Characterization of breathing patterns during patient-controlled opioid analgesia

G. B. Drummond1*, A. Bates2, J. Mann2 and D. K. Arvind2

1 Department of Anaesthesia and Pain Medicine, University of Edinburgh, Royal Infirmary, 51 Little France Crescent, Edinburgh EH16 4HA, UK
2 Centre for Speckled Computing, University of Edinburgh, Room 1.37, Informatics Forum, 10 Crichton Street, Edinburgh EH8 9AB, UK
* Corresponding author. E-mail: g.b.drummond@ed.ac.uk

Editor’s key points
- The authors have developed a system that uses accelerometers to measure and record respiratory movements.
- They also use recordings of nasal pressure to make inferences about respiratory air flow.
- Using these measurements, they have investigated respiratory patterns among patients receiving morphine via a patient-controlled analgesia system.

Background. Respiratory rate is an important measurement in patient care, but accurate measurement is often difficult. We have developed a simple non-invasive device to measure respiratory movements in clinical circumstances, with minimal interference with the patient. We investigated respiratory patterns in patients receiving postoperative morphine analgesia to assess the capacity of the device to detect abnormalities.

Methods. We studied subjects during self-administered opioid analgesia after major gynaecological surgery, and related the derived signals with a signal from a nasal cannula. Respiratory movement signals were transmitted wirelessly to a recorder from two encapsulated tri-axial accelerometer (RESpeck) sensors. We analysed the signals using two different sensor placements, each for 30 min. The nasal cannula signal was used to classify breathing patterns as obstructive or non-obstructed.

Results. We studied 20 patients for a mean duration of 49 min each. Breathing patterns were very variable, between and within patients. The median breathing rates ranged from 6.4 to 19.5 bpm. Breathing was partly obstructed in 10 patients, and six patients had repeated cycles of obstruction and transient recovery. In these patients, we found a consistent and statistically significant pattern of changes in chest wall movement, with increased abdominal and decreased rib cage movement during obstruction. In patients with slow respiratory rates, breath-to-breath times were highly variable.

Conclusions. In undisturbed subjects receiving patient-controlled morphine analgesia after surgery, abnormal breathing patterns are extremely common. Cyclical airway obstruction is frequent and associated with a typical pattern of changes in chest wall movement.

Keywords: monitoring, physiologic; respiration disorders; respiratory rate

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Opioid analgesia is very often used after surgery, and the doses required after abdominal surgery commonly cause respiratory disturbances.1,2 Breathing disturbances such as airway impairment that cause hypoventilation may be detected by pulse oximetry. However if oxygen therapy is used, as it is frequently, many episodes of obstruction are concealed.3,4 Studies using more intensive methods such as continuous capnography have found very frequent adverse events.5 Adequate monitoring to detect these events presents a substantial clinical challenge. Most currently used monitor systems require cannulae or connecting wires that can restrict patient movement and are easily displaced, the patient connections require careful supervision, and false alarms can be a substantial problem.5,6 Although the pattern of chest wall movements after abdominal surgery and the changes that occur with obstruction are complex,7 less invasive and more robust devices that can sense chest wall movements present an attractive alternative means of monitoring.8

We have developed a device, the RESpeck, which can be taped to a patient’s body to detect respiratory movements and transmit the data wirelessly to a receiver in the ward. Preliminary studies showed that the signal could be consistently related to another measure of respiration, obtained from a nasal cannula.9 Although consistent measurements of rate could be derived from the motion sensor, we were concerned that episodes of obstruction might not be detected. In the present study, we wished to characterize abnormalities of respiratory pattern, in particular those associated with respiratory obstruction, which could affect the measurement of the respiratory rate using chest wall movements, by observing patients after abdominal surgery.1 We therefore used two montages of RESpeck sensors, compared with nasal cannula...
recordings, to evaluate abnormal patterns of movement. We also observed abnormalities in respiratory timing.

**Methods**

We obtained permission from South East Scotland Regional Ethics committee to recruit patients about to undergo elective surgery. Subjects for elective major gynaecological surgery were seen at the preoperative assessment clinic, shown the device, and given information about the study. If they gave provisional consent, we then confirmed their wish to participate on the day of surgery. After surgery, patients were managed in a recovery area and given i.v. opioids (usually morphine) until comfortable. Patient-controlled analgesia (usually a dose of 1 mg morphine i.v., with a 5 min lockout) was started. The patients were studied after they had returned from the anaesthetic recovery area to the ward after surgery. The routine anaesthetic and surgical management of the patients was not affected by inclusion in the study. Those caring for the patients were aware of the study, but did not see the data collection, and care was taken to ensure that the recordings had as little effect as possible on routine practice. The usual variations found between patients, with regard to anaesthetic and surgical management, were those commonly present in routine practice in this surgical unit.

**Data acquisition**

**Respiration**

Breathing was measured using a nasal pressure cannula (SleepSense 14805-2-FT, S.l.P. Inc., Tel Aviv, Israel) placed at the subject’s nose and secured round the ears in the same way as oxygen nasal cannulae. The cannula was connected via a bacterial filter to a small enclosure (66 × 66 × 28 mm) fastened to the subject’s pillow containing a temperature compensated, calibrated pressure sensor (Freescale MP3V7007, Farnell, Leeds, UK) and a radio transmitter.

**Chest wall movements**

The RESpeck device contains a digital tri-axial accelerometer (MMA8451Q, Freescale, East Kilbride, Glasgow, UK), which internally samples data at either 12.5 or 50 Hz. The signal was filtered in software using a fourth-order Butterworth low-pass filter with a cut-off of 1 Hz. Data are transmitted using a 2.4 GHz transceiver (NRF24L01+, Nordic Semiconductor ASA, Skøyen, Oslo, Norway). We used two RESpeck devices. The device is enclosed in a plastic capsule 45 × 38 × 13 mm, and weighs 15.4 g (inset, Fig. 1). Each device was fastened inside a sealed plastic bag using double-sided adhesive tape. The bag was taped to the skin using a conforming, perforated polyester fabric tape with acrylic adhesive (Mefix, Mölnlycke Health Care Limited, Dunstable, UK) to hold the speck closely to the body surface. Using two successive positions for one of the sensors, we obtained two successive time periods of observation, with alternative sensor montages, which could be regarded to be detecting ‘abdominal’ and ‘ribcage’ paradoxical movement.

**Data analysis**

The nasal flow signal was first re-played alone, without a display of the motion sensor signals, using proprietary software (Spike 2, version 5.19, CED, Cambridge, UK). The patient breathing pattern was classified by an experienced observer who was unaware of the clinical identity or features of the patient. Limitation of inspiratory flow, indicating partial airway obstruction, was identified by a characteristic flattening of the waveform. Each patient was first classified as either having evidence of obstruction or not. Patients considered to have airway obstruction were then classified into those who showed a cyclic pattern of increasing obstruction, followed by transient recovery, or those in whom the obstruction was not clearly cyclic. An example of the cyclic form of obstruction is shown in Figure 2 (note that only the nasal signal, and not the motion sensor signals, was used.
during the initial classification process). For each cycle, markers were placed in the recording to indicate a preceding normal segment of breathing, a section that showed increasing obstruction, and a section that showed recovery from the obstruction. In this way, the nasal cannula signal was used to ‘classify’ the time segments present in each episode of obstruction.

We marked on the display the exact time at which each recovery from obstruction occurred, to allow subsequent formal analysis of these events. We used Spike software to identify the time of onset of each inspiration, and thus were able to quantify the magnitude and variation of the duration between breaths, in each subject, for the entire recording period.

Subsequent analysis used a display of all three signals. We noted the duration of each recording period, when all signals were present and when there were no large patient movements. In patients with cyclical obstruction, five episodes were chosen in each time period for sampling. Each episode sampled was related to the previously noted times of recovery from obstruction. A section of record was sampled before, during, and after recovery from obstruction (Fig. 2). We excluded any short period of irregular breathing during immediate recovery from obstruction. Spike software was used to measure the root mean square (RMS) amplitude of the nasal cannula and the summed axial signals, averaged over time, for each section of the obstructive episode. The duration of each sample section (before, during, and after obstruction) was also noted and the mean duration of each section for the five episodes was calculated. To provide a ‘control’ measure of amplitude, five points were randomly allocated as dummy episode markers throughout the entire duration of the same record. Samples of the signal were taken in relation to these markers using the mean durations of the actual samples in that patient, and these sections were analysed in the same way as the episodes of obstruction. If a dummy marker fell in a section when the trace was affected by excess patient motion, the mark was discarded and an alternative random point was allocated.

**Statistical analysis**

For each subject, we noted the duration of recording used for analysis, all the breath durations, and the total number of breaths detected. We calculated the median breath duration and the inter-quartile range of breath durations, as an index of the breath-to-breath variation in each subject. To assess body weight and infer obesity, we calculated weight as percentage expected using standard tables.11 The mean RMS amplitude values for each signal before, during, and after obstruction were compared using repeated-measures analysis of variance (ANOVA). Unless stated otherwise, data are mean (SD). Data that did not appear to be normally distributed are presented as median (quartiles).

**Results**

We interviewed 30 patients, and 25 agreed to participate and were studied. In four, acquisition of the nasal pressure signal failed, and in one, recording of one movement sensor failed. Thus, recordings from 20 patients were available for analysis. The mean age of these patients was 47 yr (range, 25–77), height 161 (7) cm, weight 73 (14) kg. The mean weight as percentage expected was 118 (22)%. The median duration of surgery was 115 (quartiles 88, 125) min and the patients were studied a median of 157 (quartiles 109, 180) min after surgery was 115 (quartiles 88, 125) min and the patients were studied. In four, acquisition of the nasal pressure signal and an alternative random point was allocated. To provide a ‘control’ measure of amplitude, five points were randomly allocated as dummy episode markers throughout the entire duration of the same record. Samples of the signal were taken in relation to these markers using the mean durations of the actual samples in that patient, and these sections were analysed in the same way as the episodes of obstruction. If a dummy marker fell in a section when the trace was affected by excess patient motion, the mark was discarded and an alternative random point was allocated.

![Fig 2](image-url) An example of an episode of obstruction. The nasal signal shows a downward deflection (pressure decrease) on inspiration. During the period of obstruction, the inspiratory signal progressively decreases and shows characteristic flattening seen during flow limitation. The subcostal sensor shows an increase in amplitude and the clavicular sensor movement decreases. After the obstruction is over, reciprocal changes occur. The segments indicated at the bottom of the chart indicate the time sections chosen in this specific episode for measurement before, during, and after obstruction.
The substantial differences in the variability (inter-quartile range) of breath duration were also associated with a greater positive skew of the distribution when the median value was greater (Fig. 4). Ten patients showed persistent airway obstruction, which was continuous in four and had cycles of obstruction and recovery in six. Two patients had a normal breathing pattern, although one of these patients talked almost continuously for the hour of the study. When this patient did stop talking, we detected mildly obstructed breathing with no evidence of cycles of recovery. There was no apparent relationship between the skew distribution of the breath durations and the presence or absence of airway obstruction (Fig. 4).

In the six patients with cycles of airway obstruction and recovery, we measured the power (RMS) of the waveform before onset, during development, and after recovery from airway obstruction. These values are presented in Figure 5, along with measures from control periods of the same mean duration.

The general pattern of movement was that obstruction led to an increase in the subcostal sensor movement and a decrease in movement of the sensor placed caudal to the clavicle. When the breathing pattern was very slow and irregular, we questioned if the nasal signal could be absent because obstruction of the upper airway was occurring, even though the nasal pressure waveform, when breaths were present, did not suggest that obstruction was present. In all cases, careful inspection of the three signals suggested that small chest wall movements were almost always associated with small fluctuations in nasal flow (Fig. 6).

**Discussion**

By using unobtrusive sensitive sensors, we obtained our data from undisturbed patients. Previous studies of patients after surgery have required some degree of supervision and intrusive instrumentation. Thus, such studies may not reflect the usual behaviour of patients receiving patient-administered opioids. In the present study, an experienced observer was able to record unobtrusively the clinical condition of the patients and any relevant events without any disturbance to the patient or interaction with the nurses conducting observations. We believe that the conditions of this study were therefore close to the ‘natural condition’ of ward patients receiving standard supervision. In addition, we studied a relatively homogenous group of patients, who would be considered to have a low risk of complications. Nasal pressure changes are widely used to assess disturbances of respiratory pattern and upper airway obstruction, and our data analysis system allows efficient acquisition of large samples. For technical reasons, we lost some nasal pressure data, and we have now modified the transmission process to improve data transfer.

We noted two types of respiratory abnormality. The first was obstructed respiration, which is known to occur in patients receiving opioids after surgery. Recumbency decreases lung volume, and this reduces airway patency, probably by reduced traction from the thorax. Opioid analgesia and the associated hypoventilation reduce ventilation, stimulate abdominal muscle contraction during expiration, which will also reduce lung volume. Abdominal compression increases airway obstruction, and phasic abdominal muscle activity is associated with airway obstruction. Recumbency also causes fluid shifts that can exaggerate airway collapse and excess fluid therapy and fluid retention associated with surgical trauma could have contributed to these effects. Although in some circumstances, upper airway obstruction associated with sedation can be reduced by positive airway pressure, this approach is ineffective after surgery. Previous reports of airway obstruction in these circumstances have emphasized that the obstruction is periodic, terminating with arousal and a period of hyperpnoea, as is common in sleep apnoea. However, four out of 10 of the subjects with obstruction had a virtually constant obstructive pattern, with no evidence of cyclic breathing.

In those patients with evidence of cyclic breathing, the pattern of movements seen during episodes of worsening obstruction was as we had predicted. During anaesthesia, airway obstruction is associated with continued abdominal movement and reduced or even paradoxical movement of the rib cage. Diaphragm action during inspiration, and abdominal muscle contraction during expiration, continue to move the abdomen during obstruction. In contrast, the chest wall ceases to move out during obstruction, and is instead forced out by abdominal contraction at the end of expiration. Thus, a single motion sensor could be ineffective in reliably detecting cyclic airway obstruction, but the differential pattern of two sensors would track this phenomenon, if it were considered clinically useful. A previous study showed that obstructive episodes in sleep apnoea patients could be identified satisfactorily by assessing differential ribcage and abdominal movements using inductance band measurements. Airway obstruction has potentially adverse cardiovascular effects, so detection could be clinically relevant.
Airway obstruction is most unlikely to explain the substantial variation in respiratory frequency that we observed. Although airway obstruction prolongs inspiration in patients with sleep apnoea, these effects are much less marked than the slow irregular breathing we observed. Slow and irregular breathing, in both volume and timing, is consistent with previous reports of reduced respiratory rate in these circumstances. Previous reports note increased variation in tidal volume after opioid administration, and a measure of breathing cycle variation would be a simple additional index of opioid effects provided by a clinical monitor.

How useful are respiratory rate or variability as a measure of excessive opioid effect? All the patients we observed with low respiratory rates were calm, undistressed, and usually kept their eyes closed. However, none were in what would be clinically described as deep sleep: all responded immediately to voice, or roused if there was extraneous noise. When spoken to, they would respond sensibly, and the respiratory rate would increase. These clinical findings are consistent with formal studies of sleep in healthy volunteers given morphine. Morphine reduces both deep and rapid eye movement sleep, so that most sleep is light (equivalent to the standard definition of stage 2). This ‘lightly asleep’ condition, which we observed and is also found in more formal studies, is not compatible with the standard concept of progressively reduced responsiveness that is implied in most sedation assessment.
scales. Progressively reduced responses are described even in those scales specifically tailored for postoperative use, such as the scale advocated by the American Society of Pain Management Nursing Guidelines. These guidelines, based on a systematic review, conclude that ‘Sedation generally precedes significant respiratory depression’. However, this statement is supported by citing studies using sedation scales that the guidelines elsewhere criticize as inappropriate. In contrast, our clinical observations show that low breathing frequency and increased variation in breath duration, features of substantial opioid effects, are present in patients who are easily roused.

However, we concur with the suggestion in the American Society of Pain Management Nursing Guidelines that ‘Respirations should be counted for a full minute and qualified according to rhythm and depth of chest excursion while the patient is in a restful/sleep state in a quiet unstimulated environment’. This suggestion is probably rarely followed in practice. In the present study, although the observation was not a formal aspect of the study, we found that nurse-recorded respiratory rate showed a poor relationship with the rates we measured, probably because the rate was counted after the patient had been roused by other recordings. The attendant staff expressed no concerns about the condition of any of the patients studied, and no adverse events occurred. Thus, if the device we have developed were to be used for routine monitoring, then the concept of an ‘acceptable’ respiratory rate, that is, one that is not associated with an adverse outcome, would have to be revised, since we frequently observed rates that are currently considered unacceptable (when measured by the usual methods).

In summary, the differential movements of two sensors can indicate episodic airway obstruction in patients with cycles of obstruction and recovery, for the two study periods. The shaded segments and closed symbols indicate the period of obstruction. The circles represent measurements made in relation to a true cycle of obstruction/recovery and the squares represent randomly placed samples of equivalent timing in the same measurement period. As expected, nasal flow amplitude decreased significantly during obstruction (ANOVA, P = 0.001). The subcostal sensor movement increased during obstruction (P = 0.003). Obstruction did not affect the sensor placed at the umbilicus, but the sensor below the clavicle moved less during obstruction.

**Fig 5** Relative amplitudes of the three waveforms in patients with cycles of obstruction and recovery, for the two study periods. The shaded segments and closed symbols indicate the period of obstruction. The circles represent measurements made in relation to a true cycle of obstruction/recovery and the squares represent randomly placed samples of equivalent timing in the same measurement period. As expected, nasal flow amplitude decreased significantly during obstruction (ANOVA, P = 0.001). The subcostal sensor movement increased during obstruction (P = 0.003). Obstruction did not affect the sensor placed at the umbilicus, but the sensor below the clavicle moved less during obstruction.

**Fig 6** Evidence that apparent apnoeic periods are associated with minimal chest wall and nasal flow changes in some patients with respiratory dysrhythmia, suggesting that airway patency is present and respiratory movements are very weak.

Authors’ contributions

G.B.D. designed the study, collected patient data, conducted the analysis, and drafted the paper. A.B. developed software, processed the patient data, assisted with data analysis, and revised and corrected the draft version of the paper. J.M.
designed and fabricated the devices, assisted with data acquisition and analysis, and revised the draft for content. D.K.A. participated in study design, and revised the draft for content. All the authors have seen and approved the final version.

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Declaration of interest
D.K.A. and A.B. are named in a patent application for the RESpeck device. ‘Method, apparatus, computer program and system for measuring oscillatory motion’, UK filing number 1009379.7.

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