Noninvasive Detection of Respiratory Failure in the Intensive Care Unit*

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We investigated the utility of a noninvasive respiratory inductive plethysmograph (RIP) to continuously monitor and record the breathing pattern of 44 patients who had been mechanically ventilated. Seven patients deteriorated on intermittent mandatory ventilatory rate of zero; seven deteriorated within 48 h following extubation; 30 were successfully extubated. Respiratory alternans was documented by RIP in 11 patients who failed whereas it was absent in all other patients. Respiratory rates in the 14 failure patients increased when compared with rates one hour before clinical deterioration and with rates of 30 patients who were successfully extubated. Total compartmental displacement/tidal volume increased in every patient who developed respiratory failure. Changes in the breathing pattern, specifically onset of rib cage-abdominal asynchrony, can be diagnosed noninvasively, thus alerting the clinical staff prior to onset of overt respiratory failure and arrest.

Respiratory muscle failure is often the underlying reason that a patient requires institution or continuation of mechanical ventilation. Failure occurs when the work of breathing increases beyond the endurance capacity of the respiratory muscles. Recent attention has been focused on respiratory muscle fatigue and its detection. Cohen et al. described the visual manifestations of inspiratory muscle fatigue, which included the following: (a) tachypnea; (b) a decline in tidal volume; (c) respiratory alternans (a cyclical alteration between predominantly rib cage and abdominal breathing); and (d) abdominal paradox (which is an inward displacement of the abdomen during inspiration because of a weakened or paralyzed diaphragm). These patterns were correlated to electromyographic (EMG) evidence of developing diaphragmatic failure. However, clinical signs are very subjective, and confident recognition of these abnormalities may be surprisingly difficult even to the trained observer. Intermittent laboratory evidence of fatigue, such as hypercarbia, are helpful but can delay appropriate treatment because they are not continuously available. Respiratory muscle fatigue can be predicted using diaphragmatic EMG and detected by measurement of the pressure gradient across the diaphragm (Pwab). Unfortunately, these techniques require technical expertise, are cumbersome for use in the intensive care unit, and may not be sensitive in detecting respiratory failure.

Tobin et al. recently showed that the breathing pattern, as monitored by respiratory inductive plethysmography (RIP), was significantly altered in patients who failed to wean from mechanical ventilation. Specifically, respiratory rates were higher, tidal volumes were lower, and mean inspiratory flows increased in patients who failed weaning as compared with their control groups. Therefore, we hypothesized that continuous noninvasive monitoring of the breathing pattern by RIP, especially thoracoabdominal motion, may aid in the detection of respiratory failure in patients being weaned or recently extubated from mechanical ventilation.

**Materials and Methods**

**Patients**

Forty-four subjects admitted to the surgical or medical intensive care units (ICU) between November 1985 and May 1986 were clinically monitored before and after extubation using continuous RIP. All had been mechanically ventilated for at least two days before meeting the attending physicians' subjective and objective criteria to begin weaning. Seven of these patients clinically deteriorated while intubated but breathing spontaneously on an intermittent mandatory ventilation rate of zero (MV = 0) and no added positive pressure. Seven others required reintubation during the first 48 hours after extubation. The decision to reintroduce mechanical ventilatory support was made by the house staff or attending physicians, or both, in conjunction with the nursing and respiratory therapy staff. It was based on clinical criteria or arterial blood gas values, or both, and not on the data recorded by RIP. Although the data from RIP was available to the clinicians, this study was completed prior to any formal training on breathing pattern analysis and prior to any analysis of the data. At the time of the study, neither guidelines nor normal values had been established for continuous respiratory monitoring. Therefore, neither the house staff nor nursing staff utilized RIP data in any systematic manner. For these reasons, the decision to reintroduce mechanical ventilatory support was not believed to be significantly influenced by RIP. The remaining 30 patients were all successfully extubated and served as a control group.

**Respiratory Inductive Plethysmography**

The breathing pattern of these patients was continually monitored.

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of >75 percent over three to four breaths. In addition, abdominal paradox by definition would be a sustained %RC that was >100 percent, whereas rib cage paradox (such as in upper airway obstruction) would have a %RC value that was continuously negative.

**Weaning Parameters**

All patients routinely underwent measurement of weaning parameters and arterial blood gases prior to their weaning trials or extubations. Spontaneous tidal volume (Vt), vital capacity (VC) and minute ventilation (Ve) were measured using a hand-held respirometer (Boehringer, Wynnewood, PA). A maximal negative inspiratory pressure (MIP) was measured with an Inspiratory Force Meter (Boehringer) following the suggested method of Marini et al.15

**Inspiratory Effort Quotient**

The inspiratory effort quotient (IEQ), as elucidated by Milic-Emili,20 helps to define a “fatiguing threshold” (0.15-0.20) above which respiratory muscle fatigue is thought to occur.21 It is calculated using the equation IEQ = (k VT/CDYN) × (VT/TVT) = MIP, where CDYN is dynamic compliance and where k is estimated to equal 0.75 in ICU patients.21 The IEQ was calculated for the failure group at baseline and when the patients failed using the VT and TVT recorded by RIP, CDYN as measured by the method of Bone,21 and the MIP which was obtained with the weaning parameters. In five of the 14 patients, the MIP had been obtained longer than eight hours prior to their decompensation and they were eliminated from the IEQ analysis; in the remaining nine patients, the IEQ was calculated on the assumption that their MIP and CDYN had not changed significantly.

**Arterial Blood Gas Analysis**

Arterial blood gas analysis was performed anaerobically (IL1301, Instrumentation Laboratory, Inc, Lexington, MA) on nine of the 14 failure patients prior to reinstitution of mechanical ventilation.

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**Figure 1.** Respiratory inductive plethysmograph tracing showing rib cage (RC) and abdominal (AB) waveforms. The electrical sum of RC plus AB equals tidal volume (Vt, bottom tracing). VT is divided into its timing components: inspiratory time (Ti), expiratory time (Te) and total (T). In addition, end-expiratory thoracic gas volume level is depicted; changes in this level represent changes in functional residual capacity (such as intrinsic positive end expiratory pressure). The shaded areas represent the integrals under each waveform during inspiration (tough to peak). The integrals under the RC plus AB waveforms, irrespective of sign (positive or negative) equal TCD (total compartmental displacement). When RC and AB are in perfect synchrony (as depicted here), the TCD will equal VT and the TCD/VT equals 1.00.

Using a computer-assisted respiratory inductive plethysmograph that automatically calibrated and displayed data over a ten-minute period (Respirgraph, Noninvasive Monitoring Systems, Inc., Miami Beach, FL). The RIP was calibrated using a natural breathing, single-breath method based on isovolume equation principles, which retains accuracy to within 20 percent of spirometry despite changes in position, breathing pattern, or end-expiratory thoracic gas volume.14,15 This range of accuracy is important, since our patients' positions could not be constant throughout the 48 hours of monitoring. All parameters were averaged over ten-minute epochs and were recorded by a modified line printer (Hewlett Packard, Thinkjet). The parameters included respiratory rate (i), tidal volume (VT-% change from calibration period), minute ventilation (VT-% change from calibration period), mean inspiratory flow (VT/VT-% change from calibration period), percent of rib cage (RC) contribution to the tidal volume (%RC), inspiratory duty cycle (Ti/TToT) and total compartmental displacement (TCD/VT (TCD/VT)). A five-minute period of spontaneous breathing during calibration enabled comparison of subsequent values of VT, VT/Ti, and VT (as % change from calibration period) whereas i, TCD/VT, Ti/TToT, and %RC were compared by absolute changes.15

The total compartmental displacement is the sum of the areas under the rib cage and abdominal signals during inspiration irrespective of algebraic sign (Fig 1). It does not depend on absolute values for VT. The TCD/VT is derived by dividing the TCD by the area under the inspiratory sum (VT) waveform. When the rib cage and abdominal signals are in perfect synchrony, the TCD/VT = 1.00. Either rib cage or abdominal paradox will cause the absolute sum of the TCD to increase out of proportion to the tidal volume and the TCD/VT will be greater than unity (Fig 2). In addition, any timing or phase delay between the rib cage and abdominal compartments will also increase the TCD/VT, as seen in patients with chronic obstructive pulmonary disease using an analogous measurement.17

The percentage that the rib cage contributed to the tidal volume (%RC(VT)) was continuously displayed by RIP on a breath-by-breath plot and denoted as %RC. Therefore, respiratory alternans could be discriminated as a cyclical and repetitive variation in the %RC.

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**Figure 2.** Respiratory inductive plethysmograph analogue tracing from a patient with partial upper airway obstruction showing RC (rib cage) paradox (i.e., inward movement of the RC during inspiration [inspir]). Because the RC and AB (abdominal) waveforms are opposite in directions, the absolute sum of their integrals during inspiration (i.e., the TCD [total compartmental displacement], shaded area) is much larger than the electrical sum (tidal volume [VT]) integral. Thus, the TCD/VT is much greater than unity (1.89). Expir, expiration.
RESULTS

Patient Population

The population who developed respiratory failure consisted of ten men and four women with an average age of 78 ± 3 years (range, 57 to 86 years) who had been mechanically ventilated for 7.1 ± 1.8 days. Diagnosis included cardiogenic pulmonary edema (n = 5), status post (S/P) abdominal or thoracic surgery (n = 3), chronic obstructive pulmonary disease (n = 2), and aspiration pneumonia (n = 4). Seven patients were intubated at the time of their decompenation, while seven had been extubated. Respiratory failure developed 19.4 ± 5.2 h (range, 1.5-48 h) after weaning had begun or extubation had occurred. None of the patients required any further resuscitation beyond reinitiating mechanical ventilatory support. The control group contained 11 women and 19 men whose ages ranged from 35 to 94 years (76 ± 2 years) who had been mechanically ventilated for 5.5 ± 1.0 days. Diagnosis included cardiogenic pulmonary edema (n = 14), S/P abdominal or thoracic surgery (n = 9), chronic obstructive pulmonary disease (n = 5), stroke (n = 1), and drug overdose (n = 1). All patients had acceptable weaning parameters which were similar (Table 1) except for a lower mean Ve in the failure group. These parameters were measured prior to the weaning trial by a handheld respirometer (not by RIP).

Respiratory Rate

The respiratory rate increased significantly (p<0.001) in the intubated and extubated failure patients during the one hour preceding reinitiation of mechanical ventilation (Table 2). No significant changes occurred in the control groups, nor were the initial periods different between any of the groups. However, respiratory rates during the failure periods were significantly higher (p<0.002) when compared to their respective control groups (Table 2).
values (p<0.001) (Fig 3) as well as when compared with their respective intubated and extubated controls (p<0.001; Table 2).

Respiratory Alternans

Eleven of the 14 patients demonstrated respiratory alternans as documented on the compressed plot of the RIP breathing pattern (Fig 4). Clinically, however, this was much more difficult to detect because the alteration between the rib cage compartment and the abdominal compartment often occurred over a series of breaths and therefore was not readily appreciated by the observers. Clinically discernible abdominal paradox occurred in one patient who also had the highest PaCO₂ recorded (80 mm Hg). His RIP tracings showed a five-minute period of respiratory alternans followed by five minutes during which his %RC was continuously greater than 100 percent.

Tidal Volume and Minute Ventilation

Tidal volume decreased by 8±13 percent in the failure patients (p>0.1). Seven of the 14 showed decreases in V̇₁ (−10 to −139 percent), while seven showed no change or increases (0 to 77 percent). Minute ventilation increased (31±20 percent), but not significantly (p<0.1). The V̇₁ in five patients decreased (−6 to −119 percent) while nine had increases in V̇₁ (20 to 202 percent).

Arterial Blood Gases

The PaCO₂ was 55.8±5.8 mm Hg prior to reinstating mechanical ventilation in the nine patients in which it was measured. In seven of these nine patients, the PaCO₂ was greater than 48 mm Hg. The change in PaCO₂ compared with baseline values (11.9±4.0 mm Hg) was significant (p<0.02). This hypercarbia developed despite an increase in V̇₁/TI (151±16 percent vs 214±32 percent; p>0.1).

![Figure 3](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21581/) Description: The ratio of total compartmental displacement (TCD) to tidal volume (V̇₁) is shown for each intubated (solid circles) and extubated (open circles) failure patient when mechanical ventilation was reinstituted (failure) and one hour prior. The TCD/V̇₁ rose in each subject. Vertical bar tacks represent the mean±SE for the seven intubated (with solid circles) and seven extubated (with open circles) patients, respectively; asterisk = <0.001 compared with value one hour prior to failure.

![Figure 4](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21581/) Description: Ten-minute compressed plots of respiratory inductive plethysmographic tracings in patient 12 when stable (top-7:58) and just prior to reintubation (bottom-8:14). Each vertical bar represents one V̇₁ (tidal volume). The dashed line above V̇₁ is the ratio of total compartmental displacement (TCD) to V̇₁. The dashed line below V̇₁ is the %RC (ie, the percentage that the rib cage (RC) contributed to each individual V̇₁). Compared with the stable period (top plot), the bottom plot shows an increase in TCD/V̇₁, a decrease in V̇₁ and V̇₁/VMIN (V̇₁ or minute ventilation), no significant change in respiratory rate (f) and a cyclical variation over a period of a few breaths in the %RC from +150% to −50 percent, indicating respiratory alternans.
Figure 5. Inspiratory effort quotient for nine failure patients when they developed respiratory failure (failure) and one hour prior. Dashed line indicates the fatiguing threshold for respiratory muscles. None of these patients was in the fatiguing range one hour prior to failing, whereas six equalled or surpassed the threshold when they required reinstitution of mechanical ventilation. Asterisk = p < 0.02 for mean ± SE (hartack with solid circle) compared with one hour prior to failure.

Inspiratory Effort Quotients

Inspiratory effort quotients were computed in nine of 14 respiratory failure patients. Only five of these nine had ABGs available and therefore no comparisons between ABGs and IEQ were done. None of the IEQ were initially greater than the “fatiguing threshold” (0.15 to 0.20), whereas six of nine patients’ IEQ were equal to or greater than 0.15 when respiratory failure developed (Fig 5). These latter IEQ calculations were based on the assumption that neither MIP nor Cdyn had significantly changed. If either or both had decreased during the failure period (which may have occurred considering that respiratory failure ensued), then the IEQ would be underestimated by our calculations. Significant intrinsic positive end expiratory pressure (PEEP), which is detectable on RIP tracings by an increase in end-expiratory thoracic gas volume (Fig 1) and which would have required modification of the IEQ,19 was not seen in our patients.

Predictive Power of Parameters

An increase in f >11 breaths/min occurred in eight of 14 of the failure periods and in four of 60 control periods (diagnostic accuracy = 56 percent, Table 3). Respiratory alternans was present in 11 of 14 of the failures and in five of the control periods (diagnostic accuracy = 80 percent). An elevation of TCD/Vt >0.22 also occurred in 11 of 14 failure tracings, but in only three control periods (diagnostic accuracy = 92 percent). No more than one of these changes was present in any single control, whereas at least two were present in 13 of 14 failure periods (post hoc analyses). Therefore, the presence of 2/3 abnormal parameters (increase in f >11, increase in TCD/Vt >0.22, and/or respiratory alternans) occurring over one hour had a diagnostic accuracy approaching 99 percent in these 44 patients (74 periods).

Discussion

Inability to be successfully weaned from mechanical ventilatory support, as well as the need to institute or reinstitute such support, often is due to the inability of the patient’s respiratory muscles to keep pace with ventilatory demands.1,3 Therefore, the decision to discontinue mechanical ventilation is usually preceded by a clinical trial of spontaneous breathing while the patient remains intubated.1,4 This “endurance evaluation” can be as short as a few minutes in the postoperative state to as long as 24 hours in long-term ventilator-dependent individuals. Intermittent, informal breathing pattern analysis (ie, recording of f, estimation of the Vt) is usually coupled with intermittent laboratory tests (ABG, MIP, spirometry) during the periods immediately preceding and following extubation. Unfortunately, the clinician’s estimation of breathing pattern cannot be continuous and is often in error.7,8

Recently, Tobin et al11,25 reported that formal breath-
ing analysis was helpful in monitoring for respiratory failure. Although the present study has certain similarities to that of Tobin et al, the patients and protocols were distinctly different. First, the present study involves twice as many failure patients. Second, the patients who failed in our study could not be distinguished from their controls on the basis of age, days of mechanical support, or weaning parameters. This differs from the failure patients in studies of Tobin et al who were older (69 ± 4 vs 41 ± 5 years), had been maintained on mechanical support longer (42 ± 12 vs 3 ± 1 days), and had worse MIP values (−26 ± 1 vs −43 ± 4 cm H₂O) than those successfully weaned controls. It is, therefore, not surprising that the patients in studies of Tobin et al failed weaning much more quickly (0.7 ± 0.5 h) than those who failed in the present study (19.4 ± 5.2 h). Because patients of Tobin et al uniformly failed within 100 min of their trials, their total failure period was analyzed. In our study, the wide range of time prior to having to reinstitute mechanical ventilation (1.5 to 48 h) required analysis to be confined to the hour preceding reinstitution of support in order to maintain uniformity. Despite these differences, our study supports the concept of Tobin et al of using breathing pattern analysis in monitoring patients for weaning failure.

In our study, analysis of the breathing patterns in the 14 patients who developed respiratory failure showed significant findings: (a) an increase in f; (b) rib cage-abdominal asynchrony (increased TCD/Vt); (c) respiratory alternans; and (d) no significant fall in central respiratory drive (Vt/Ti) despite hypercarbia. We recently reported that the coefficient of variation for f in 50 intubated but stable patients over one hour was 26 percent. Therefore, the increases seen in the 14 patients who developed respiratory failure in the present study were both clinically and statistically significant (Table 2). This finding is in agreement with Tobin et al who reported a mean increase of 11.4 in the respiratory rates of seven patients who required institution of mechanical ventilation. Similarly, Cohen et al noted that tachypnea was common in patients who developed EMG evidence of developing diaphragmatic fatigue during an unsuccessful attempt at discontinuing ventilatory support. Just prior to reinstituting mechanical ventilation in the study by Cohen et al, the respiratory rate slowed. Therefore, tachypnea may not be detected in the latter stages of respiratory failure even though it may have been present earlier. This may explain why the respiratory rate increased in only eight of 14 failure epochs in the present study.

The TCD/Vt is an objective quantification of thoracoabdominal coordination. An increase in this parameter indicates rib cage-abdominal asynchrony, resulting in an inefficient breathing pattern (Fig 2). Gilbert et al described asynchronous breathing in six of ten patients who required intubation secondary to exacerbation of chronic obstructive pulmonary disease (COPD). This abnormal breathing pattern was present in only five of 25 similarly afflicted patients with COPD who recovered without being placed on mechanical ventilation. In our study, all the unsuccessfully weaned or reintubated patients had an increase in their TCD/Vt measurements (Fig 3). In 11 of 14 (79 percent), the increase was greater than 0.22 whereas this degree of elevation was seen in only three of the 60 (5 percent) control intubation and extubation periods. Tobin et al also found that patients who failed weaning had objective evidence of thoracoabdominal asynchrony. However, their parameters did not significantly change during unsuccessful weaning trials, perhaps because the thoracoabdominal coordination measurements were significantly abnormal at the commencement of the weaning period. Asynchronous breathing is believed to cause a marked increase in the work of breathing and, therefore, in carbon dioxide production (VCO₂). An increase in VCO₂ may have been the cause of hypercapnia in the nine patients who had documentation by ABG, since (a) central respiratory drive as estimated by mean inspiratory flow increased (48 ± 37 percent) and (b) the minute ventilation in these patients did not consistently decrease (1 ± 19 percent change from one hour prior to failure). However, since neither VCO₂ nor dead space ventilation was measured in this study, we cannot be certain.

The extreme of asynchronous breathing is abdominal paradox. This was clinically seen in only one of our patients; interestingly, he also had the highest PaCO₂ (80 mm Hg) and TCD/Vt (3.69). Respiratory alternans was present in 11 of the 14 (79 percent) failures (Table 2), but in none of the controls. This was documented on the RIP printout (Fig 4) but was often difficult to appreciate on examination because (a) the alteration between the rib cage and abdominal compartments occurred intermittently over a series of breaths; (b) the patients were often in a sitting position, thus obscuring accurate clinical assessment of rib cage-abdominal interaction; and (c) rib cage and abdominal movement occurred in three dimensions which is difficult to appreciate by most observers.

Tobin et al questioned whether respiratory alternans occurred in their patients who failed weaning attempts. They analyzed the breath-to-breath variability of %RC over one-minute epochs and failed to show a bimodal distribution. The definition of respiratory alternans in the present study was based on continuous ten-minute displays of %RC (Fig 4) and not on variability analysis which may account for the difference between our results and the conclusions of Tobin.
Roussos\(^4\) has suggested that rib-cage abdominal "discoordination" is a sign of developing respiratory muscle fatigue which is adapted as a protective mechanism against exhaustion. The present findings are consistent with this concept in that increases in TCD\(V_t\), which occurred in all patients who failed (Fig 3), were detected prior to the onset of respiratory alternans.

Respiratory muscle fatigue is objectively measured using diaphragmatic EMG power spectrum shifts or P\(_{\text{di}}\).\(^5\) Cohen et al\(^6\) and Roussos\(^3\) suggested that muscle fatigue underlay the inability of their patients to wean successfully. The data using P\(_{\text{di}}\) measurements during unsuccessful weaning attempts is more controversial. Although changes in P\(_{\text{di}}\) alone failed to explain the hypercarbia which developed in a small heterogenous group of patients who required reinstitution of mechanical ventilatory support,\(^10\) the ratio of P\(_{\text{di}}\) to maximum transdiaphragmatic pressure (obtained during a Mueller maneuver) appeared to be more predictive in another group of patients with COPD.\(^28\) Milic-Emili\(^9\) suggested that the IEQ, by incorporating the main factors which promote respiratory muscle fatigue, may help to predict unsuccessful weaning outcomes. None of the IEQ in our patients who failed had elevated values prior to failure; however, six of nine had increases greater than the fatiguing threshold within one hour (Fig 5). This suggests that relative inspiratory muscle fatigue developed over time, especially when viewed in association with asynchronous rib cage-abdominal efforts (increase in TCD\(V_t\)), which occurred to some degree in every patient in the failure group (Fig 3). The actual causes of respiratory failure were not investigated but also could have included a worsening of pulmonary mechanics, increasing metabolic demands and/or muscle weakness.\(^3\)

Accurate predictors of respiratory failure exist for only a few diseases. Although standard weaning criteria\(^13,14\) are usually helpful, they are unfortunately neither 100 percent sensitive nor specific. Neuromuscular drive as measured by airway occlusion pressure (P\(_{\text{ao}}\)) has recently been shown to have some predictive value in patients with COPD,\(^29\) whereas diaphragmatic strength as assessed by transdiaphragmatic pressure (P\(_{\text{d}}\)) was not helpful.\(^10,28\) In our study, none of the weaning parameters nor initial breathing patterns was predictive of failure or success (Table 1). However, trend monitoring using RIP has been helpful.\(^11\) Indeed, in our patient population, we found that the combination of two out of three criteria derived from monitoring with RIP for one hour (increase in respiratory rate >11, increase in TCD\(V_t\) >0.22, and/or respiratory alternans) had a diagnostic accuracy of 99 percent in rapidly and noninvasively assessing respiratory failure (Table 3). Although future studies will be necessary to corroborate and expand these findings, it is apparent that continuous breathing pattern analysis has opened up a new and pragmatic approach to monitoring the critically ill pulmonary patient.\(^19\)

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Courses in Diagnostic Ultrasound and in Doppler Echocardiography

Wake Forest University, Bowman Gray School of Medicine, Center for Medical Ultrasound, will offer courses in Diagnostic Ultrasound: Echocardiography in Winston-Salem, October 24-28, February 6-10, 1989, and May 15-19, 1989. They will also present the Fifth Annual Doppler Echocardiography Seminar, September 8-10, 1988. For information contact Ms. Jo Patterson, Program Coordinator, Center for Medical Ultrasound, 300 South Hawthorne Road, Winston-Salem 27103 (919:748-4505).

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