Electrical Impedance Pneumography for Simple Nonrestrictive Continuous Monitoring of Respiratory Rate, Rhythm and Tidal Volume for Surgical Patients*

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Controversial reports concerning theory and use of impedance pneumography necessitated clinical evaluation of the technique. Recorded data from nine control subjects, 12 patients during surgical anesthesia, and seven patients during recovery from surgery form the basis of the study. Useful correlation (mean \( r = 0.89 \)) was obtained between impedance waveform amplitude and tidal volume during surgical anesthesia. Control correlation was about the same (mean \( r = 0.87 \)). Artifacts were easily recognized and not a problem. Intentional complete airway obstruction was easily detected by this noninvasive method. The monitoring equipment was easy to use, electrically safe, and the ability to obtain the ECG from the same electrodes make it especially useful during surgical anesthesia and in the recovery room.

Impedance pneumography is the direct measurement of the thoracic impedance changes associated with respiration in order to provide a display representing respiration. One function may be to count respirations. The degree of association of the amplitude of the impedance waveform with the respiratory tidal volume has been previously examined, and most investigators report the existence of at least qualitative correlation. An informative review of this field with many valuable references has been presented by Baker and Geddes.†

Different electronic techniques and equipment have been used for indirect nonrestrictive respiratory monitoring by impedance pneumography. Conflicting reports on the clinical usefulness of the method led us to perform our own evaluation. Correlation of the amplitude of the impedance waveform and tidal volume measured by the Wright respirometer was studied in normal control subjects and patients under surgical anesthesia. We occluded the airway of several patients during spontaneous respiration to find that the waveform was drastically reduced or absent. Evaluation of the recorded data showed that respiratory rate and rhythm was reliably obtained during surgical anesthesia and in the recovery room.

**Methods**

A prototype of a commercially available patient monitoring system* was used to test the usefulness of impedance derived waveforms in regard to quantitative calibration of tidal volume, apnea detection and display of respiratory rhythm. A two-channel recorder was used to monitor the ECG and the respiratory impedance waveform; the respiration generated trigger signal was also recorded on a marker channel. In order to quantitatively assess the waveform amplitude correlation with tidal volume, we used a Wright respirometer as a reference during surgical anesthesia while recording both controlled and spontaneous breathing. The amplitudes of inspiratory were manually recorded from this reference on the impedance tracing being formed. All tidal volumes were listed but 30 from each subject were chosen for the correlation studies. Three tidal volumes in each of the 100 ml gradations from 100 to 1000 ml were selected from the list for each subject. These 30 tidal volumes and corresponding impedance waveform amplitudes comprised the correlation study data points. Nonpatient control subjects were used to ascertain the degree of correlation of both the direct method (Wright respirometer) and indirect method (impedance) with a wedge spirometer.** This device was considered to be the known standard, as it exhibits a flat frequency response within 5 percent to 22 cycles per second.

Since an impedance device can produce respiration-like waveforms by simply moving the chest or arms without breathing, impedance waveforms were recorded during total obstruction of the airway during spontaneous respiration.

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The recovery room experience on seven subjects can only be reported qualitatively as no tidal volume studies could be made there. The Wright respirometer could not be used on these awakening subjects. Figure 3 is a representative recording from a recovery room patient demonstrating a movement artifact. The recovery room patients were resting quietly.

![Figure 1](image-url)  
**Figure 1.** Airway occlusion for 15 seconds between spontaneous respirations. Electronically generated triggers, indicating respiration detection, are shown as short horizontal lines near the bottom edge of the illustration.

**Table 1—Correlation Coefficients During Surgical Anesthesia, Comparing Impedance Waveform Amplitude and Wright Respirometer Measurements**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age</th>
<th>Surgery</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>25</td>
<td>Small Bowel Resection</td>
<td>0.88</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>50</td>
<td>Hand Operation</td>
<td>0.99</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>45</td>
<td>Radical Mastectomy</td>
<td>0.92</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>16</td>
<td>Hand Operation</td>
<td>0.90</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>57</td>
<td>Hand Operation</td>
<td>0.98</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>52</td>
<td>Colon Resection</td>
<td>0.94</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>40</td>
<td>Exploratory Laparotomy</td>
<td>0.78</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>32</td>
<td>Tubal Ligation</td>
<td>0.97</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>50</td>
<td>Knee Operation</td>
<td>0.87</td>
</tr>
<tr>
<td>10</td>
<td>F</td>
<td>42</td>
<td>Tubal Ligation</td>
<td>0.99</td>
</tr>
<tr>
<td>11</td>
<td>F</td>
<td>33</td>
<td>Tubal Ligation</td>
<td>0.97</td>
</tr>
<tr>
<td>12</td>
<td>F</td>
<td>24</td>
<td>Rhinoplasty</td>
<td>0.50*</td>
</tr>
</tbody>
</table>

*Inverted waveform

Mean 0.89

This was usually done at the end of surgery just prior to termination of the anesthesia. Seven patients were also monitored in the recovery room to ascertain if the device could reliably detect and record the respiratory waveform in that environment. These patients were recovering normally from anesthesia and breathing adequately.

Many factors are known to affect the performance of a device based upon impedance measurement. Important considerations in this respect are that the Roche instrument operated on a constant current of less than 500 microamperes at 50 kHz and was AC coupled, with a time constant of about 3.5 seconds. The electrodes were round chlorided silver metal foil plates (1.8 cm diameter) held in place by adhesive, and an electrolyte gel was used. The standard electrode position was as follows: the two current electrodes were attached bilaterally on the mid-axillary lines at the level of the xiphoid process, and the third electrode was put on the right shoulder.

**RESULTS**

As expected from the experience of others, simultaneous recordings on nine control subjects demonstrated that the Wright respirometer was a suitable instrument for accurately measuring tidal volume during surgery. The correlation coefficient comparing the wedge spirometer with it was 0.99 or more in all cases. The mean correlation coefficients comparing the impedance device with the Wright respirometer and the wedge spirometer were both 0.87. The quantitative results of the surgical monitoring of 12 patients are shown in Table 1, where a similar mean correlation coefficient \( r = 0.89 \) is shown, with the use of impedance pneumography with the Wright respirometer as reference.

The airway occlusion tests demonstrated that attempted spontaneous respiration during endotracheal tube obstruction caused at least a diminution of the amplitude of the impedance waveform. As an example, measured tidal volumes are shown for the last breath before occlusion and for the first breath after occlusion in Figure 1. Respiratory attempts were seen during the period of occlusion but were barely discernible on the record. The respiratory waveform was not of sufficient amplitude to activate the monitor circuitry indicating the occurrence of a respiration. A marker channel on the recorder (bottom edge of chart) was connected to indicate when the monitor circuitry detected a respiration. The monitor detected breathing during unobstructed respiration, but not during the period of airway occlusion. The indication of the electronic detection of each respiration is seen in all recordings at the edge labeled "RESPIRATION TRIGGERS." The monitor contains an audible and visible alarm, but they were not activated for these tests. Figure 2 demonstrates a more discernible attempted respiration during airway occlusion. The attempted respiration can be compared with a 510 ml tidal volume respiration, which immediately preceded the occlusion. This illustration demonstrates the most misleading example of false respiratory indication in our records, although other artifacts were recorded. For instance, movement artifacts caused by resting hands on the patient's chest, manipulation of abdominal contents near the diaphragm, and body movement in general were occasionally observed. Heart signals were evident in some tracings and could be identified as such, because the ECG was recorded from the same electrodes used for the impedance signal.

The recovery room experience on seven subjects can only be reported qualitatively as no tidal volume studies could be made there. The Wright respirometer could not be used on these awakening subjects. Figure 3 is a representative recording from a recovery room patient demonstrating a movement artifact. The recovery room patients were resting quietly.

**Figure 1.** Airway occlusion for 15 seconds between spontaneous respirations. Electronically generated triggers, indicating respiration detection, are shown as short horizontal lines near the bottom edge of the illustration.

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ly and therefore demonstrated very few movement artifacts. The heart signal was variable in occurrence and amplitude among patients, and an example of this type of signal is evident in the same illustration. Generally, the recorded data show that the instrument measures rate and displays rhythm well during surgery and in the recovery room.

**DISCUSSION**

Inhalation normally caused an increase in impedance. Subject 12 exhibited inverted impedance waveforms, and thus created an unacceptable correlation coefficient of 0.5. Standardization of electrode position was attempted but deviation from standard is occasionally dictated by the site of the surgery. Subsequent tests demonstrated that a more caudal position of the electrodes than our standard can cause the inverted impedance waveform, and we attribute the one case of poor correlation and inverted waveform to poor electrode location. It should also be realized that any modification of the patient or electrode position causes changes of the calibration of the impedance waveform for tidal volume.

Regardless of the degree of correlation reported for impedance pneumography, the method has been suspected to be invalid. Although this skepticism is not prevalent, some clinicians have heard that impedance pneumography measures the distance between the electrodes applied to the patient or is simply an electrode artifact. Impedance measurements for plethysmography and spirometry were reported to be in error in 1967. Those reporting the error attempted to utilize impedance measurements to quantitate blood flow in the bovine eye. After very meticulous analysis and experimentation, they determined that the method was not practical. Although many important aspects of impedance measurement were reported, they extrapolated their findings to condemn respiratory impedance measurement without reporting any experimental evidence. Two years later, this clarifying point was reported as a letter to the editor, along with a rebuttal by the original investigators. The rebuttal

![Figure 2](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/20947/) Discrenible respiratory attempt during airway occlusion. One electronically generated trigger, indicating respiration detection, is shown as a short horizontal line near the bottom of the illustration.

![Figure 3](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/20947/) Typical movement artifacts produced by recovery room patient. Electronically generated triggers, indicating respiration detection, are shown as short vertical lines at the bottom edge of the illustration.
did not contain mention of impedance pneumography, but the original article had already been the basis of much opinion formulation concerning the method.

Since 1967, there has been enough experience reported in the literature to indicate that impedance pneumography is useful and that there is a sound basis upon which to proceed with development and clinical evaluation. Confidence that some of the applied current passes through the lung has been increased greatly by detailed investigations in dogs that showed that resistivity changes of the lung tissue are the cause of the transthoracic impedance changes associated with respiration.4 Impedance pneumography performed with the electrodes on the back of the hands is clear evidence that the phenomenon is not merely an electrode artifact. Moreover, an ability to calibrate the waveform, has been reported in at least four more papers.6-9 Besides the necessity to recalibrate for each patient, it was reported in one instance that clamping an endotracheal tube produced a flat respiratory waveform,4 while a more forceful claim has been made that the impedance method is the only method of monitoring which cannot give a false indication of an occluded airway of disconnected respirator on an anesthetized patient.7 In the third report, there were no tests with an occluded airway, but the clinical use of impedance spirometry during and following anesthesia with various agents was reported. Changes in breathing patterns were clearly demonstrated with little or no artifactual interference.6 The fourth study was performed with a guard-ring system. Apnea and breathing rate detection were recommended although mechanical and theoretic problems were reported. Correlation between impedance waveform amplitude and tidal volume were very good if the subject or electrodes were not moved.4 The guarding-ring concept described by Graham9 shows promise for both respiration monitoring and detection of pulmonary edema. Cooley and Longinii11 found that the increased sensitivity of the system over the other electrode systems made it well adapted for monitoring and for breathing pattern studies. Separate lobes of the lung could be studied by use of their system. Severinghaus and co-workers12 demonstrated impedance changes associated with pulmonary edema, making the addition of an important parameter to the capability of the guard-ring system.

The system which we tested during surgery and in the recovery room cannot be considered artifact free. Subject movement can produce artifact signals larger than the respiratory signal. The cardiac associated signals were not a problem, because they were much smaller than normal respiratory signals. They probably degrade the information in regard to tidal volume correlation but only to a minor degree as the results indicate. The existence of these signals did not interfere with determination of a rate or rhythm or apnea detection.

Acceptably low leakage current of ten microamperes or less makes the equipment safe, and the applied current (500 microamperes) is acceptable because of its high frequency (50 kHz). The ease of applying the electrodes to make the noninvasive indirect measurements, cognizance of artifact sources, and the ability to obtain ECG from the same electrodes makes the system especially useful for monitoring situations where there is no access to the patient's airway. We and others have adequately demonstrated this during surgical anesthesia and in the recovery room.

REFERENCES

1 Baker LE, Geddes LA: The measurement of respiratory volumes in animals and man with use of electrical impedance. Ann NY Acad Sci 170:687-688, 1970

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