Thoracic impedance used for measuring chest wall movement in postoperative patients

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Summary
Thoracic impedance (TTI) and rib cage inductance band (IB) signals were measured in 10 patients during the first night after abdominal surgery, and compared by successive correlation of the change in each signal. Poor matching of the signals occurred, on average, for 94 min either because of movement or differences in the waveform. There were frequent episodes of transient poor correlation, generally associated with transient respiratory disturbance, predominantly airway obstruction (58%). Thoracic impedance measurements are simpler than inductance band methods for detecting rib cage movement and may be useful for large studies of respiratory abnormalities in patients after operation. (Br. J. Anaesth. 1996;77:327–332)

Key words

Breathing abnormalities, including episodes of central and obstructive apnoea and disturbed chest wall movements, are frequent after major surgery. Central and obstructive apnoea can be distinguished by measures of both chest wall movement and airway flow. We know of no studies of patients after operation in which the reliability of such measurements has been assessed, and only one in which the number of artefacts has been reported. This type of information is particularly important if automated methods of data analysis are contemplated.

Chest wall movement is commonly attributed to contributions from the rib cage and abdomen, and the motion of these two “compartments” can be used to predict respired volume. After operation, abdominal movements are frequently abnormal or even paradoxical, whereas rib cage movement remains in phase with respiratory effort and better indicates inspiratory activity. Chest wall movement is measured most often by means of inductance bands which detect changes in the self-inductance of a coil placed round the chest wall in an extensible band: changes in the signal are thought to represent changes in area, although this may not be correct. Circumferential length sensors have also been used. Such devices can estimate tidal volume but are affected by body motion, posture, sleep and airway obstruction, and the bands can be inconvenient. We have re-examined the value of transthoracic impedance (TTI) to indicate rib cage movement. The method is simpler and less obtrusive, using adhesive electrodes to measure the voltage generated across the chest surfaces by the presence of a small constant current, usually applied via the sensor electrodes themselves. Previous studies attempted to relate TTI directly to expired volume, but this is now recognized as being inappropriate. TTI has been compared previously with inductance bands but not in patients after surgery, so the suitability of the two methods for this is not known. We have studied how well TTI and rib cage inductance signals compare, to give a qualitative index of rib cage movement, how reliable these methods are and the reasons for discrepancies between the signals.

Patients and methods
Patients gave informed written consent and local Ethics Committee approval was granted. We studied 10 patients after major abdominal surgery over the first night after operation while they were in a surgical high dependency unit. Criteria for admission to the study were an abdominal incision extending above the umbilicus and age more than 40 yr. Patients were excluded if they were chronically hypercapnic or had a body weight more than 130% of that expected on the basis of sex, age and height. Analgesia was provided with either a thoracic extradural infusion or i.v. patient-controlled injections of morphine.

Transthoracic impedance was measured with a device constructed in the Department of Medical Physics and Medical Engineering. It gave a constant current of 1.5 mA rms, frequency 70 kHz and was connected to the chest wall via two Medicotest ECG electrodes, one on the right mid-axillary line at a level corresponding to the V6 ECG electrode position and the other medial to the top of the left anterior axillary line. Earlier studies showed these positions gave more reliable waveforms than when electrodes were placed in both mid-axillary lines. The amplifier output was filtered (bandwidth 0.01–1.4 Hz, $-6 \text{ dB octave}^{-1}$).

Rib cage movement was measured with an inductance band placed round the rib cage immediately below the axillae. It used an alternating current of 100 kHz and self-inductance was measured with another device made by the Department of Medical Physics and Medical Engineering.
Physics and Medical Engineering. The amplifier output was filtered (bandwidth 0.03–16 Hz, −6 dB–octave−1). Another band was placed around the abdomen at the level of the umbilicus, but only the signal from the rib cage inductance band was used for comparison with the TTI signal.

Gas flow at the nose was measured from pressure fluctuations in a nasal oxygen cannula system19 measured using a differential transducer (Furness FC10, Bexhill, Kent). Signals were sampled continuously every 88 s with an AD converter (PCM8, Medical Systems Corporation, Digitimer, Welwyn Garden City, UK) and recorded on magnetic tape. Each record was replayed onto an eight-channel chart recorder (Graphtec WR3600) at 60 mm min−1 to allow inspection of the waveform patterns. Signals were passed also to a second AD converter into respiratory logging software (Cardas version 2.07, Oxcams, Oxford) sampling at 20 Hz. Each patient provided approximately 6 h of recorded data.

The waveforms were compared by taking successive 10-s blocks of data of the TTI and rib cage impedance signals. In each 10 s, samples of each signal were obtained at 5 Hz, giving 50 values. Each value was subtracted from the following one to give the relative changes of each signal which were then correlated by least squares linear regression (SPSS 4.0 for Unix V/386 Intel 80386). The strength of the correlation gave an index of the similarity of the two signal waveforms. These correlation estimates are presented as discrete values in the figures that have expanded time scales. For each patient, the correlation values of each 10-s block were plotted using a time scale of 40 cm h−1. A typical short section of such a plot is shown in figure 1. The general pattern of these values was either a consistent excellent correlation with r values greater than 0.8, with occasional transient decreases in the r value; or periods of time when the r values were variable and consistently less than 0.8. If the r value was less than 0.8 for more than 30% in any 5 min this was termed “poor matching” and these periods measured for each patient. The chart records were inspected to determine the reason for the poor correlation, and classified into two categories: patient movement, recognized by a short (1–5 min) episode where all

<table>
<thead>
<tr>
<th>Patient No</th>
<th>Total time measured (min)</th>
<th>No. of episodes</th>
<th>Total duration of episode (min)</th>
<th>TTI abnormal</th>
<th>Inductance abnormal</th>
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<td>185</td>
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<td>13</td>
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<td>4</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>133</td>
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</table>

Figure 1 A sample of successive correlation plot illustrating the method of analysis. The horizontal bars (X–X, Y–Y) represent times when the correlation coefficient was less than 0.8 (line A–A) for more than 70% of the time. The first bar (X–X) indicates a period of 3 min caused by movement, and the second (Y–Y) a persistent period of poor matching. At the start of the plot, there was a transient episode of loss of correlation (Z) (r<0.6, line B–B).

Figure 2 A plot of successive correlation values and the measured variables during a period of patient movement. Note also the poor nasal flow at the start of the trace, before arousal at about 30 s.
signals became markedly disturbed; or a poor relationship between the TTI and inductance band waveform shapes. In these latter periods, a signal with an unclear and complex waveform was classified as “abnormal” (usually a decrease in amplitude or a biphasic pattern). Results are presented for either one, or both, signals being of this type.

In the rest of the recording, when matching of the signals was generally good, episodes of transient decrease in the $r$ value could occur when $r$ became less than 0.6, usually for only one or two values. Each of these events was identified, related to the chart recording of the original signals and classified according to the apparent reason for the poor correlation. The respiratory pattern of the patient was inferred from the nasal flow signal leading up to the event, in relation to the rib cage and abdominal inductance signals, and classified as showing: apnoea, normal nasal flow pattern, mild or severe obstruction of nasal flow, or an abnormally large breath (usually after an episode of obstruction). Obstruction to flow was also recognized by a change in the waveform of the nasal flow signal. The TTI and inductance band signals were classified into one of the following categories: absent or low amplitude signal, stable waveform, change in baseline (successive cycles having different amplitude of turning points), large change in signal amplitude, change in waveform or signal waveform that was opposite in phase to the other signals (paradoxical waveform).

The relationships between these states for the three signals were investigated by logical analysis using Minitab PC version 8.2 run using DOS 6.2.

**Results**

We studied 10 patients (five females), mean age 68 yr and weight 89% of expected (range 72–100%). The waveforms were poorly matched for a mean of 94 min (table 1). Motion artefact accounted for 11 min of poor matching. An episode of movement is shown in figure 2. Inadequate waveform matching accounted for the remainder of the time that the signals were poorly matched. The TTI waveform was poor on average for 58 min per patient. Both signals were poor for a mean of 16 min. An episode when the TTI signal was poor is shown in figure 3. TTI amplitude was small and the wave was biphasic in comparison with rib cage and abdomen inductance band signals. Four of 10 subjects were responsible for the majority of the poor TTI signals: 58, 129, 141 and 185 min, respectively.

There was no apparent relationship between the method of analgesia and the inadequate waveform. Periods of poor waveform generally started and

![Figure 3](http://example.com-figure3.png)

**Figure 3** Poor correlation associated with a TTI signal which is biphasic and of low amplitude.

![Figure 4](http://example.com-figure4.png)

**Figure 4** Change in correlation associated with change in waveform of the TTI signal: recordings in the same patient, the second 15 min after the first.
ceased with episodes of movement, probably indicating times when the patient moved into a different position. Figure 4 shows a change in correlation after a period of movement in a patient. The poor matching is associated with a change in the TTI waveform which shows a decrease in thoracic impedance at the onset of inspiratory flow.

If the correlation of waveforms was satisfactory ($r > 0.8$ for $>70\%$ of the time), the correspondence between TTI and rib cage inductance band signals was very good, even when there were transient changes in the pattern of respiration (fig. 5) or episodes of airway obstruction (fig 6). Episodes of severe airway obstruction resulted in transient reduction in correlation, either because of changes in waveform (fig. 7) or changes in the signal baseline (fig. 8).

There were a total of 390 episodes of transient poor correlation in the 10 patients, with patients showing between 9 and 81 episodes of this type (table 2). More than 50% were associated with airway obstruction. Large breaths after an episode of obstruction accounted for 18% of events. In 17% of transient poor correlation events, there was no abnormality in the nasal flow signal. Baseline position change of the TTI signal most frequently reduced the correlation (45% of episodes), for example with airway obstruction (fig. 8). Changes in waveform of the TTI signal caused 25% of episodes, and in 19% there was no clear fault. Most commonly, the inductance band signal associated with a transient reduction in the correlation did not change (34% of episodes). The baseline changed in 25% of the episodes, the waveform altered in 15% and a
Thoracic impedance to measure chest wall movements

small signal was present in 13%. Absent airway flow and no signal from the TTI trace (which could indicate central apnoea) was noted only once. During inspection of the paper records it was evident that satisfactory correlation values could persist despite minor disturbances in the baselines of the signals, and in the signal waveform and amplitude, such as in figure 8. The traces were not examined systematically for this, as objective criteria for such events would have been difficult to establish.

Discussion
Chest wall impedance has been used to monitor respiration for many years. The early development of the method has been reviewed by Pacela. Realizing that independent movements of rib cage, abdomen, and trunk contribute to lung volume changes and that TTI is related to rib cage dimension has tempered the hope that TTI could be related directly to lung volume, although alternative approaches using electrode arrays may provide more information on lung volume. Comparisons of TTI with other methods have only been for short periods of time, often for only a few minutes. We set out to use TTI to indicate chest wall movement and thus classify abnormalities of breathing. We have found from studies of oesophageal pressure in such patients that the most frequent respiratory abnormality is obstructive apnoea. In this case, the rib cage inductance band signal remains in phase with respiratory efforts, whereas abdominal movements may cease or become paradoxical. Nasal flow often changed abruptly. In this study we are reasonably confident therefore that the decreases in flow represented obstruction rather than hypopnoea (when the flow waveform was attenuated but of similar shape) or change to mouth breathing (which we found to be almost always only expiratory).

For comparison, we used inductance bands. If the output signal is AC-coupled to remove baseline fluctuations, this method gives a long-term satisfactory qualitative index of movement, being disturbed only when the patient changes position. In this study, the inductance band system was judged to give a poor signal for a single prolonged episode (114 min) in only one subject and in 15% of the isolated events of poor correlation. However, inductance bands and TTI obviously detect different physical characteristics, and some of the discrepancies we found may be caused by other but nevertheless "real" changes, such as intrathoracic fluid shifts, which alter TTI measurements. Visual inspection and previous experience of the relationship between lung volume and chest wall dimension measurements led us to classify the simpler waveforms as "correct" although this is to some extent arbitrary. The frequency of breathing was generally approximately 15 (range 7–30) bpm. Consequently, the sample rate of 5 Hz used gave 10–40 samples for each breath, usually 20. More rapid sampling would give small increments between successive values that could be affected by noise in the signals. With 10 s for each correlation, we compared the correspondence of the waveform over approximately two breaths which is probably what is done when comparisons are "by eye", and the number of samples was sufficiently great to ensure a good chance of detecting correlation. We detected three types of loss of correspondence between the signals. The first type, classified as movement artefact, disturbed both signals equally. The second type, poor waveform correspondence, was often judged to be the "fault" of the TTI signal: only on one occasion did the inductance method give a poor signal. Finally, there were frequent events when there was temporary loss of correlation between the signals. However, inspection of these events showed that on most occasions the TTI signal remained "interpretable". The most common reason for poor correlation was a baseline shift. The TTI apparatus we used was intended for measurement of the duration of inspiration and expiration of each breath and had an extended low frequency response for this purpose, and this reduced its capacity to recover from baseline changes. A reduction of the low frequency response of the TTI system would reduce the incidence of these episodes.

In 25% of cases, the baseline shift was associated with an episode of obstruction, and it may be that the shift was caused by changes in blood volume in the chest during obstruction. Another common reason for poor correlation was a change in waveform (99 of 390 events), and an uninterpretable signal was present on only four occasions. The method we used of testing for waveform comparability gives false positives: occasions when the TTI signal, alone, could be useful but the comparability of the waves was poor. The false negative rate, when the correspondence between the signals may have been poor but the correlation method did not indicate this, is probably small. We had no automated method or specific criteria for identifying false negative events, but carefully examined each chart, several times, without finding this possibility.

Studies of respiratory movement are generally for short measurement periods. Overnight studies measuring respiratory movement or gas flow are uncommon, the study of Catley and colleagues being an exception. They measured chest wall movements and interpreted paradoxical movements as airway obstruction, but gave no details of how much time satisfactory signals were absent. In another study using a simplified inductance band system, 14 of 63 records were excluded because of inadequate quality, and artefacts occurred at 0.2–0.7 per hour, which is a very low rate compared with this study. These were detected by inspection of the charts only, perhaps a less rigorous test of signal quality. Similar studies by others, using inductance bands or chest wall sensors, used computerized methods for analysis.

Table 2 Incidence of abnormal waveforms associated with transient poor correlation. Values are percentage of total episodes of poor correlation

<table>
<thead>
<tr>
<th>Abnormality</th>
<th>TTI</th>
<th>Inductance</th>
</tr>
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<tbody>
<tr>
<td>Small wave</td>
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</tr>
<tr>
<td>Normal</td>
<td>19</td>
<td>34</td>
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<tr>
<td>Baseline shift</td>
<td>45</td>
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<tr>
<td>Abnormal waveform</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>Other</td>
<td>8</td>
<td>13</td>
</tr>
</tbody>
</table>
but provided no details of the means of validation of the data.

A more recent study involved 20 patients, each studied both before operation and for 60–70 h after operation. An observer was present continuously to exclude artefact, but no details are provided of the proportion of record excluded.

We believe that our study is the first report of the quality of postoperative respiratory monitoring. The quality of these signals was affected by patient factors such as motion and also by technical factors such as electrode contact, position, and the position and stability of the inductance bands. Ideal signals would be obtained from a patient who slept in one position for the whole night: such a patient would certainly be over-sedated and likely to develop pressure sores, atelectasis and sputum retention (at least). Thus loss of signal is inevitable: breathing should not be a completely continuous process. Clinical investigations require differentiation of central and obstructive apnoea and this can be done with an index of the presence or absence of respiratory movements and a nasal flow signal. This study showed that TTI can provide this index, and as TTI measurements are simpler than inductance band methods, larger numbers of patients may be studied more easily.

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References


