymmetry and influence of right ventricular ejection on pulsatile Z .¹⁴

Additional considerations

The first derivative of the impedance cardiogram can be used to assess other indices of myocardial performance. Among these are:

1. *The Heather Index* obtained by dividing maximum dz/dt by the time elapsed since the preceding R wave of the ECG (or RZ interval in ohms/sec²) which approximates the ratio of the pre-ejection phase by the ventricular ejection time,¹⁹

2. *Left Ventricular Ejection Time* measured from the dz/dt wave form which yields results similar to those obtained by the study of the pulse wave tracing,¹⁹ and

3. *The Siegel Index*²⁰ which claims that the point B of the dz/dt wave form correlates well with the isovolumetric period of ventricular contraction $(dz/dt)_{\max}$ and can, therefore, be used to

assess myocardial isometric time-tension relationships.

Accumulation of fluid in the chest will alter basic thoracic impedance (Z_0). Pomerantz, *et al.*,^{21,22} noted that as little as 50 ml of fluid in the pleural cavity produced significant impedance changes. Therefore, these measurements can be used both for the diagnosis of pleural effusions and early pulmonary edema and to follow their course. Luepper, *et al.*,²³ found that changes in Z_0 could quantitate changes in central blood volume. Keller and Blumberg²⁴ noted impedance changes during haemodialysis. Pulmonary emboli, pneumothorax and pulmonary atelectasis have been diagnosed by Berman, *et al.*²⁵ by the impedance method. Impedance cardiography can also assess peripheral circulatory adequacy if encircling electrodes are placed around the affected extremity.⁹ Finally, all these manoeuvres can be carried out in most anaesthetized patients, especially when invasive methods are considered to be contraindicated. The technique is especially useful when unexpected circulatory failure or increased pulmonary fluid content occur during surgery.

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RÉSUMÉ

La recherche de méthodes non-invasives pour la mesure du débit cardiaque, du travail myocarde, du contenu fluide du thorax et de l'état de la circulation périphérique, a gagné du terrain durant la dernière décennie. La cardiographie par impédance est un exemple des travaux qui ont porté fruit à ce sujet; découverte dès 1930, elle ne fut perfectionnée et utilisée à fond que trente ans plus tard, au cours des explorations lunaires Appolon. Il s'agit d'une méthode pléthysmographique électronique qui mesure l'impédance thoracique durant les phases du cycle cardiaque. Une formule dérivée par Kubicek et coll. permet le calcul du volume d'éjection, et donc du débit cardiaque, en fonction de changements d'impédance thoracique. La méthode permet aussi de mesurer le rapport des durées respectives de la contraction isovolémique ventriculaire et de la phase d'éjection (index Heather). Hill et coll. ont établi une formule par laquelle il est possible de mesurer la durée d'éjection ventriculaire gauche et Siegel et coll. pour leur part ont conçu une méthode de calcul de la contraction isométrique du myocarde en fonction de changements d'impédance thoracique.

Le cardiogramme par impédance s'obtient par l'encerclement de la base du cou et de la poitrine du malade par quatre rubans (2.5 cm de large) en mylar aluminisé. Un courant électrique de 4 milliampères et de 100 kilohertz est introduit entre la seconde et la troisième électrode; son voltage amplifié permet d'obtenir la courbe des variations d'impédance thoracique par rapport au temps.

La pléthysmographie des membres s'obtient par le placement des électrodes autour de l'extrémité choisie dont elle mesure la circulation sanguine.

Plusieurs auteurs ont souligné le manque de précision de cette technique: on reconnaît de façon générale, qu'elle surestime les valeurs mesurées. Cependant, la reproductibilité des résultats rend la technique utilisable pour mesurer des changements plutôt que des valeurs absolues.

Les erreurs au début sont attribuables au fait qu'on a assumé que le thorax était cylindrique et à contenu homogène; la morphologie individuelle des patients introduit des variations particulières qui se retrouvent dans la mesure de leur impédance thoracique.

La cardiographie par impédance possède deux avantages importants: la simplicité relative des appareils de mesure et leur prix économique.

De plus, elle peut s'employer durant l'anesthésie sans aucune crainte des complications qui accompagnent parfois l'emploi de méthodes invasives plus précises. La recherche du méthodes de mesures non-invasives demeure une priorité et nous croyons que la cardiographie par impédance représente une avance importante dans ce sens.