

Bioimpedance Cardiography Measurements of Cardiac Output and Other Cardiovascular Parameters

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Impedance cardiography was first proposed by Kubicek and colleagues [1] for measurement of stroke volume, cardiac output, and other cardiovascular parameters for aerospace programs [2]. Since that time, software refinements and technical improvements in bioimpedance measurement methods that are used in determining left ventricular ejection time, change in impedance with systole, and other markers of systole and diastole provide greater accuracy of noninvasive hemodynamic data.

Impedance cardiography increased in popularity in the United States in the late 1990s and early 2000s for three main reasons: (1) the use of pulmonary artery catheters decreased after researchers reported that they were associated with increased hospital morbidity (pulmonary embolism, infection, bleeding, and pulmonary artery rupture) and mortality [3,4], and the Society of Critical Care Medicine developed a consensus statement about using these catheters in patients who have a variety of diseases and disorders [5]; (2) thoracic bioimpedance method by one company (Cardiodynamics International, San Diego, California) was widely available and found to be accurate for many patient populations; most notably, after open heart surgery [6,7], chronic heart failure [8,9], and when mechanically ventilated [10]; and (3) research results demonstrated the value of non-invasive impedance cardiography data in a variety of clinical settings, including hospital, ambulatory, and specialty care (ie, atrioventricular optimization during

left ventricular permanent pacing [11]), and for a variety of purposes, including diagnosis, assessment, prognosis determination, and management.

Not all bioimpedance cardiography systems are alike. The algorithm that is used to determine baseline bioimpedance during diastole and changes in impedance during systole vary by company, although they may be modifications of a popular algorithm that was developed to measure aortic stroke volume by means of its impedance change. Additionally, system type (whole-body or thoracic bioimpedance cardiography) and the methods that are used to collect data are not consistent between manufacturers. Thus, it cannot be assumed that one system is equal to another. It is important for nurses who use this technology to be vigilant about reviewing the available research that is associated with the device being used to ensure that bioimpedance cardiography data accurately reflect data that are collected by traditional (invasive cardiac output) techniques. Vigilance includes reviewing published research results from peer-reviewed journals as it relates to the patient population of interest. Not all devices have been tested for accuracy and reliability in similar patient populations. Devices may be housed to appear similar, but it is not acceptable to believe that two systems by two manufacturers work similarly and provide similar result accuracy. This paper describes impedance technique and device types, discusses available hemodynamic data parameters, discusses differences between impedance cardiography and data that are derived from invasive pulmonary artery catheters, and explains how nurses can apply bioimpedance cardiography in a variety of patient populations.

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Impedance technique and device types

Bioimpedance cardiography is based on measurements of impedance (or resistance) to transmission of a small electrical current throughout the body (whole-body bioimpedance) or chest area (thoracic bioimpedance). In the body, electrical current passes through conduits of high and low conductance. Conduits of low impedance (lowest resistance, equals high conductance) are blood (150 Ω /cm) and plasma (63 Ω /cm). Resistance of electrical current is higher (lower conductance) for cardiac muscle (750 Ω /cm); lungs, reflecting air (1275 Ω /cm); and fat (2500 Ω /cm) [12]. Thus, when alternating low-level electrical current is applied to the whole body or thoracic area, the primary distribution is to the blood and extracellular fluid. Changes in the body's resistance to electrical current flow over time (in milliseconds) are associated with dynamic changes in the blood and plasma. As the aortic valve opens and blood is ejected swiftly into the aorta and the arterial branches, impedance to electrical current flow is decreased. During diastole, impedance to electrical flow returns to baseline. In the capillaries and venous system, blood volume is mostly constant because these vessels are nonpulsatile. Therefore, the changes in impedance that are noted by a thoracic bioimpedance cardiography device reflect an increase in aortic pressure during systole, whereas changes in whole-body impedance reflect a proportional increase in the measurable conductance of the whole body during systole [12].

Whole-body bioimpedance devices

To collect patient signals, these systems usually use two pairs of proprietary electrodes that inject (transmit) current (placed just proximal to the wrists and ankles on the internal side), and another pair of electrodes that sense (receive) baseline and changes in impedance (placed approximately 5 cm proximal to the injecting electrodes). In patients who have severe peripheral edema or severe peripheral vascular disease, electrodes may be placed higher up on the lower leg; if a venous graft wound is present (ie, when a vein is harvested for coronary artery bypass grafting) the lateral side of the ankles can be used [13].

Thoracic bioimpedance devices

In these devices, manufacturers may use one or two pairs of injecting and sensing electrodes to meet

their needs. When the system calls for one injecting and one sensing electrode, they often are placed at the left base of the neck and along the xiphoid process, respectively [14]. When the system calls for two pairs of electrodes, the sensing and injecting electrodes are placed 180° apart (opposite sides) at the base of the neck (sensing electrodes are proximal to injecting electrodes) and at the midaxillary line at the level of the xiphoid process [15]. In both systems, the electrodes mark the upper and lower limits of the thorax.

Although all systems require injecting and sensing electrodes to measure bioimpedance and calculate stroke volume, differences between device manufacturers abound. In some systems, the placement of electrodes is critical to receiving accurate hemodynamic data, whereas in others, electrode placement is less critical and can be done by an untrained operator. Some systems require separate ECG electrodes to measure pulse rate and obtain ECG data; other systems collect ECG data through the two pairs of electrodes that already are placed for bioimpedance data collection.

Hemodynamic data

Hemodynamic data is obtained by two methods: parameters that are measured directly from data obtained from the sensing and ECG electrodes and parameters that are calculated from measured data. The injecting electrodes deliver low-amperage, high-frequency (30 kHz, 1.4 mA to 75 kHz, 1.8 mA; varies by manufacturer) alternating current through the whole-body or thorax, and the sensing electrodes detect baseline bioimpedance (during diastole, when aortic blood volume decreases) and changes in bioimpedance (at the beginning of each systole as aortic blood volume increases [maximum impedance gradient]) with each cardiac cycle. In addition, systems measure a third variable: ventricular ejection time so that stroke volume can be calculated. Examples of measured and calculated parameters are listed in Table 1. Normal values are not included because these vary slightly by manufacturer.

Parameters that are available through bioimpedance cardiography do not mimic data that are obtained by pulmonary artery catheter (Table 2). Of most importance are the unavailability of right atrial and pulmonary artery wedge pressure (PAWP) values and the availability of contractility parameters through bioimpedance data. The significance of each is described below.

Table 1
An example of measured and calculated parameters derived from a bioimpedance cardiography system

| Measured parameters | Calculated parameters |
|---|---|
| Thoracic or whole-body fluid content (intravascular and extravascular volume) | Stroke volume/stroke index |
| Heart rate | Cardiac output/cardiac index |
| Acceleration index | Systemic vascular resistance/systemic vascular resistance |
| Velocity index | Left cardiac work/left cardiac work index |
| Pre-ejection period | Systolic time ratio |
| Left ventricular ejection time | |

Right atrial pressure can be obtained and entered into the bioimpedance device by palpating the right internal jugular vein for elevated pressure and using a formula to change cm H₂O pressure into mm Hg (divide cm H₂O measurement by 1.36 to derive mm Hg value). Although elevated jugular venous pressure is a surrogate for elevated right atrial pressure values, in one study, only 63% of patients who had New York Heart Association (NYHA) functional class III–IV symptoms and advanced heart failure had an elevated jugular venous pressure when hospitalized [16]. As a marker for obtaining right atrial pressure data, right jugular venous pressure has good specificity but less than adequate sensitivity. When present, an elevated jugular venous pressure was associated with an increased risk for death or hospitalization for heart failure and death from pump failure [16]. As a hemodynamic parameter, right atrial pressure availability is valuable to clinicians for diagnosis, assessment, and management. In addition, right atrial pressure data are necessary to calculate systemic vascular resistance/index. When a default or inaccurate right atrial pressure value is entered into the bioimpedance system, systemic vascular resistance data do not reflect actual patient values. The level of inaccuracy may not prevent using the data to monitor changes in systemic vascular resistance over time, especially when making changes in pharmacologic therapies that are known to affect this parameter in patients who have hypertension and chronic heart failure.

There is no reliable equivalent to obtaining PAWP values. Two studies found that B-type natriuretic peptide (BNP) values correlated with PAWP values in patients who had decompensated chronic heart failure who received care in an ICU with invasive hemodynamic monitoring; PAWP and BNP values decreased

with therapy [17,18]. However, when serial BNP measurements were compared with invasively derived data in a study of 39 patients who had severe heart failure, there was no correlation between BNP and any hemodynamically derived variable over a 36-hour period even though a decrease was noted in PAWP and BNP from baseline to 12 hours of therapy. A change in BNP was not associated with a change in PAWP in any of the patients [19].

Researchers have tried to correlate PAWP to thoracic fluid content index, an impedance cardiography variable that is described in Table 2. In a study that directly compared PAWP readings with thoracic fluid content index data that were collected at the same time, correlation was $r=0.05$ ($P=.71$) [9]. In another study that used similar methodology, researchers converted thoracic fluid content index and PAWP values into quartiles to reflect hypovolemia, normal volume, moderate hypervolemia, and severe hypervolemia. In addition, quartile values for thoracic fluid content index were specified for men and women. There was a moderate positive correlation between thoracic fluid content index and PAWP ($r=0.39$; $P=.025$); however, researchers did not believe that the correlation was strong enough to allow for clinical decision making without further study [8].

PAWP data are needed to calculate pulmonary vascular resistance/index. For some patient populations, the need for PAWP or pulmonary vascular resistance/index data might be arbitrary; however, in patients who have advanced chronic heart failure, PAWP value while hospitalized was associated with survival after hospital discharge, functional status, and freedom from symptoms, and was considered to be a more important variable than cardiac output [20,21]. Additionally, PAWP is associated directly with left ventricular end-diastolic pressure and volume. Using PAWP to monitor improvement in volume and congestion in patients who have advanced or recently decompensated heart failure can be beneficial. Freedom from congestion predicted good survival in patients who were discharged from the hospital after NYHA functional class IV symptoms [22]. The inability to receive systemic vascular resistance data (when right atrial pressure data is unavailable), compounded with the lack of PAWP data (or an equivalent), could minimize the benefits of bioimpedance cardiography monitoring depending on the setting, purpose for monitoring, and patient population.

An advantage to bioimpedance cardiography monitoring is the ability to obtain specific indices of left ventricular contractility that are not available with a pulmonary artery catheter (see Table 2 for

Table 2
Hemodynamic data

| Impedance cardiography | Pulmonary artery catheter |
|--|---|
| Stroke volume/stroke index | Stroke volume/stroke index |
| Cardiac output/cardiac index | Cardiac output/cardiac index |
| Systemic vascular resistance/systemic vascular resistance | Systemic vascular resistance/systemic vascular resistance index |
| Not available | Pulmonary vascular resistance/pulmonary vascular resistance index |
| Left cardiac and stroke work/left cardiac and stroke work index | Left cardiac and stroke work/left cardiac and stroke work index |
| Not available | Pulmonary capillary wedge pressure |
| Not available | Right atrial pressure |
| Other contractility parameters: | |
| Systolic time ratio: the ratio of electrical to mechanical systole. Provides data on electro-mechanical heart performance; as heart failure worsens the ratio of electrical to mechanical systole becomes higher. | Not available |
| Pre-ejection period: the time interval from the beginning of electrical stimulation of the ventricles to the opening of the aortic valve. Reflects isovolumetric contraction phase of systole. | |
| Left ventricular ejection time: Time measured from the opening to the closing of the aortic valve; represents mechanical systole. | |
| Velocity index: represents the peak velocity of blood flow in the aorta. In patients who have heart failure, this parameter may remain in the normal range, even though the acceleration contractility index is reduced. | |
| Acceleration index: The initial acceleration of blood flow in the aorta; occurs within the first 10–20 milliseconds after the aortic valve opens. The stronger the ventricle contracts, the higher the value; measured in seconds squared. | |
| Thoracic fluid content: represents the electrical conductivity of the chest cavity (requires a thoracic bioimpedance cardiography device to obtain this data); determined by intravascular, intra-alveolar, and extravascular (interstitial) fluids in the thorax. Uses impedance data and divides it by 1. Thus, high impedance = less thoracic volume = low thoracic fluid content. Low impedance = more thoracic volume (because electrical current has less resistance to changes in blood and plasma versus air) = high thoracic fluid content. | Not available |

terms and definitions). In patients who have advanced, chronic heart failure, the availability of specific contractility parameters provides additional data for determining worsening of left ventricular function and prognosis (major heart failure events and mortality).

Impedance cardiography was used to predict the occurrence of major heart failure events. In the PRospective Evaluation of cardiac Decompensation in patients with heart failure by Impedance Cardiography Test (PREDICT) multicenter trial, researchers wanted to learn if noninvasive thoracic impedance cardiography parameters could predict short-term risk, defined as all-cause death or emergency depart-

ment visit or hospitalization due to worsening heart failure. Data were collected every 2 weeks for 26 weeks in 212 patients. Twenty-nine percent of all subjects had events. When impedance cardiography data, vital signs, baseline characteristics, and a visual analog scale of how patients felt at the time of each office visit on a scale of 1 to 100 were analyzed, important variables that preceded an event were identified. These variables included lower self-rating on the visual analog scale, higher NYHA functional class, lower systolic blood pressure, and three impedance cardiography parameters: lower velocity index, higher thoracic fluid content index, and diminished left ventricular ejection time. When the

three impedance cardiography variables were combined and compared with other statistically significant variables that preceded a heart failure event, the composite impedance cardiography score had the strongest association for a subsequent heart failure event [23]. Therefore, when combined with other variables—especially visual analog scale, NYHA functional class, and systolic blood pressure—impedance cardiography can identify patients with advanced heart failure who are at the highest and lowest risk for a heart failure event.

Impedance cardiography contractility parameters provide objective data in chronic heart failure that are related to changes in functional status and prognosis. In a study of 64 ambulatory patients, baseline data were compared with data at 3 months. Changes in stroke index, left ventricular ejection time, and systolic time ratio correlated significantly with changes in NYHA functional class, 6-minute walk distance, patient visual analog scale score, and quality of life score using the Minnesota Living with Heart Failure Questionnaire [24]. Another group of researchers used systolic time ratio to predict mortality in ambulatory patients who had advanced heart failure. A greater systolic time ratio reflected a longer pre-ejection period (isovolumetric contraction), diminished left ventricular ejection time, or both and was associated with worsening left ventricular function. In this study, 78% of patients that expired had an elevated systolic time ratio compared with 60% of patients who survived ($P < .007$). Researchers concluded that elevation of systolic time ratio correlated with NYHA functional class and mortality when reviewed as an isolated parameter, and that it may be useful in risk stratification and management of outpatients who have heart failure [25].

After cardiac transplantation, acute rejection is a main complication that requires early identification and treatment. Researchers used thoracic bioimpedance in 35 patients who had undergone heart transplants to determine if hemodynamic parameters would predict acute rejection at the time of endomyocardial biopsy. The acceleration index was significantly lower in patients who had acute rejection episodes than in patients who had normal biopsies [26]. As a diagnostic parameter, acceleration index is an early indicator of failing left ventricular contractility; it decreases before stroke volume does. In this study, the sensitivity was 71% and the specificity was 100%. Thus, bioimpedance cardiography was a quick and noninvasive technique that identified worsening contractility. It could be used in between routinely ordered invasive procedures at ambulatory follow-up visits.

Therapeutic value of impedance cardiography

Resistant hypertension

Failure to achieve an adequate response to anti-hypertensive therapy is a burden to clinicians. In a hospital or ambulatory setting, aggressive treatment of resistant hypertension can be individualized when serial hemodynamic measurements beyond blood pressure values are available to the health care team. Specific classes of drugs may work better in hypertensive patients who respond with elevated systemic vascular resistance versus increased cardiac output. Angiotensin-converting enzyme inhibitors, angiotensin receptor blockers, thiazide diuretics, β -blockers, and calcium channel blockers have different effects on cardiac output, total peripheral resistance, systemic vascular resistance, and plasma volume that can lead to transient symptomatic hypotension and fatigue [27]. When new drugs are added and used in combination, precise tracking of hemodynamic measurements can prompt corrections in hemodynamic abnormalities and facilitate optimum drug use and dosing. An intensive treatment program was set up for 3 months in 104 patients who had resistant hypertension. Drug selection was based on hemodynamic data and a predefined algorithm or a hypertension specialist's medical opinion. Taler and colleagues [28] found that both treatment groups had lowered blood pressure in 3 months, but that the serial hemodynamic measurement/drug selection with algorithm group was more likely to have a blood pressure less than 140/90 mm Hg (56% versus 33%; $P < .05$). The impedance cardiography hemodynamic monitoring/drugs by algorithm arm of Taler and colleagues' trial was replicated by community physicians in a case series of 21 patients who had uncontrolled blood pressure and were taking two agents. Researchers enhanced pharmacologic decision making when guided by impedance cardiography [29].

Psychologic mood states have been believed to influence hemodynamic responses. Impedance-derived variables and the profile of mood states (POMS) were measured in 71 normotensive and hypertensive individuals to determine relationships. Participants with high tension–anxiety by POMS had lower stroke volume, and those with higher fatigue-inertia POMS had lower cardiac output and higher total peripheral vascular resistance [30]. There was no association between POMS, heart rate, and blood pressure or between POMS anger-hostility and hemodynamic variables, even though older research showed that high anger or hostility increased blood pressure. Researchers concluded that mood states were associated

with hemodynamic variables that underlie blood pressure and that stroke volume, cardiac output, and total peripheral resistance may be more sensitive to subtle differences in mood than are heart rate and blood pressure.

Pacemaker

After pacemaker insertion, changes in cardiac function can cause suboptimal timing of the atrioventricular (AV) interval during AV sequential (dual chamber right ventricular and biventricular) pacing, which lead to changes in left ventricular preload that reduce systolic performance. Doppler echocardiography is an established method to optimize AV interval; however it is costly, time-consuming, and operator dependent. Because it is expected that hemodynamic measurements are altered with suboptimal AV interval timing, using impedance cardiography to optimize the AV interval offers a simple, cost-effective solution. Researchers found that impedance cardiography was a useful hemodynamic monitoring technology for AV optimization in acute atrioventricular pacing with temporary wires in refractory patients who had heart failure [31,32], in biventricular pacemaker follow-up when patients were programmed with synchronous right and left ventricular pacing [33–35], and during permanent left ventricular pacing [11]. In most studies, impedance cardiography was compared with quantitative tissue Doppler echocardiography and was found to be precise ($r=0.67-0.844$).

Heart failure

Most research on the value of impedance cardiography was conducted in patients who had heart failure, because it represents a costly, debilitating medical condition with abnormal hemodynamics. In addition to using impedance cardiography to predict future events (PREDICT trial), prognosis, and heart failure diagnosis, clinicians used impedance cardiography to aid in decision making when initiating and titrating intravenous agents that prompt changes in hemodynamics [36,37], when weaning patients from intermittent infusion therapy [38], and when transitioning patients from intravenous inotropic to intravenous vasodilator therapy [39]. In these situations, the additional hemodynamic information was useful in tailoring therapies to individual patients. Current intravenous agents that alter hemodynamics (nesiritide, dobutamine, milrinone) are not advocated for outpatient intermittent infusion; however, noninvasive trending of cardiac output and other hemody-

dynamic variables can provide prognostic information that aids in decision making about end-of-life care that might include use of these therapies. In addition, hemodynamic monitoring may assist clinicians in learning how to optimize newer intravenous agents that alter contractility (ie, calcium sensitizers) or neuroendocrine activation (ie, vasopressin antagonists), once approved for use in acute decompensation.

Other patient populations

Because impedance cardiography assesses dynamic changes in blood and plasma, it can be used as an alternative to invasive hemodynamic monitoring in many settings beyond traditional critical care or anesthesia and in many patient populations. Recurrent intradialytic hypotension causes patient discomfort and clinician interface in patients who require acute or chronic hemodialysis. Using impedance cardiography, researchers found that patients who experienced symptomatic hypotension during dialysis had a greater decline in blood volume and cardiac output than did stable patients. The real issue was that these patients had a significant decrease in systemic vascular resistance when compared with stable patients who had an increase in systemic vascular resistance [40]. Using this information, impedance cardiography monitoring can be used during dialysis treatments, as a means of assessing the usefulness of prevention or control interventions, in patients who are known to have recurrent intradialytic hypotension.

In peripartum women who have preeclampsia, thoracic fluid content monitoring may provide benefits beyond monitoring of cardiac output and vasoconstriction. Impedance cardiography monitoring was used to measure thoracic fluid content in 134 peripartum women in uncomplicated early labor ($n=72$), with preeclampsia ($n=50$) or in pulmonary edema ($n=12$). Women who had peripartum pulmonary edema had significantly higher thoracic fluid content by impedance cardiography than did those who had mild or severe preeclampsia. A thoracic fluid content of at least $65 \text{ k}\Omega$ was associated with peripartum pulmonary edema (sensitivity 83.3%, specificity 86.9%, negative predictive value of 98.1%). Using this information, thoracic fluid content monitoring may lead to medical intervention in peripartum women who have preeclampsia, even when overt clinical symptoms are absent [41].

In chronic fatigue syndrome, the cause is unknown but there is accumulating evidence of a problem with circulation. Thus, researchers used impedance cardiography to measure cardiac output and assess its relationship to presenting symptoms.

Impedance cardiography findings in 38 patients who had mild (n=20) or severe (n=18) illness were compared with 27 matched, sedentary control subjects. Patients who had severe chronic fatigue syndrome had significantly lower stroke volume and cardiac output than did control subjects and less severely ill patients, which provided a preliminary indication of reduced circulation [42]. Using this information, methods to improve circulatory insufficiency could be targeted in patients who have severe symptoms from chronic fatigue syndrome. Regular impedance cardiography monitoring could provide evidence of therapy effectiveness, and may aid in future treatment modalities and clinical implications.

As described above in three studies of different patient populations, monitoring changes in circulation and hemodynamic status may play an important role in advancing science and patient management. Impedance cardiography is a feasible method for continuous or intermittent noninvasive hemodynamic assessment of patients. In settings that use bolus thermodilution method as a standard of care (especially critical care and anesthesia), bias and precision between hemodynamic data collection methods in specific patient populations must be assured. In many patient settings (especially emergency and outpatient care), health care providers do not rely on invasive hemodynamic monitoring in clinical assessment and decision making; however, patients may benefit from one-time or regular monitoring of impedance cardiography hemodynamics as an adjunct in guiding medical therapy, determining therapeutic intervention effectiveness, and aiding in prognosis determination.

Summary

Validation studies that correlate well with standard thermodilution techniques and data that report the usefulness of noninvasive technology in providing unbiased hemodynamic information in a variety of patient populations and clinical settings should prompt nurses to consider impedance cardiography as an adjunct to, or possibly as a replacement for standard invasive hemodynamic monitoring techniques. Hemodynamic data that are provided in impedance cardiography systems are not directly equivalent to those of a pulmonary artery catheter. Impedance cardiography provides contractility data that can augment traditional hemodynamic information. Current systems measure whole-body or thoracic impedance to electrical current, and are user friendly, easy to apply, and safe. The use of impedance cardiography may augment the relationships

between hemodynamic parameters and cardiovascular and circulation disorders that may prompt or advance patient care.

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