Reference Values for Volumetric Capnography in Spontaneously Breathing Subjects

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Abstract

The aim of this study is to determine typical volumetric capnography parameters in spontaneously breathing subjects during repeated measurements. Capnography is a simple non-invasive technique for monitoring the CO_2 concentration in the exhaled breath. It is used to detect early adverse respiratory events and life-threatening conditions by cardiologists, pediatrics, in respiratory therapy and emergency care. Although it describes the patient's cardiorespiratory dynamics the technique is still underutilized due to a lack of quantitative means for assessing it. In the clinical environment the respiratory profile of the patient is evaluated through the visual inspection of the recorded waveform, the capnogram. An automated analysis of the capnogram would allow a quantitative assessment of the cardiorespiratory states of both healthy and diseased patients. The typical feature values determined in this study for healthy subjects are comparable with values reported in related literature.

Keywords: volumetric capnography, respiratory monitoring

1. INTRODUCTION

Current trends in monitoring and patient safety confirmed capnography as a standard of care in many clinical environments. In expired respiratory gases, capnography reflects the elimination of CO_2 by the lungs, the production of CO_2 by tissues and circulatory transport of CO_2 to the lungs. Nowadays capnography monitors are small, very robust and easy to use which allows integration into patient monitors, defibrillators and ventilators [1]. Despite the broad clinical employment capnography still remains underutilized due to a lack of knowledge concerning the wide range of applications of the technology. The recording generated by respiratory monitor, the capnogram has a typical shape given by the physiology of the lungs. Respiratory dysfunctions modify the shape of capnogram and the characteristics of each condition is reflected from gross to indiscernible changes of the morphology.

Related literature is scarce and few studies analyze repeated measurements. One of the first studies discussing volumetric capnography in a group of spontaneously breathing patients with various cardiopulmonary conditions measured in different measurement settings is that of Verschuren et al.[2]. Tusman et al. presents in his studies normal values for volumetric capnography parameters in healthy spontaneously breathing subjects and anesthetized patients based on a new method of feature extraction [3], [4].

In this study we computed physiological based volumetric capnography parameters and analyzed the variability of parameters between repeated measurements. The objective of this study was to present volumetric capnography reference values and inter-measurement variability in spontaneously breathing subjects.

2. MATERIALS AND METHODS

2.1 Volumetric Capnography

Capnography is the monitoring of the concentration or partial pressure of CO_2 in the respiratory gases. The volumetric capnogram is visualized as a graph that displays the elimination of CO_2 concentration against the volume expired in one breath. The most important features related with the respiratory state are those that describe the shape of the capnogram signal (Figure 1a).

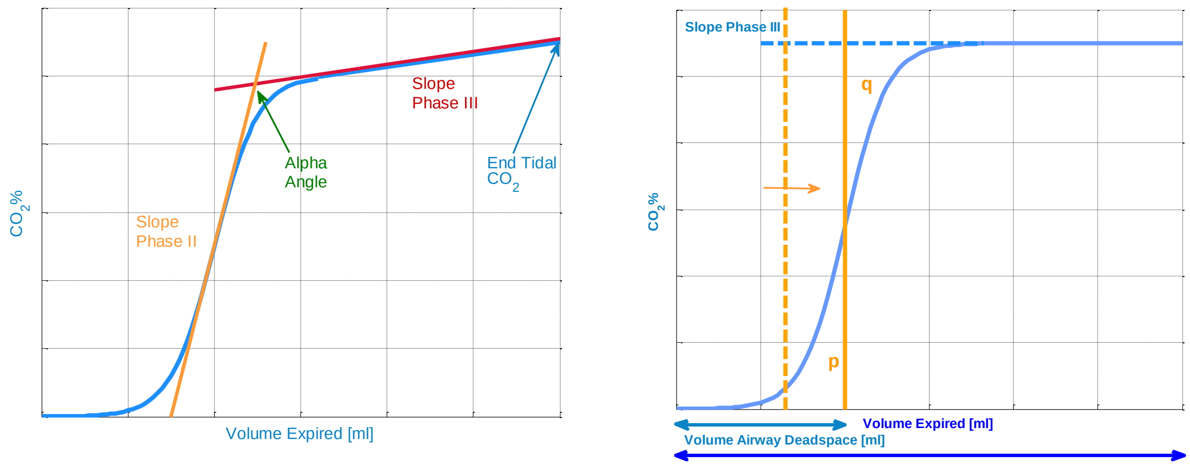

Figure 1a (left side): Volumetric capnogram signal, abstract representation. S_{II} and S_{III} are marked as extrapolated straight lines. Figure1b (right side): Abstract representation of Fowler's method for calculating $VD_{aw.}$ S_{III} was represented as an extrapolated straight line.

Expired volume (V_{exp}), is recorded during the expiratory phase and represents the part of the ventilatory cycle from the beginning of the expiratory flow to the beginning of inspiratory flow. As shown in Figure, V_{exp} represents the length of the capnogram. Vexp is the final volume sample from the expired volume signal. Next, in assessing the height of the capnogram, end-tidal CO_2 ($ETCO_2$) is computed as the end expiratory CO_2 concentration determined from the CO_2 waveform, just before the start of the next inspiration.

Slope phase III (S_{III}) was computed in MATLAB® by linear least-squares regression on the points bounded by 30% to 70% of expired CO2 volume [5]. There are many definitions regarding the implications of slope phase III, but most clinicians agree that it reflects ventilation inhomogeneities within the lungs, also known as the ventilation/perfusion ratio (V/Q) mismatch [3]. Another feature which describes the inclination of the capnogram, α angle,was calculated as the angle between the intersection of the extrapolated regression lines of the slopes of the phase II and III

The volume of airway deadspace (VD_{aw}), is the volume of the conducting airways at the 'midpoint' of the transition from dead space to alveolar gas [5]. In order to extract VD_{aw}, Fowler's method of 'equal area triangles' was implemented in MATLAB ® [6]. For illustration purposes, in Figure 1b, right side, the extrapolated slope phase III line was depicted as a straight line. The vertical line was moved iteratively with a step of 1 ml towards the right limit and the iteration loop stopped after the trapezoidal integration resulted in a lower area triangle (*p*) greater than the upper triangle area (*q*).

2.2 Study Design

Volumetric capnography measurements were collected from 10 healthy subjects with no previously recorded lung diseases. Measurements were acquired with a commercially available Philips NM3 respiratory profile monitor with the Capnostat 5 (Respironics, Inc) mainstream CO_2 sensor was used for acquiring respiratory measurements. The subjects breathed into the respiratory device for a single measurement of 10 minutes. The subjects had in total 10 measurements, taken on multiple days. In order to avoid the inclusion of outlier breaths in the analysis, all breaths which were outside the ±50% median expired volume of a measurement were removed (as suggested by Tusman et al. [2]). Additionally, all breaths below 200 ml of expired volume per breath were excluded.

2.3 Data Analysis

Data processing software (FlowTool Physiologic Waveform Viewer ©, Respironics) was used for processing and visualization of raw waveform recordings. Next, algorithms for feature extraction were implemented in MATLAB ® (Mathworks, Natick, MA, USA). Statistical analysis was performed using MATLAB ®. The reference values were computed on the pooled measurements of the subjects. The feature values are presented as mean ± standard deviation, median and inter-quartile range (IQR) and are compared with reference values from related studies. The variability between measurements is described using the coefficient of variation Cv. The coefficient of variation was calculated as standard deviation (σ) divided by mean ($\bar{x}$) and represents the average value of each subjects measurement. The following formulas were employed,

$$\bar{x} = \frac{1}{t}\sum_{i=1}^{t} x_i \qquad \sigma_x = \sqrt{\frac{1}{t-1}\sum_{i=1}^{t}(x_i - \bar{x})^2} \qquad C_v = \frac{1}{n}\sum_{i=1}^{n}\frac{\sigma_i}{\bar{x}_i}\cdot 100$$

where *t* denotes the number of respiratory measurements of one subject, *n* denotes the number of subjects and *x* denotes the corresponding parameter extracted from the feature values (in this case, the mean value per measurement was used).

3. RESULTS

The feature values presented in Table 1 were computed by pooling together all the single breath values of the subjects.

Method	V_{exp} [ml]	$ETCO_2$ [%]	S_{III} [%/L]	α Angle [°]	VD_{aw} [ml]
Mean ± SD	549.40 ± 155.52	5.44 ± 0.43	1.81 ± 1.14	147.87 ± 11.86	134.75 ± 28.96
Median	521.9	5.42	1.56	148.50	131.2
Q1-Q3	442.47 - 625.9	5.14 - 5.77	1.16 - 2.14	140.36 - 156	110.7-159.6
CV (%)	13.56	4.22	22.80	3.73	5.21

Table 1 Typical reference values for volumetric capnography in healthy subjects. Data was presented as mean ± standard deviation, median, IQR. The coefficient of variation (C_V) represents the variability in-between measurements of all subjects.

4. DISCUSSION

The reference values reported in Table 1 could be used in a clinical setting to interpret cardiopulmonary conditions. For validation, the values obtained were compared with typical values from other reference studies of volumetric capnography and the results were in agreement

In an earlier study of Tusman's [7], the mean of S_{III} is 0.009 mmHg/ml, which converted in [%/L] in order to compare with our value is 1.18 for a chosen barometric pressure of 760 mmHg. This value is comparable to ours, 1.81 ± 1.14, and the small differences can be accounted to the different algorithms used. S_{III} has the highest C_v compared to the other features (Table 1) and this may be due to the fact that S_{III} is very sensitive as the slope is the tangent of an angle. Therefore, using the corresponding angle of S_{III} would render a lower C_v and also a more precise feature value. In support of this theory, the smallest C_V was obtained for α angle, 3.73. Its value of 148.50°, could only be compared to that of Tusman et al. [2] who obtained 157°. The small difference in values could be explained by different feature extraction algorithms used.

VD_{aw} is 131.2 (110.7-159.6) or 134.75 ± 28.96 in healthy subjects, these values being similar with those obtained by Astrom et al. [8] for females 100 ± 14 and 136 ± 23 for males. Tusman et al.[3] used a different method than Fowler's to calculate VD_{aw} and found a smaller value of 92 (39). Verschuren et al. [2] obtained a higher value 178 (mean), that could be justified by the older age of subjects.

5. CONCLUSION

In this paper we present reference values for volumetric capnography parameters in healthy spontaneously breathing subjects. Moreover we analyze the variability of respiratory parameters between repeated measurements. The values obtained, comparable to those found in related literature, makes this study a valuable addition to volumetric capnography monitoring and diagnostics.

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