Role for Impedance Cardiography in the Diagnosis and Management of Acute Heart Failure

a report by
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The diagnosis and management of acute heart failure requires knowledge of hemodynamics beyond that offered by the traditional vital signs of blood pressure and heart rate. In the past, an advanced determination of hemodynamic status required the insertion of a catheter directly into the heart. As a result of the significant patient morbidity and mortality associated with this invasive procedure, non-invasive techniques are being considered as an acceptable alternative. One of the most researched of these new technologies is impedance cardiography (ICG). The method of ICG is based on the idea that the human thorax is electrically an inhomogeneous, bulk conductor. A high frequency measurement current injected across the thorax results in a waveform signature of voltage changes, produced by varying resistances and sensed by two pairs of electrodes placed at the edge of the chest (see Figure 1). Voltage changes (delta Z) are the consequence of fluid alterations within the thorax. They arise from changes in the intra-alveolar and interstitial thoracic compartments as a result of edema, and dynamic changes resulting from volumetric alterations and velocity changes of aortic blood flow produced by the heart’s泵ing. These measurements are potentially an important tool for the evaluation and management of patients with acute heart failure.

The accuracy of the cardiac output measurements obtained from ICG has been frequently compared to the invasive measures acquired by thermodilution techniques. A recent meta-analysis of over 200 studies found a correlation of 0.81 for ICG determined stroke volume and cardiac output, when compared to traditional measurements. In general, ICG assessments are considered less variable and more reproducible than many other techniques used to monitor acute heart failure. Besides being noninvasive, the major advantage of ICG technology is that it can also be utilized for continuous monitoring and identifying trends.

The Cardiovasculogram

The electrocardiogram depicts the electrical events of the cardiac cycle. The ICG derived waveform depicts a mechanical event signature representative of the cardiovascular coupling during this sequence. The graphical complex of this waveform is termed the ‘cardiovasculogram’. The different intervals and deflections within the cardiovasculogram are correlated with events within the cardiac cycle by phonocardiology and echocardiography (see Figure 2). The primary deflection of the impedance waveform is associated with the systolic time intervals and stroke volume, while the diastolic time intervals, such as the isovolumic relaxation time of the ventricles (IVRT), coincide with the duration of the second deflection of the ICG waveform. The pre-ejection period (PEP) is the time of isovolumic contraction, beginning with the initiation of the QRS complex and ending with the opening of the aortic valves. The left ventricular ejection time (LVET) begins after the PEP and ends at the closure of the aortic valve. Finally the dZ/dt waveform can be used to determine when ejection ends.

Parameters Measured by ICG

Stroke volume is determined from the magnitude of the changes in the electrical conductance of current as it traverses the thorax by way of the aorta. The maximum deflection rate of the first waveform of the impedance cardiogram (dZ/dtmax) is related to the stroke volume (SV) by the equation SV = rho * L^2 / Z0 * LVET * dZ/dtmax (where LVET = left ventricular ejection time, rho = resistance measure of blood, L = length of the thorax). ICG determined SV multiplied by the heart rate provides a continuous estimate of cardiac output. From this measure other parameters such as total peripheral resistance can also be derived.

Central fluid volume status can be difficult to assess in patients with acute heart failure. Baseline thoracic impedance (Z0) and its inverse (thoracic fluid content = TFC) have been strongly correlated with thoracic intravascular fluid volumes. Therefore, Z0 provides a noninvasive and continuous measure of the central fluid status.

ICG-derived cardiac time intervals have been used to estimate cardiac contractility. The ICG PEP/LVET ratio was first used by Capan to non-invasively estimate the cardiac ejection fraction. Other contractility

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estimates, based on the maximal slope of the systolic waveform ($dZ/dt_{\text{max}}$), include the Heather Index (HI = $dZ/dt_{\text{max}}/QZ1$; where $dZ/dt_{\text{max}}$ is the maximum deflection of the initial waveform and QZ1 is the time from the beginning of the Q wave to peak $dZ/dt$) and the acceleration contractility index (ACI). These acceleration indices have been reported to more accurately estimate contractility than the PEP/LVET ratio and are conceptually similar to the ventricular $dp/dt$ measures.3

Role of ICG in the Diagnosis of Acute Heart Failure

The value of ICG measurements in the diagnosis of acute heart failure is uncertain. However, the sensitivity of the current standard ED tools of chest X-ray, BNP, and physical examination are also questionable. Most heart failure experts think that advanced hemodynamic monitoring can play an important role in early diagnosis and management.11-13 As long as the ICG values for stroke volume and thoracic fluid volume appear to be relatively accurate, they can be considered an excellent addition to current diagnostic methods.

Early differentiation of heart failure from other common serious conditions, such as emphysema, sepsis or shock due to dehydration, can significantly alter management plans and impact outcomes. ICG technology can be used in the acute setting as a diagnostic adjunct when the primary hemodynamic state is uncertain and the information obtained can be critical to the determination of the patient’s underlying pathophysiologic condition.14 ICG often provides the missing piece of the hemodynamic puzzle and has been found to aid in the identification of conditions that mimic acute heart failure. In patients presenting with a primary complaint of shortness of breath the ED-IMPACT trial demonstrated that cardiac output and TFC information acquired through ICG monitoring changed diagnosis and treatment in 5.3% and 23.6% of patients, respectively.16 This is a greater impact than was seen with the addition of pulse oximetry technology to vital sign determinations.

The clinical assessment of the amount of fluid in the lungs and the central vascular compartment is often based on information from chest X-rays and findings on physical exam. Unfortunately, these methods are somewhat subjective and not easily tracked quantitatively. A cut-off baseline $Z_0$ value of 24.0 ohms has been found to predict an increased thoracic fluid volume with a sensitivity of 92% and a specificity of 79%.7,8 In fact, changes in total intravascular volume as small 590ml over 10 minutes can be detected by differences in TFC, as measured by ICG.17 Peacock et al. found significant differences between patients with cardiomegaly ($Z_0=17.5\pm5.5$) or abnormal pulmonary fluid on their chest X-ray ($Z_0=17.2\pm4.2$) when compared with normal ($Z_0=23.4\pm5.4$), but no differences between patients with cardiomegaly and abnormal pulmonary fluid.9 It was concluded that impedance measurement might detect pulmonary fluid not apparent on chest radiographs.

The O/C ratio (see Figure 2) is calculated as the
amplitude of the impedance cardiogram during diastole (point O) divided by the maximum height during systole (point C) and has been shown to strongly correlate to the invasively measured ventricular wedge pressures (PCWP) over a range of 3–30mmHg (r = 0.92, standard error of the estimate, 3.2mmHg). The combined measurement of cardiac output and PCWP, or Z0 by ICG, is reflective of the state of the Starling Curve, and might be a useful tool in detecting systolic heart failure.

Differentiating systolic from diastolic congestive heart failure is often difficult. ICG allows for a relative determination of cardiac contractility and accurately measures diastolic time intervals such as IVRT, a standard measure of diastolic function. A previous study demonstrated that clinicians could distinguish systolic from diastolic mechanisms in the patient with acute heart failure, in the emergency department, using ICG-derived information.

Role for ICG in the Management of Acute Heart Failure

Goal-directed therapy that optimizes important physiologic parameters has been found to improve outcomes in a number of cardiovascular disease states. Significant improvements in the control of resistant hypertension have been demonstrated using ICG measures in a directed treatment algorithm. There is some evidence that a similar approach may be useful in the emergency management of acute heart failure. Milzman et al. found an improvement in symptoms and vital signs in acute heart failure patients when treatment was guided by ICG-derived cardiac output measurements. Currently, an on-going study involving over 20 multinational centers is designed to demonstrate whether the use of ICG will allow physicians to reduce heart failure events compared with standard care.

The Stevenson Four-Quadrant method of differentiating acute heart failure presentations into distinct clinical/pathophysiologic categories with significant treatment implications has proven to be a practical tool for guiding management of these patients. One area where ICG measurements may have the greatest impact is in aiding this clinical categorization of the acute heart failure patient. The measurements obtained from ICG can potentially be used in conjunction with BNP measurements to determine the general status of the heart failure patient, and assist in the assignment of their heart failure classification by the four-quadrant method (see Figure 3). Warm versus Cold, and Wet versus Dry are descriptive profiles indicating the degree of perfusion and pulmonary congestion and have implications in diagnosis and management. Specific therapy can target the hemodynamic management of acute heart failure based upon knowledge of the relative systemic vascular resistance (SVRI). While the terminology of these profiles is somewhat subjective, the more objective measures of flow and thoracic fluid content offered by ICG could work to improve the determination of the clinical condition without invasive measurements.

Monitoring Heart and Circulatory Function

On-going clinical monitoring and assessment of the circulatory function during the course of the resuscitation process is critical for patients in acute heart failure. Thermodilution measures cardiac output at only one point in time and assumes a steady state. Furthermore, it tells us little about cardiac contractility and is usually impractical in the emergency department setting. Echocardiography is effective in determining contractility, but is not amenable to continuous monitoring and cannot be used to measure cardiac output without significant expertise. ICG monitoring overcomes these limitations and has been used successfully to detect early changes in cardiac function and thoracic fluid content.

In clinical trials using ICG, realtime monitoring of changes in thoracic fluid status was potentially useful in guiding and monitoring the results of therapeutic interventions or changes in clinical condition.

While ICG may be most helpful in those patients whose thoracic fluid status is changing, impedance derived parameters have also been used for monitoring circulatory responses to vasoactive therapy, as well as tracking the impact of diuresis and noninvasive, positive pressure ventilation on cardiac output.
Reading the ICG Heart Failure Waveform

The practice of reading an ECG has become an essential skill for clinicians. Through a process of graphical analysis, the electrocardiographic waveform provides an image of the functioning of the electrical myocardium. The ICG waveform has similar potential for defining the mechanical operation of the heart and the conjoining circulation. This waveform is rich in information concerning systolic contractility, diastolic and atrial functioning, and venous return. There is also evidence that an analysis of typical ICG waveforms may be used in the diagnosis of such pathologic states as mitral regurgitation and IHSS.

Conclusions

As our population grows older, the efficient diagnosis and management of acute heart failure will become one of the greatest challenges in medical care. ICG is a potential tool to facilitate this process. However, it will take a period of collective experience in which physicians who routinely treat heart failure patients become familiar with the ICG parameters and the clinical context of their meaning.

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