WHITE PAPER

Respiratory Rate Measurement in Respironics CO_2 Sensors

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ABSTRACT

Respiratory rate measurement in Respironics CO_2 sensors consists of a robust breath detection algorithm with an adaptive threshold criteria followed by a selectable screening/validation algorithm. This screening algorithm termed the ReNÉ algorithm uses waveform morphology including the area under portions of the waveform to exclude breaths which are unlikely to be "real" breaths. These two algorithms have been developed over a twenty year period and are in use in hundreds of thousands of systems worldwide.

INTRODUCTION

The clinical utility of time-based capnography, end-tidal CO_2 monitoring, and volumetric capnography have found widespread adoption in the last few years. Time-based capnography has either been mandated or strongly recommended for patient monitoring during general anesthesia, conscious sedation, resuscitation, intubation, weaning, transport and a variety of other procedures. The reliability of capnographic measurements depends upon the environment and the robustness of respiratory rate and end-tidal measurement algorithms. The goal of a robust CO_2-based respiratory rate algorithm should be to achieve performance as near as possible to airway flow, the "gold" standard for respiratory rate, while at the same time interpreting the value in the context of the end-tidal CO_2 value. (1)

In the mechanically ventilated intubated subject (Figure 1), the patterns for both CO_2 and flow are generally consistent breath to breath depending upon the mode of ventilation. Most breath detection/ respiratory rate measurement algorithms can perform well with such waveforms. However, even with mechanical ventilation, challenging capnographic waveforms are often associated with modes of ventilation permitting spontaneous breathing.

In the non-intubated subject (Figure 2), the respiratory rate is interpreted as a reflection of respiratory drive and its measurement is generally more susceptible to either equipment or patient associated artifact. The increasing use of capnometry to monitor respiration in non-intubated, spontaneously breathing patients receiving procedural sedation or patient controlled analgesia has raised the bar for accuracy of breath detection/ respiratory rate measurement algorithms. Accurate measurement during these procedures (and in the non-intubated patient in general) is important because low respiratory rate and hypoventilation could be a precursor to cessation of ventilation and its associated sequelae. During these procedures accurate respiratory rate measurement is more prone to false breath detection or missed breaths for reasons including irregular breathing patterns, "feeble" respiratory efforts (Figure 2), cardiogenic oscillations (2), movement of the patient and/or patient interface, other patient associated artifact (e.g. coughing, talking) and difficulties in acquiring an adequate alveolar gas sample.

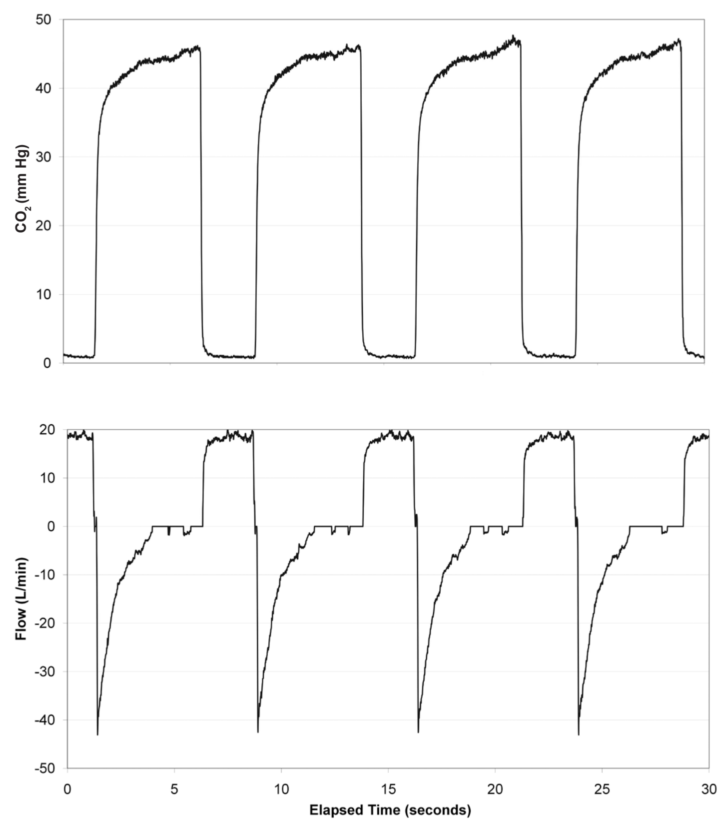

Figure 1 - CO_2 and flow curves for subject receiving volume-controlled mechanical ventilation

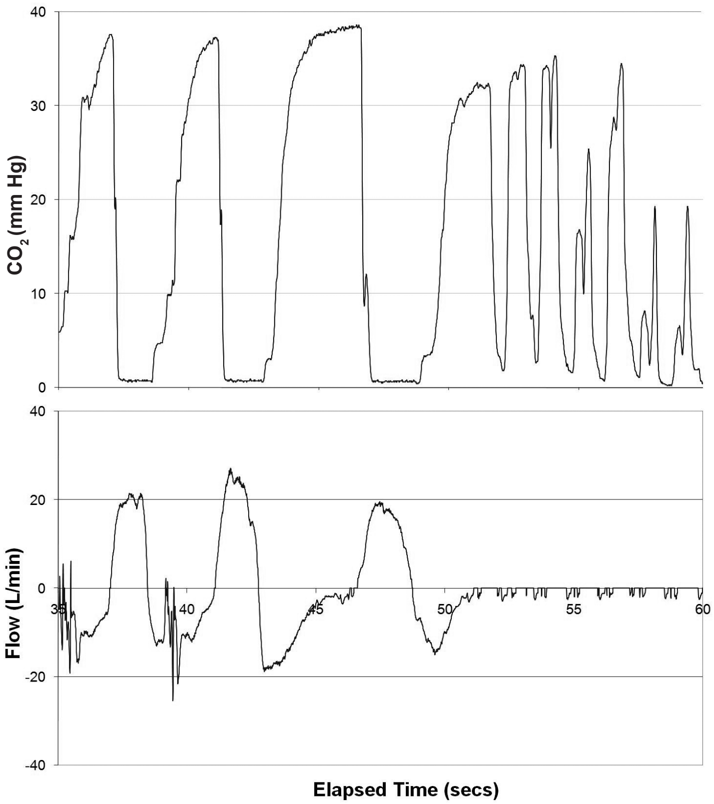

Figure 2 - CO_2 and flow curves for subject during procedural sedation illustrating an "apneic" interval with feeble respiratory efforts between 52 and 63 seconds.

ADAPTIVE BREATH DETECTION (ABD) ALGORITHM

Overview

The adaptive breath detection algorithm used in Respironics capnometers does not depend upon certain assumptions about the nature of the CO_2 waveform often made in other algorithms. For example, there is no requirement that the CO_2 return to zero or near zero during the inspiratory phase. The only assumptions are concerned with minimum time periods for each respiratory phase.

To improve the quality of reported values, the CO_2 waveform samples are passed through a smoothing filter to reduce spurious noise artifact. End-tidal CO_2 and inspired CO_2 values are determined from this filtered waveform. End-tidal CO_2 ($PETCO_2$) is calculated as the peak value of the smoothed CO_2 waveform of each detected breath. $PETCO_2$ values are saved as breath by breath, 10 second and 20 second maximum values. Inspired CO_2 is calculated as the minimum value of the smoothed CO_2 waveform of each detected breath. Inspired CO_2 are saved as breath by breath, 4 breath and 20 second averages.

Respiration rate is measured as the period from detected leading edge of the CO_2 waveform to next leading edge, and is calculated breath to breath as well as averaged over 8 breaths.

ABD Algorithm

Thresholds are derived dynamically from the minimum and maximum excursions of the CO_2 waveform with rules including a minimum duration for an excursion. Two adaptive thresholds, the leading edge and trailing edge thresholds, are used. A valid breath is defined as when the leading edge threshold is exceeded followed by when the trailing edge is crossed. Note in Figure 3, the crossing of the leading and trailing thresholds are indicated for a subject receiving mechanical ventilation with easily identifiable waveforms and a subject receiving procedural sedation with an erratic breathing pattern.

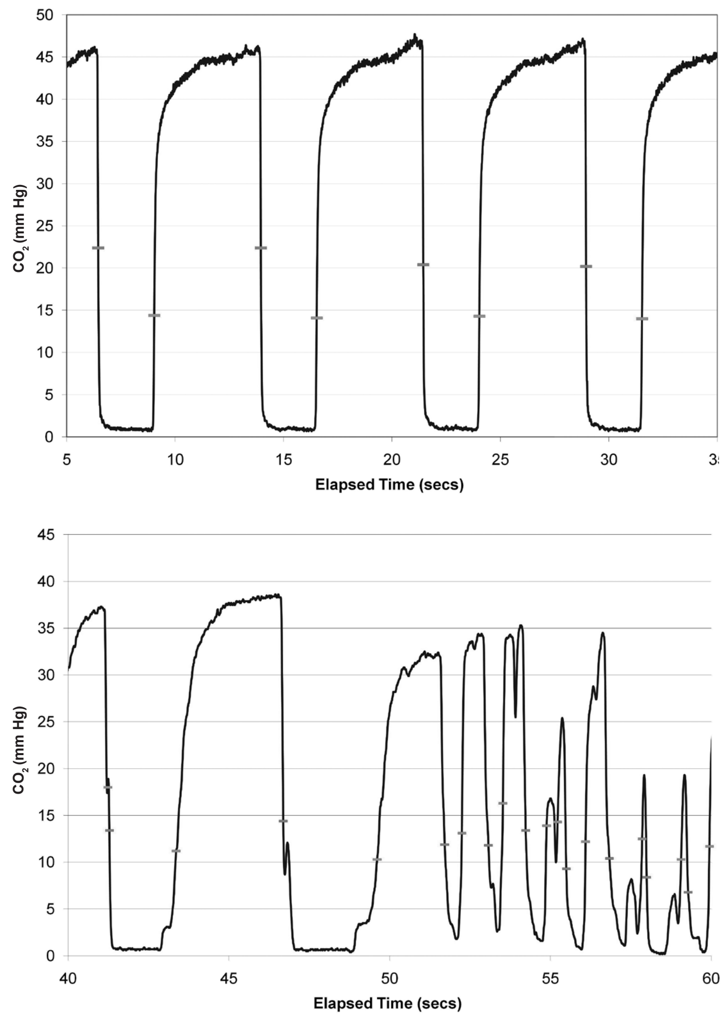

Figure 3 - Illustration of threshold crossings with CO_2 curve for (a) subject receiving mechanical ventilation and (b) subject during procedural sedation.

RENÉ ADAPTIVE RESPIRATORY RATE FILTERING ALGORITHM

Overview

Fluctuations in the level of CO_2 sometimes occur when very small volumes of air move past an on-airway CO_2 sensor, or when very small amounts of air enter and exit the nares when using a nasal cannula, (see Figure 3). These fluctuations often represent volumes of air too small to clear the anatomic deadspace, and therefore may not represent actual respiratory efforts. The ReNÉ adaptive respiratory rate filtering algorithm rejects these small CO_2 fluctuations that may be qualified as a breath by the adaptive breath detection algorithm, but are considered less likely to be actual breaths given attributes of their morphology. The ReNÉ algorithm "qualifies" previously "detected" breaths and is not an adaptive averaging algorithm which increases or decreases the averaging interval based upon variability of the breath-to-breath interval (3). Such an adaptive averaging approach will tend to miss "apneic" intervals.

The ReNÉ algorithm, integrated with the ABD algorithm, includes waveform morphology such as area and time criteria for breath qualification. For example, the ReNÉ algorithm includes a running average of the areas of qualified breaths bounded by the capnogram and a dynamic threshold which is compared to the area of the current "accepted" breath. If this area exceeds the predetermined fraction of running average area and meets other time and morphologic criteria then the breath is accepted, otherwise it is rejected (Figure 4).

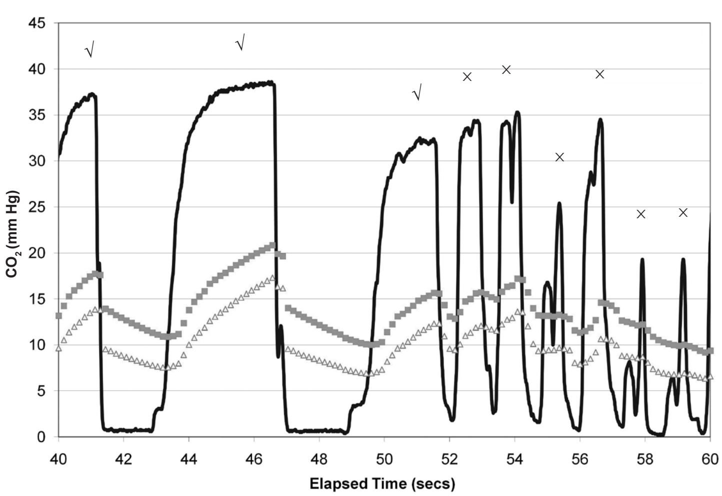

Figure 4 - (√ = Accepted breath; X = Rejected breath)
(■ = LET, leading edge threshold)
(Δ = TET, trailing edge threshold)

Clinical Testing

The accuracy of the ABD and ReNÉ algorithms was assessed using capnograms and flow waveforms collected from adult volunteers who were administered a combination of target controlled infusions of a sedative hypnotic and a short acting opioid.(4) These algorithms were compared to a traditional threshold approach using a pneumotach-based gold standard for breath rate. Note that the pneumtach based flow measurements of smaller gas movements (i.e tidal volumes < 200 ml) were not considered to clear the airway dead space and as such were not counted as breaths. For 24 subjects studied, the ReNÉ algorithm's detected average breath rate bias was 0.97 bpm (SD ±2.92 bpm) relative to the gold standard versus 3 bpm (SD ±4.7 bpm) for the traditional threshold approach. Compared to a traditional threshold technique, the ReNÉ algorithm reduced average error by 68% and S.D. of the error by 38% (4).

REFERENCE

(1) Folke M, Cernerud L, Ekström M, Hök B. Critical review of non-invasive respiratory monitoring in medical care. Med Biol Eng Comput. 2003; 41:377-83.

(2) Smith, T.C., Green, A. Hutton, P. Recognition of cardiogenic artifact in pediatric capnograms. J. Clin. Monit., 1994; 10: 270–275.

(3) Colman J, Cohen J, Lain D. Smart Alarm Respiratory Analysis (SARA™) Used in Capnography to Reduce Alarms During Spontaneous Breathing. Anesth Analg, 2008; 106; S-1–S-39.

(4) Orr JA., Brewer LM, Westenskow DR, Johnson KB. Evaluation of breath rate measurement by capnometry in non-intubated sedated volunteers, Anesthesiology, ASA 2009 meeting, A1292.