Association between Capnogram and Respiratory Flow Rate Waveforms during Invasive Mechanical Ventilation

C. C. Rasera and P. M. Gewehr

Abstract—Capnography refers to the continuous and noninvasive measurement of carbon dioxide (CO₂) concentration in respiratory gases and it provides a real-time assessment of ventilatory status. The aim of this paper is to demarcate the inspiratory and expiratory segments of a time capnogram using data from respiratory flow rate waveforms. The measurements were obtained from 38 infants under mechanical ventilation in intensive care unit. A comparison was made between CO₂ and respiratory flow waveforms to determine the inspiratory segment (phase 0) and the expiratory segment and its subdivisions (phases I, II, and III). The coefficients of determination were 0.83 (p < 0.001) for end-tidal CO₂ pressure and inspiratory flow during rebreathing; and 0.97 (p < 0.001) during the weaning process. The end of expiration almost coincides with the downslope of the CO₂ waveform in the capnograms when there is no rebreathing, during the weaning process. However, in the presence of rebreathing, the alveolar plateau is prolonged and includes a part of inspiration, in addition to the expiratory alveolar plateau.

Index Terms—Capnogram, invasive mechanical ventilation, monitoring device, respiratory flow rate.

I. INTRODUCTION

Capnography refers to the continuous and noninvasive measurement of carbon dioxide (CO₂) concentration in respiratory gases, which is often by infrared made spectrometric analysis during the respiratory cycle. All capnographs provide a single value for CO₂, usually from end-expiration to end-inspiration, designated end-tidal CO₂ pressure (PetCO₂) and a continuous plot of expired CO₂ levels over time, producing a capnogram [1], [2].

The information provided by the capnography, as PetCO₂ and the waveform capnogram can be used as a tool to pulmonary problem diagnoses and respiratory monitoring during the time that the patient remains in invasive mechanical ventilation (IMV) [3], [4]. The device can also be used to monitor patients in emergency response situations, during anesthesia procedure and pediatric intensive care unit [5].

The capnogram shows breath-to-breath CO₂ elimination curves, and it allows visual inspection of changes in CO₂ concentrations by means of a waveform on the screen, paper recording, or even digitized measurements [2]. In addition, the capnography provides a real-time assessment of ventilatory status [6].

The usual representation of capnograms that is commonly used in clinical practice is CO₂ concentration displayed against time during inspiration and expiration, with PetCO₂ on the Y-axis and time on the X-axis. The shape of the capnogram usually has four phases and two angles (Fig. 1) [1], [7].

The normal adult capnogram has an almost square wave pattern (Fig. 1), marked by alternating inspiratory (phase 0) and expiratory phases. Expiration itself consists of three successive phases: (I) a latency phase, corresponding to the expiration of the anatomical dead space, thus the CO₂ concentration equals zero, because the dead space is void of CO₂; (II) slope phase, marked by an increase abruptly of CO₂ concentration, corresponding to expiration of mixed air; and (III) plateau phase, reflecting the elimination of alveolar air resulting in a peak at the end of tidal expiration (PetCO₂ close to alveolar carbon dioxide tensions) [2], [8].

![Fig. 1. Example of a normal capnogram with the inspiratory (phase 0) and expiratory phases (I, II, and III), α and β angles and end-tidal carbon dioxide pressure (PetCO₂).](image)

These three phases are separated by two well-defined transitions: α and β angles [3]. In normal conditions, the alpha angle is approximately 110°, this angle can increase in certain situations (e.g., in patients with altered ventilation-perfusion). The second angle in the capnogram (beta) occurs between phase III and the beginning of the inspiration. In normal conditions, the beta angle is nearly 90 degrees; however, it can increase in situations where CO₂ is reinhaled [1], [9].

Partial reinhalation of previously exhaled CO₂ may impair the efficacy of mechanical ventilation in improving CO₂ removal and unloading ventilatory muscles. At constant alveolar ventilation, any CO₂ concentration above zero in inhaled gases causes an increase of arterial CO₂ tension by an equal amount. Accordingly, significant CO₂ rebreathing increases alveolar ventilation requirements to maintain desired arterial CO₂ tension. This can limit the beneficial effects of inspiratory assistance provided by IMV [10].
According to Thomas et al. [7] the review of the capnograph waveform may help the physician in diagnosis and establishing response to treatment in patients with respiratory alteration and other conditions. In addition, to being able to recognize the normal shape of the capnogram, physicians need to be familiar with the most common abnormal shapes that can occur and with the capnogram segments [1].

Thus, the aim of this paper is to demonstrate the advantage of demarcating the inspiratory and expiratory segments of a time capnogram using the data from expiratory and inspiratory flow rate waveforms. In addition, delineating various components of a time capnogram would allow us to better understand the components of normal and pathological waveforms.

II. MATERIAL AND METHODS

This study was approved by the ethics committee of Pequeno Príncipe Hospital, Curitiba, Brazil. The research was carried out in the hospital’s cardiac critical care unit between September 2011 and January 2012. Informed consent was obtained from the parents or the caregivers responsible for the patients.

A total of 38 infants were evaluated from 2 days to 3 months of age, both sexes during the post-operative period of cardiac surgery. The characteristics of the patients are presented in Table I. Patients who had sepsis, some respiratory complication (e.g. pneumonia and pleural effusion) or the children who progressed to death were excluded. Vital parameters and ventilator settings were continuously monitored.

The capnographic curves and respiratory flow rates were analyzed in two moments during the period that the patient remained in intensive care unit:

A) During the use of mechanical ventilation equipment, at the time that the physician suspected of rebreathing;
B) During weaning process, before extubation of IMV, in this stage the patient was in good clinical conditions.

### TABLE I: CHARACTERISTICS OF THE PATIENT.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Patient (n = 38)</th>
</tr>
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<tbody>
<tr>
<td>Age (month)</td>
<td>1.41 ± 0.6</td>
</tr>
<tr>
<td>Sex (male/female)</td>
<td>15/23</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>2.30 ± 1.6</td>
</tr>
<tr>
<td>Vital Parameters</td>
<td>Instant A</td>
</tr>
<tr>
<td>Cardiac Frequency</td>
<td>79.7 ± 3.5</td>
</tr>
<tr>
<td>Respiratory Frequency</td>
<td>27 ± 2.8</td>
</tr>
<tr>
<td>Body temperature (°C)</td>
<td>36.4 ± 1.2</td>
</tr>
<tr>
<td>Pulse Oxygen Saturation (%)</td>
<td>96.1 ± 1.7</td>
</tr>
</tbody>
</table>

Values are expressed as mean ± standard deviation or number of patients.

Patients undergoing IMV were ventilated by Inter 5 Ventilator (Intermed, São Paulo, Brazil), using limited pressure, time-cycled ventilators in either assist control mode or synchronous intermittent mandatory ventilation mode.

PetCO$_2$ and CO$_2$ waveforms were monitored using a sidestream capnography module (Fig. 2) (CO$_2$CGM OA1000, Ronseda, Shenzhen, China) placed between endotracheal tube and the circuit of ventilator through an airway adapter. The CO$_2$ monitoring began immediately after calibration performed according to the manufacturer’s recommendations.

The data of respiratory flow rates were obtained from GMX Slim graphic monitor (Intermed, SP, Brazil) which was coupled to the mechanical ventilation. The analysis was done through an adapter connected between the endotracheal tube and the ventilator circuit. The monitor data were saved through Wintracer Software (Version 3.3.5 Beta, Intermed, SP, Brazil) in a notebook.

In order to measure the deformation of capnogram related to time; some variations of waveform parameter were calculated; they were defined in relation to the beginning of expiration (T$_{0}$), i.e. from the start of phase II on the capnographic curve.

On each of the recordings, the beginning and the end of inspiration and expiration were identified on the flow rate waveforms. Perpendicular lines were drawn through these points to intercept CO$_2$ waveforms to determine the inspiratory and expiratory segments of each capnogram in the study.

In addition, two indices were measured indirectly:

- The α angle between the intermediate and the initial slopes;
- The β angle was defined by the prolongation of the line between the terminal slope (phase III) and the descending slope (phase 0).

For comparison and quantitative analysis of CO$_2$ waveforms in two moments of each patient, it was necessary to select good quality cycles according to criteria of amplitude, duration and, when possible, regularity of the curve [11].

In this study, we systematically eliminated the CO$_2$ cycles that did not meet the following criteria: 1) validity lasting between 1 and 4 seconds; 2) symmetry for at least 5 cycles; and 3) good regularity of expiratory phases.

The data recorded were analyzed statistically; the association between PetCO$_2$ and respiratory flow rate was analyzed using the Pearson product-moment correlation coefficient and simple linear regression. Statistical analysis was performed using MedCalc Statistical Software version 10.4.5 (Mariakerke, Belgium).

III. RESULTS

The waveform analysis was assessed during the use of IMV, at the time that the physician suspected of rebreathing. For the 38 measurements, PetCO$_2$ was 37.1 ± 1.28 mmHg
and inspiratory flow value was 7.51 ± 0.8 L/min. The correlation between flow rate and PetCO₂ measurements was \( r^2 = 0.8336 \) (p < 0.001) (Fig. 3 A).

During the weaning process, before extubation of IMV, the PetCO₂ mean value was 39.6 ± 1.35 mmHg, while the inspiratory flow value was 6.28 ± 0.9 L/min. The correlation between flow rate and PetCO₂ measurements was \( r^2 = 0.9744 \) (p < 0.001) throughout the study period (Fig. 3 B).

The mean period that the patients remained in IMV was 14 days, the minimum and maximum time of IMV were 11 and 19 days, respectively.

When capnogram angles were analyzed, the patients had a mean value of α angle of 115° ± 1.3° and β angle of 90.4° ± 1.8°, during weaning process. However, in capnograms recorded in patients with rebreathing the mean value for α and β angles were 117° ± 2.1° and 106.4° ± 3.23°, respectively, as shown by the shaded area beyond phase III with the β angle higher than 90° (Fig. 4).

Fig. 4 shows the respiratory flow rate waveform and capnogram recorded during prolonged invasive mechanical ventilation with \( ab = \) inspiration; \( ba = \) expiration; 0 = inspiration phase; I, II, and III = expiration phase.

IV. DISCUSSION

Capnography has become the standard of care for basic respiratory monitoring for all intubated patients in the intensive care unit, and PetCO₂ is commonly measured during mechanical ventilation of children in postoperative period [1]. The extension of this technique to intubated infants has been limited by technical problems associated with the capnographic indices [5], [12].

Despite the relatively simple technology behind capnography and the ease with which capnographic measurements are obtained, the interpretation of the results requires a profound knowledge of the physiological bases of CO₂ production, transport, and elimination [1].

Breen and Bradley [13] suggested in 1997 that CO₂ spirography (CO₂ concentrations versus inspired and expired volume during respiratory cycle) should be used to detect rebreathing. By integrating airway-measured flow and CO₂ pressure, they computed overall expired and inspired CO₂
volume during intermittent positive pressure ventilation in a circle anesthesia circuit. They concluded that CO₄
spirography (in contrast to time capnography) is required to
detect inspiratory valve incompetence during mechanical
ventilation. However, according to Shankar and Philip [14]
the method suggested by Breen and Bradley is complex and
may not be suitable for routine clinical use.

Otherwise, the comparison between respiratory flow rate
and CO₄ waveforms to determine inspiratory and expiratory
segments of the time capnogram can be easily analyzed in
infants patients with instruments available in intensive care
unit.

Graphic extrapolation from the respiratory flow waveform
to the time capnogram clearly demarcates the inspiratory
segment (phase 0) and the beginning of the expiratory
segment in the time capnogram. The end of expiration almost
coincides with the down slope of the CO₄ waveform, there is
no rebreathing or minimal rebreathing in clinically stable
patients during weaning process (β angle is approximately
90°). However, in capnograms recorded in patients with
suspected rebreathing, the diagnosis was confirmed, as
shown by the shaded area beyond phase III with the β angle
higher than 90° (Fig. 4).

The normal adult capnogram has an almost square wave
pattern, however in 2005 Thompson and Jaffe [3] described
the CO₄ waveform in neonatal and infants patients more
rounded than the adult waveform, in accordance with Fig. 4
found in our study.

According to Shankar and Philip [14] capnographs using
sidestream sensor technology may not allow comparison
between CO₂ waveforms and flow rate waveforms because of
the longer response time of sidestream CO₂ analyzers.
However, we have used a sidestream capnography and this
choice has not compromised the measurements and analyzes.

The analysis of CO₂ pressure through capnography during
prolonged mechanical ventilation of neonates is poorly
documented in the pediatric literature. The additional dead
space, mechanical problems, low weight, small flow and
respiratory pressure may limit the clinical value of
capnography with infants [3].

In order to reduce these limitations we have used the
sidestream capnograph that requires a small sample cell and,
therefore, a low flow rate (50 ml/min). For the neonate with
high respiratory rates and low tidal volumes, this rate of gas
avoids the dilution of alveolar CO₂. Thus, the device provides
precise measurements in newborns patients.

One of the limitations of this terminology is that it is
unknown precisely where in the time-capnogram, inspiration,
and expiration begin. It is generally assumed that inspiration
begins when the CO₂ concentration decreases abruptly at the
end of phase III caused by inhalation of CO₂-free gases [15].
However, this is not always true, as can be seen from our
observations. The alveolar plateau is prolonged during
rebreathing and the time capnograph cannot help us identify
the inspiratory prolongation of the alveolar plateau occurring
because of rebreathing of CO₂. Thus, during rebreathing, the
plateau may indeed include a part of inspiration (phase 0) in
addition to the expiratory alveolar plateau [14].

V. CONCLUSION

We have analyzed CO₂ concentration and respiratory flow
rates from our subjects and the comparison between these
two methods can determine inspiratory and expiratory
segments of the time capnogram.

We believe that incorporation of flow direction
information into sidestream capnography would allow a
more physiologically meaningful interpretation of time
capnograms. The present results could be a guideline for
clinicians in the physiological interpretation of the
capnogram and it could help clinicians to get accurate
respiratory information about the infant patient during the
rebreathing.

Demarcation of a time capnogram into inspiratory and
expiratory components using flow rates will not only
facilitate prompt detection of rebreathing, but will also allow
application of standardized and physiologically appropriate
nomenclature for better understanding and interpretation of
time capnograms.

In addition, the knowledge of alteration in the CO₄
waveform can help the health professionals to change the
mechanical ventilatory parameters in order to obtain a
capnographic wave closest to normal thereby improving the
lung function of patients.

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