Impedance Cardiography:
Summary of Recent Literature
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Until recently, hemodynamic monitoring has been primarily limited to data acquisition via a pulmonary artery catheter (PAC) and confined to critical care units, cardiac catheterization laboratory, and the operating room. Noninvasive hemodynamic monitoring via impedance cardiography (thoracic electrical bioimpedance) has evolved over the past 50 years as an acceptable means of assessing and managing hemodynamic status, not only in settings traditionally associated with hemodynamic monitoring, but also in other areas of the hospital and in the home care arena.

Overview of Impedance Cardiography

Impedance cardiography (ICG) uses external electrodes to input a high frequency, low amplitude current (similar to an apnea monitor) and measure electrical resistance changes in the thorax. Impedance (Z) changes are generated by blood volume and flow velocity increases and decreases in the ascending aorta during systole and diastole. Impedance to electrical current decreases during systole due to increased blood volume, flow velocity, and alignment of red blood cells. The pulsatile impedance changes directly reflect ascending aortic flow and thus left ventricular function. (Figure 1) The base thoracic impedance (Zo), pulsatile impedance/time changes (dZ/dt), and ECG are used to calculate stroke volume, cardiac output, and contractility parameters. Table 1 lists the ICG hemodynamic parameters, definitions and normal values.

Table 1.

<table>
<thead>
<tr>
<th>ICG PARAMETERS</th>
<th>DEFINITION</th>
<th>NORMAL VALUES</th>
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</thead>
<tbody>
<tr>
<td>Cardiac Output (CO)</td>
<td>Liters of flow/min from left ventricle</td>
<td>4-8 L/min</td>
</tr>
<tr>
<td>Stroke Volume (SV)</td>
<td>Volume ejected/beat from left ventricle</td>
<td>60-120 ml/beat</td>
</tr>
<tr>
<td>Systemic Vascular Resistance (SVR)</td>
<td>Afterload, resistance to left ventricular ejection</td>
<td>800-1200 dyne.sec/cm$^5$</td>
</tr>
<tr>
<td>Change in impedance/time (dZ/dt)</td>
<td>Magnitude and rate of impedance change, direct reflection of force of left ventricular contraction</td>
<td>0.8-2.5 ohms/second</td>
</tr>
<tr>
<td>Pre-ejection period (PEP)</td>
<td>Systolic time interval measuring length of time for isovolumetric contraction, Q wave to opening of aortic valve</td>
<td>0.05-0.12 second</td>
</tr>
<tr>
<td>Ventricular ejection time (VET)</td>
<td>Systolic time interval, measuring the length of time for left ventricular ejection, opening to closing of aortic valve</td>
<td>0.25-0.35 second</td>
</tr>
<tr>
<td>Acceleration contractility index (ACI)</td>
<td>Direct reflection of myocardial contractility, calculated from rate of change of blood flow and peak acceleration in ascending aorta</td>
<td>2-5 sec$^2$</td>
</tr>
<tr>
<td>Left cardiac work index (LCWI)</td>
<td>Reflection of myocardial oxygen demand</td>
<td>3-5 kg.min/m$^2$</td>
</tr>
<tr>
<td>Thoracic fluid status (Zo)</td>
<td>Base thoracic impedance, primarily reflects interstitial, alveolar, and intracellular fluid</td>
<td>Men 20-30 ohms, Women 25-35 ohms, Infants 30-45 ohms</td>
</tr>
</tbody>
</table>
Several noninvasive ICG devices are available. The differences between the devices are primarily related to their: impedance signal processing; use of estimated versus measured ventricular ejection time (VET) and thoracic length; and assumptions regarding the shape of the thorax. These factors are important components of ICG based stroke volume equation.

The most recent advance in ICG is incorporation of a patented signal processing technique (IQ™ System, Wantagh Incorporated Bristol, PA) which precisely identifies the opening (B point) and closing (X point) of the aortic valve, allowing exact measurement of the VET. The raw \( \frac{dZ}{dt} \) waveform is converted to a time-power-frequency distribution, then into a normalized power spectrum which clearly defines the “B” and “X” points (Figure 2) and the \( \frac{dZ}{dt}_{\text{max}} \) (C point). The thoracic length is measured between the sensing electrodes which define the thorax and is entered into the computer. The shape of the thorax is based on a form of an ellipsoid model. This system has demonstrated improved clinical utility due to the integration of measured values for VET, \( \frac{dZ}{dt} \), and thoracic length into the stroke volume calculation, modified from earlier equations.  

Other currently available devices estimate the VET based on the QRS of the ECG and the raw \( \frac{dZ}{dt} \) impedance waveform. “Ensemble averaging” (SORBA Medical Systems, Inc., Brookfield, WI) stacks the \( \frac{dZ}{dt} \) impedance waveforms and ECG complexes. The computer or operator places a cursor marking the average peak \( \frac{dZ}{dt} \) and the beginning and end of systolic ejection to obtain VET or the points are identified by pre-designated timing and position estimates. For example, aortic valve opening, the B point, is considered to be 15% of the height of the \( \frac{dZ}{dt} \). Thus, the B and X points, and the \( \frac{dZ}{dt}_{\text{max}} \) are based on estimated averages of 6 to 16 waveforms and ECG complexes rather than measured values. This technology can enhance signals however, signal strength and regularity is necessary to avoid incomplete or erroneous information processing. The operator may
choose from two stroke volume equations, Kubicek or Sramek, which varies the thoracic length calculation and the shape of the thorax, utilizing either a truncated cone or a cylinder model.

A third manufacturer of ICG (BioZ System, CardioDynamics, San Diego, CA) incorporates digital signal processing and an R wave detection system, modifying the original technology (Bomed Medical Manufacturer, Inc) to establish \( \frac{dZ}{dt}_{\text{max}} \), the “B” and “X” points and VET. (P.C. Dennis G Hepp, Chief Technology Officer, 10/21/97) This system utilizes the Sramek-Bernstein stroke volume equation which includes a weight correction factor and derives the volume of electrically participating tissue using an estimated thoracic length based on the patient's sex, weight, and percent of their height. Thus deviations from the standard body habitus may contribute to error in the calculation of stroke volume. A truncated cone is the thoracic shape model. Validation studies are not currently available from the manufacturer or in the literature.

**Efficacy of ICG**

The majority of research compares ICG with intermittent thermodilution cardiac output, little work has involved comparison of the other ICG parameters to available clinical measurements.

All measurements of cardiac output are estimates. Even the “true gold standard for cardiac output comparisons, the direct Fick method, has six steps, and is subject to inherent variability and technical inaccuracies. Of the multiple means to estimate cardiac output, bolus thermodilution method is the most widely used and considered by many to be the “clinical standard”. A limitation of bolus thermodilution method is the reliance on precise and consistent user technique. For example, the cardiac output value documented is dependent on use of: proper computation constant; accurate injectate volume; accurate injectate temperature measurement; proper injection technique; consistent timing of injection during the respiratory cycle; and consistent averaging strategies. Additionally, continuous cardiac output techniques reflect the dynamic nature of the cardiovascular system and left ventricle whereas intermittent bolus thermodilution measurements provide a “snap shot” in time.

Table 2 summarizes recent research comparing ICG to other methods of cardiac output estimation. The correlation coefficients and level of agreement of impedance cardiography compared to other methods of cardiac output estimations reflect the same degree of variability as the data comparing thermodilution to other cardiac output measurement devices.
Table 2. Comparison of ICG with other methods of cardiac output estimation.

<table>
<thead>
<tr>
<th>Source</th>
<th>Comparison</th>
<th>Population</th>
<th>n</th>
<th># of data points</th>
<th>r</th>
<th>Bias &amp; Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thangathurai, 1997, J Cardioth Vasc Anes</td>
<td>• TD Bolus • ICG-Wang</td>
<td>Intraoperative oncologic surgery (post software update)</td>
<td>23 (11)</td>
<td>256 (127)</td>
<td>0.89 (0.93)</td>
<td>Bias 0.1 ± 1.0 L/min, Limits of Agree -1.9 to 2.1 L/min (Bias -0.1 ± 0.8 L/min, Limits of Agree -1.7 to 1.5 L/min)</td>
</tr>
<tr>
<td>Wo, 1995 Curr. Science</td>
<td>• TD Bolus • ICG-Wang</td>
<td>Critically ill</td>
<td>68</td>
<td>842</td>
<td>0.86</td>
<td>Bias -0.06 ± 0.62 L/min/m²</td>
</tr>
<tr>
<td>Shoemaker, 1997, submitted for publication</td>
<td>• TD Bolus • ICG-Wang</td>
<td>ED: Severely injured/hemorrhaging (139), Medical (129), High risk surgical (274), ICU (138)</td>
<td>68</td>
<td>2192</td>
<td>0.85</td>
<td>Bias -0.12 ± 0.72 L/min/m²</td>
</tr>
<tr>
<td>Roessler, 1996, CCM</td>
<td>• TD Bolus • ICG-Wang •</td>
<td>High risk OR</td>
<td>28</td>
<td>234</td>
<td>0.89</td>
<td>NR</td>
</tr>
<tr>
<td>Shoemaker, 1996, CCM</td>
<td>• TD Bolus • ICG-Wang •</td>
<td>ED: severely injured, hemorrhaging</td>
<td>75</td>
<td>NR</td>
<td>0.75</td>
<td>NR</td>
</tr>
<tr>
<td>VanDeWater, 1995, J Clin Engineer</td>
<td>• TD Bolus vs. • ICG-Kubicek • ICG-Bernstein • ICG-Wang • ICG-Wang •</td>
<td>Critically ill • Critically ill • Critically ill • CABG</td>
<td>21</td>
<td>21</td>
<td>87</td>
<td>17</td>
</tr>
<tr>
<td>Pianosi, 1996, Am J Card</td>
<td>• Indirect Fick • ICG-Bernstein •</td>
<td>Healthy children during exercise</td>
<td>30</td>
<td>NR</td>
<td>0.82</td>
<td>Bias 0.14 ± 1.05 L/min., 95% CL -0.12 to 0.44 L/min.</td>
</tr>
<tr>
<td>Wong, 1996, Acta Anes Sin</td>
<td>• TD Bolus • ICG-Wang •</td>
<td>CABG</td>
<td>18</td>
<td>128</td>
<td>0.86</td>
<td>Bias -0.66 ± 0.915 L/min, 95% CL 0.12 to 0.98 L/min. Limit of Agree -2.49 to 1.17 L/min.</td>
</tr>
<tr>
<td>Belardinelli, 1996, Am J Card</td>
<td>• TD Bolus • Fick vs. ICG-Bernstein •</td>
<td>CAD, history of MI, during exercise</td>
<td>25</td>
<td>45</td>
<td>TD 0.90 Fick 0.93</td>
<td>NR</td>
</tr>
<tr>
<td>Fuller, 1992, Clin. Inv. Med.</td>
<td>• TD Bolus • Dye Dilution • Fick • Angiography vs. ICG-Kubicek •</td>
<td>Meta-analysis (28 studies)</td>
<td>NR</td>
<td>2688</td>
<td>TD 0.82 Dye 0.83 Fick 0.80 Ang 0.65 Mean = 0.81</td>
<td>NR</td>
</tr>
</tbody>
</table>

TD: Thermodilution bolus cardiac output; ICG: Impedance cardiography; NR: Not reported; CL Confidence limits
Clinical Applications of Impedance Cardiography

Outpatient and home care of patients previously hospitalized is becoming increasingly common, particularly for those who are in New York Heart Association Class III and Class IV heart failure. ICG provides home health care nurses concrete data for cardiovascular medication dosage adjustment and early intervention based on thoracic fluid status (Zo), stroke volume and cardiac output.\(^{18}\)

Emergency department management of congestive heart failure may be optimized and the degree of pulmonary congestion quantified. The Zo has been found to correlate closely with chest radiographic findings and associated with Forrester subsets.\(^ {19}\) Clinical classification of heart failure and the impedance derived cardiac index and Zo parameters are described in Table 3. Zo values of < 19 ohms are reported to have 90% sensitivity and 94% specificity for identifying chest radiographic findings of pulmonary edema. A Zo of 14.8 ohms is consistent with alveolar edema and a Zo of 18.5 ohms is associated with interstitial edema.\(^ {20,21}\) The effectiveness of therapeutic interventions to relieve pulmonary congestion may be evaluated by a subsequent increase in Zo.

### Table 3.

<table>
<thead>
<tr>
<th>Subset Classification</th>
<th>N</th>
<th>Heart Rate</th>
<th>MAP mmHg</th>
<th>CI L/min/m²</th>
<th>Zo ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. No pulmonary congestion or peripheral hypoperfusion</td>
<td>37</td>
<td>95</td>
<td>109</td>
<td>4.18</td>
<td>23.5</td>
</tr>
<tr>
<td>II. Isolated pulmonary congestion</td>
<td>38</td>
<td>95</td>
<td>103</td>
<td>4.19</td>
<td>17.1</td>
</tr>
<tr>
<td>III. Isolated peripheral hypoperfusion</td>
<td>23</td>
<td>96</td>
<td>99</td>
<td>2.66</td>
<td>28.4</td>
</tr>
<tr>
<td>IV. Pulmonary congestion and peripheral hypoperfusion</td>
<td>12</td>
<td>96</td>
<td>110</td>
<td>1.96</td>
<td>15.1</td>
</tr>
</tbody>
</table>

Other applications in the heart failure population include analysis of the impedance waveform, dZ/dt for the presence of an abnormal O wave in the early diastolic phase. Patients with left ventricular dysfunction, particularly related to diastolic dysfunction, exhibit large O waves which may be attenuated by position changes and therapeutic interventions to reduce preload. The O wave in patients with severe heart failure is less responsive to these maneuvers, than in those with moderate failure. Investigators suggest that the appearance of the O wave has prognostic value and that it may be used an indicator of the effectiveness of interventions.\(^ {22-24}\)

The therapeutic effect of fluid administration or resuscitation can be rapidly assessed by noninvasive continuous monitoring of stroke volume and cardiac output.\(^ {25}\) ICG has been used successfully to evaluate hemodynamic status of critically ill patients in the operating room\(^ {4,7,26}\) and critical care units.\(^ {5,6}\) Specific applications relate to the early diagnosis of hemodynamic derangement, prompt and continuous evaluation of a patient’s response to interventions, criteria for PAC use, and early discontinuation of invasive hemodynamic monitoring.

Several investigators have reported the utility of contractility indices to screen for coronary artery disease.\(^ {27,28}\) Significantly lower values of ICG derived contractility parameters (ACI, dZ/dt) have been identified, both at rest and with exercise, in patients with coronary artery disease (CAD) compared to those without CAD or those with angina but without CAD. No differences in cardiac index and other hemodynamic indices were found between the groups.
Longitudinal evaluation of hemodynamic changes during pregnancy via ICG has value in identifying and managing cardiovascular complications such as insufficient increase in plasma volume or pregnancy induced hypertension.\textsuperscript{29} ICG has been validated as a reproducible means to monitor the course of hemodynamic changes.\textsuperscript{30,31}

A number of investigators have examined the use of ICG in neonates, infants, and children as it can be used on patients too small for PAC, is more practical than Fick, dye dilution, or Doppler techniques, and provides data without risk of complications. ICG has been used to evaluate myocardial dysfunction in children receiving chemotherapy and cardiotoxic agents.\textsuperscript{32} Agreement with pulsed Doppler ultrasound is reported to be 6\% to -0.7\% in newborns\textsuperscript{33} and dye dilution comparison shows a bias of 0.35±0.58 l/min.\textsuperscript{34} Several studies compare ICG to Fick derived cardiac output values in children with intracardiac shunts. Mean differences range from ≤ 5\%\textsuperscript{35} to -16\%.\textsuperscript{36} The disparity may be, in part, attributed to use of a measured thoracic length resulting in less differences\textsuperscript{35} as opposed to an estimated length which is associated with greater differences.\textsuperscript{36}

**Impact of Impedance Cardiography**

Advantages of continuous, noninvasive hemodynamic monitoring include: rapid diagnosis and assessment of cardiopulmonary status; immediate evaluation of the response to interventions; avoidance of risks and complications associated with invasive monitoring; and the ability to acquire hemodynamic data where ever and whenever a patient’s condition may require it. Initiation of ICG requires only a few minutes for electrode placement and data acquisition. Delays in diagnosis and treatment associated with transporting the patient to the critical care unit, gathering of equipment and supplies, and insertion of a PAC, are avoided.

Current controversy surrounding PAC use\textsuperscript{37,38} and costs associated with invasive monitoring is motivating practitioners to better define specific criteria for PAC use. Initiation of noninvasive hemodynamic monitoring prior to invasive catheterization provides more objective criteria in those patients who require invasive monitoring. For example, a specific indication for invasive PAC monitoring of an unstable critically ill patient is the inability to acquire an adequate impedance signal (dZ/dt < 0.3). As an adjunct to invasive monitoring, institution of noninvasive hemodynamic surveillance also permits earlier removal of a PAC thus reducing risks of infections associated with indwelling central catheters.

Continuous monitoring of cardiac output reflects the dynamic nature of ventricular function, pathophysiologic alterations, and response to therapies. Intermittent cardiac output assessment does not reflect the effects of the respiratory cycle, nursing activity, position changes, fluid or medication administration, or other interventions on myocardial contractility and the cardiovascular system on a minute to minute basis.

Heart failure “places a significant economic burden on society….many hospitalizations (could be) prevented by improved outpatient care”.\textsuperscript{39} Emergency department, home care and outpatient management of heart failure patients that is guided by cardiac output, stroke volume, and thoracic fluid status provides more objective evidence of improvement or deterioration. Quantitative ICG hemodynamic data supplements physical assessment findings, daily weights, and functional status classification; affords rapid optimization of therapy; and may prevent or reduce hospital readmission for heart failure.
Additional applications of ICG include the ability to optimize potentially high risk surgical patients, particularly the elderly, preoperatively and continue noninvasive monitoring during the surgery. Noninvasive hemodynamic surveillance elevates the level of monitoring in patients who may be at risk of cardiovascular complications but, typically would not merit insertion of a pulmonary artery catheter. Likewise post-operative monitoring of their hemodynamic status may continue in areas outside of the critical care unit, provide early indication of cardiovascular dysfunction, and afford an opportunity for “pre-crisis” intervention.

**Economic Considerations**

Direct costs associated with ICG are related to the lease or purchase of the device and disposables. There are no hidden costs associated with ICG and as stated previously, ICG has no patient risks or device associated complications. Cost savings afforded by ICG are related to improved ability to rapidly assess and diagnosis, initiate therapy, and re-evaluate the patient’s hemodynamic and thoracic fluid status. This, in turn, may: prevent hospital admissions from the emergency department; reduce critical care and hospital length of stay; and maintain patient flow through the emergency department and inpatient units. Timely evaluation and interventions also decrease complications, thus costs, secondary to delayed diagnosis and treatment. For example: reduced cardiac output and oxygen delivery leading to oxygen debt accumulation may be averted prior to cell injury and organ dysfunction; or, prevention of a delayed or misdiagnosis of the etiology of dyspnea; or, diagnosis of right ventricular failure induced gastrointestinal complaints and dysfunction versus those of abdominal origin. As well, additional cost reductions may be realized by ICG monitoring in locations other than the cardiac catheterization laboratory or critical care units.

Finally, significant savings (over $600 per patient for initial set-up) are afforded when noninvasive hemodynamic monitoring is employed in lieu of PAC. Additional supplies, services, and nursing time are required for the duration of time the PAC remains in place. A recent comparison of continuous cardiac output monitoring to intermittent bolus thermodilution technique showed a reduction in nursing time required for hemodynamic monitoring using continuous hemodynamic monitoring. Costs associated with potential complications of PAC insertion and large vascular access, such as pneumothorax or infection, are avoided with noninvasive methods. The net economic impact of ICG is potentially a significant reduction in both an organization’s costs and patient charges.

**Conclusion**

In the current climate of shrinking health care reimbursement and increasing focus on patient centered care, ICG is one method of enhancing patient care as well as improving the appropriate use of resources. Hemodynamic and thoracic fluid status data may be obtained quickly, accurately, and without risk, providing a global clinical perspective. Patients benefit from the ability of practitioners to immediately obtain real time hemodynamic data, especially those patients who need hemodynamic monitoring, but assessment and treatment are delayed due to inaccessibility of personnel, critical care beds or the cardiac catheterization laboratory. Careful review and critique of the literature differentiates the available ICG technologies, supports utilization of ICG in areas not traditionally associated with hemodynamic monitoring, and validates the use of ICG in place of, or as an indication for, pulmonary artery catheterization.
ICG References