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## Original Contributions

### THE USE OF END-TIDAL CAPNOGRAPHY TO MONITOR NON-INTUBATED PATIENTS PRESENTING WITH ACUTE EXACERBATION OF ASTHMA IN THE EMERGENCY DEPARTMENT

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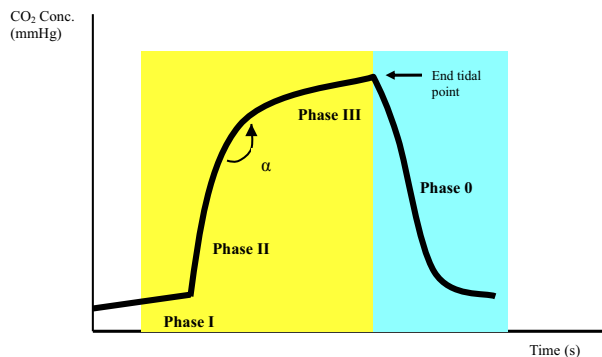
□ **Abstract—Study Objective:** To determine if the slope of Phase II and Phase III, and the alpha angle of the expiratory capnographic waveform, as measured via computer-recognizable algorithms, can reflect changes in bronchospasm in acute asthmatic non-intubated patients presenting to the emergency department (ED). **Methods:** In this prospective study carried out in a university hospital ED, 30 patients with acute asthma were monitored with clinical severity scoring and peak flow measurements, and then had a nasal cannula attached for sidestream sampling of expired carbon dioxide. The capnographic waveform was recorded onto a personal computer card for analysis. The patients were treated according to departmental protocols. After treatment, when they had improved enough for discharge, a second set of results was obtained for capnographic waveform recording. The pre-treatment and post-treatment results were then compared with paired-samples *t*-test analysis. **Results:** On the capnographic waveform pre- and post-treatment, there was a significant difference in the slope of Phase III ( $p < 0.001$ ) and alpha angle ( $p < 0.001$ ), but not in the Phase II slope ( $p = 0.35$ ). There was significant change in peak flow meter reading, but it was poorly correlated with all the capnographic indices. **Conclusion:** The study provides some preliminary data showing that capnographic waveform indices can indicate improvement in airway diameter in acute asthmatics in the ED. Capnographic waveform analysis presents several advantages in that it is effort-independent, and provides continuous monitoring of normal tidal respiration. With further refined

studies, it may serve as a new method of monitoring non-intubated asthmatics in the ED. © 2009 Elsevier Inc.

□ **Keywords—**capnography; end tidal; acute asthma; emergency department

#### INTRODUCTION

Capnography comprises the continuous analysis and recording of carbon dioxide (CO<sub>2</sub>) concentrations in respiratory gases. “Time capnography” (commonly referred to as just capnography) is the continuous plot of levels of expired carbon dioxide over time, producing a capnogram. This allows for visual inspection of changes in CO<sub>2</sub> concentrations by means of a waveform display, paper recording, or even digitized measurements. It is the analysis of such waveforms that forms the basis of this study. Capnometry, discrete measurements of carbon dioxide concentrations, was first developed during World War II as a means of monitoring the internal environment of submarines (1). In the 1950s, capnometers were used experimentally during anesthesia to measure expired CO<sub>2</sub>. But it was only in the early 1980s that capnometry became widely used, mainly in the anesthetic practice (2). Today, capnography is considered essential in monitoring metabolic and respiratory functions during anesthesia. Its role has spread beyond the



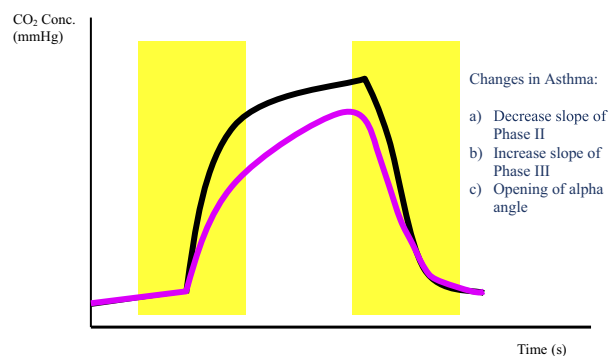
**Figure 1. The single breath capnographic waveform.**

realms of anesthesia, and capnography is now used in Emergency Medicine to confirm and verify endotracheal tube placement, monitor ventilatory status of respiratory-impaired patients, monitor ventilation of patients during sedation and analgesia, evaluate ventilator settings and circuit integrity, assess effectiveness of cardiopulmonary resuscitation, and for early detection of changes in airway resistance and circulatory collapse. Newer detection methods, for example, Microstream® (Novometrix, USA) technology, has allowed for more accurate recordings in smaller samples, thereby extending the use of capnographic monitoring not only to non-intubated patients but even to pediatric patients. Much in line with these advances, scientists and clinicians are looking into other uses of capnography; among them, the analysis of the capnographic waveform to provide information on airway obstruction in non-intubated asthmatic patients.

The normal capnogram has an almost square-wave pattern (Figure 1) marked by alternating inspiratory ( $P_{\text{insp}}\text{CO}_2 = 0$ ) and expiratory phases ( $P_{\text{exp}}\text{CO}_2$ ) (2–4). Expiration itself consists of three successive phases: 1) a latency phase (Phase I), corresponding to the expiration of the anatomical dead space ( $P_{\text{exp}}\text{CO}_2 = 0$ ), which is indistinguishable from the preceding inspiration; 2) slope phase (Phase II) marked by a very rapid rise in  $P_{\text{exp}}\text{CO}_2$ , corresponding to expiration of mixed air; and 3) plateau phase (Phase III), reflecting the elimination of alveolar air (slightly increasing  $P_{\text{exp}}\text{CO}_2$ ), resulting in a peak at the end of tidal expiration ( $P_{\text{et}}\text{CO}_2$  close to alveolar carbon dioxide [ $P_{\text{A}}\text{CO}_2$ ] tensions) (4,5). The end-tidal peak is occasionally referred to as the end-tidal point. This well-defined shape of the normal capnogram depends on a variety of factors. Normal aerobic metabolism will consume oxygen and result in the production of carbon dioxide. This will be carried by an adequately functioning circulatory system to the lungs where, in the normal lung, matched gas distribution and alveolar ventilation with pulmonary perfusion will ensure normal gas exchange. In the absence of bronchial obstruction, the

verticality of Phase II indicates a regular separation front between the anatomical dead space air and alveolar air. The elimination of alveolar air is synchronous, and this is reflected by the sudden rise in Phase II and the subsequent elimination of alveolar air, which is indicated by the almost horizontal plateau of Phase III.

Asthma is a disease characterized by bronchial hyper-reactivity, inflammatory exudates, and mucous plugging. The hallmark of asthma is the narrowing of the smaller airways causing obstruction to flow within the airways, especially during expiration. In asthma, airway obstruction causes regional decreases in airflow and, consequently, alveolar ventilation. This is responsible for the “parallel heterogeneity” of ventilation-perfusion ratios (V/Q ratios). Each bronchopulmonary territory is characterized by its own V/Q and determining its own partial pressure of  $P_{\text{A}}\text{CO}_2$ . Alveolar air is then evacuated at different times during expiration, resulting in desynchronization. This results in increased mixing of alveolar air from certain bronchopulmonary territories with dead space air from other territories. On the capnogram, this causes deformation of the normal curve, marked by the loss of verticality of Phase II, opening of the angle between Phase II and Phase III (alpha angle also known as angle Q), and the increased inclination of Phase III (Figure 2) (4). In severe cases, the capnogram takes on a “shark’s fin” appearance. These changes in the capnogram are of particular interest as they indicate changes in airflow. This may provide the means for closer, continuous, and objective monitoring of airway diameter and airflow in patients with acute asthma. You et al. conducted one of the first studies on adult asthmatics and published a report in 1992. They initially studied the end-tidal slope, which was measured manually, and reported good correlations with forced expiratory volume at 1 s ( $\text{FEV}_1$ ) as percentage of predicted. In this study, they were among the first to suggest the usefulness of computerization of capnogram analysis (6).



**Figure 2. The capnographic waveform: changes in asthma.**

The present study was undertaken to identify capnographic waveform indices that could be used in monitoring non-intubated acute asthmatic patients, and to use entirely computer-generated algorithms to obtain and analyze these indices.

The objectives of this study were to: 1) Record and analyze the expiratory capnographic waveform via sidestream monitoring using a nasal cannula in patients presenting to the emergency department (ED) with an acute attack of asthma; 2) Analyze the changes in the capnographic waveform after treatment, on symptomatic improvement and on discharge from the ED; 3) Analyze the capnographic waveform with indices that might be included in a future computer algorithm for waveform analysis; 4) Correlate the capnographic waveform changes with peak flow measurement.

## METHODS

### *Study Design*

A prospective case series study was conducted on patients presenting to the ED with symptoms suggestive of asthma for a 2-month period.

### *Setting*

This study was conducted in the ED of Hospital Universiti Sains Malaysia in Kubang Kerian, Malaysia. It is a regional tertiary referral center with an ED attendance rate exceeding 70,000 patients per year. It is also a teaching institution and university hospital involved in the training of undergraduate medical students as well as providing residency-based specialty training in many fields, including Emergency Medicine. This study was approved by the departmental board review and the hospital Ethics Committee.

### *Selection of Participants*

Patient recruitment was done by the simple sampling method. Inclusion criteria for enrollment into this study were all adult patients who presented with symptoms of acute breathlessness or wheezing and with a known confirmed history of asthma (based on medical records notes). Those with an unclear diagnosis of asthma were excluded from the study. The patients selected were initially examined clinically by doctors working in the ED and were managed according to standard departmental protocols, for example, Wright's peak flow meter reading (PEFR), beta-2 agonist nebulizer with oxygen

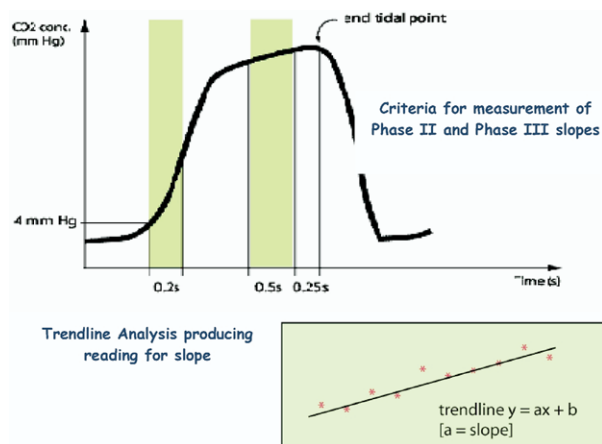
wall driven, and either intravenous steroid or oral prednisolone. If the "need-to-treat" criteria existed, these patients were then started on nebulizer therapy and enrolled in the study. Patients were excluded from the study if they presented with severe life-threatening events where priority and attention was directed toward treatment. PEFR was measured in each patient before and after the treatment was completed. An average of three capnograms was then recorded using Novamatrix® (Novamatrix Inc., Wallingford, CT) capnometry. Capnographic measurements were then used to aid the management of these severely ill patients. Patients were also excluded from the study if chronic obstructive pulmonary disease (COPD) was suspected to be the primary diagnosis, due to the irreversibility of at least some airway obstruction that is well documented in this disease (7). All patients whose symptoms were not completely relieved by nebulizer therapy or required admission were also excluded.

### *Interventions*

The decision to treat by the attending doctor was not influenced by the researcher. When the decision to start nebulizer therapy was given, the researcher then initiated capnographic monitoring in tandem with ongoing therapy. A nasal cannula, which served as the sampling port for sidestream capnography, was applied to the patient. They were then directed to breathe normally. One end of this specially designed nasal cannula provided oxygen from a humidified wall source (all patients in this study were given oxygen at a rate of 3 L/min via this nasal cannula) and the other end was connected to an aspiration pump and the sampling port (8,9).

### *Methods and Measurement*

An average of three capnograms was then recorded using Novamatrix® capnometry and stored within a Novamatrix Novacard® personal computer card. Waveforms were deemed adequate when there were at least three waveforms of regular morphology that were not deformed and did not have significant artifact. Nebulizer therapy was then started with the nasal cannula in situ. All patients were treated with oxygen-driven wet nebulizers. At the conclusion of nebulizer therapy, once the attending doctor had decided that the patient was "fit for discharge," the post-treatment capnographic waveforms were again recorded and stored. Graphs were then redrawn from the digitized data. These digitized data were in the form of carbon dioxide readings taken 48 times per second for a 10-s interval. We initially converted all data



**Figure 3. Capnographic waveform indices and trendline analysis.**

into Microsoft Excel® (Microsoft Corporation, Redmond, WA) format (\*.xls) due to the ease of graphical representation and analysis with this software.

#### Data Collection and Processing

Individual graphs were then available for analysis. For each patient, capnograms were recorded and analyzed pre-treatment and post-treatment. We decided to study the slope of Phase II as measured for 0.25 s from the first point when the measured CO<sub>2</sub> rises above 4 mm Hg; and the slope of Phase III as measured for 0.75 s to 0.25 s (total time 0.5 s) from the end-tidal peak to ensure the consistency of points of measurement. Each capnogram was analyzed for Phase II slope (referred to subsequently as “slope”) and Phase III slope (referred to as “plateau”). The slopes were measured in the segments mentioned above by calculating a *linear trendline* using Microsoft Excel Chart Wizard® (Microsoft Corporation). This was expressed in a  $y = ax + c$  formula where the “a” represented the slope of the segment analyzed. The slope and plateau lines together would create an obtuse angle, and this we referred to as “angle alpha” (angle Q). All patients had three capnograms done for slope and plateau and, therefore, three values of Q were calculated. Mean readings were then taken of the three initial readings (Figure 3).

#### Primary Data Analysis

Variables were reported as mean with standard deviations (SD). Statistical analysis was performed using SPSS (Version 9.0; SPSS Inc., Chicago, IL) and Stata (Version 7.0; StataCorp LP, College Station, TX).

Among the statistical tests used were frequency analyses, paired *t*-tests for comparison of means, and Wilcoxon non-parametric signed-ranks tests for analysis of categorical data. A comparison study was carried out between the PEFR readings and all the capnographic indices. A value of  $p < 0.05$  was considered to be statistically significant.

## RESULTS

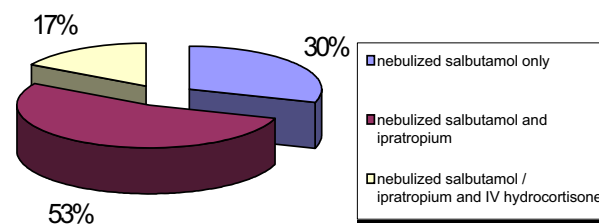
A total of 36 patients were initially enrolled in this study. Four patients were eliminated from the study due to inability to analyze their capnographic records, primarily due to lack of adequate waveforms not deformed by artifacts. Two other patients were excluded due to missing or incomplete data. Data from 30 patients were submitted for analysis. The ages of our patients in this study ranged from 10 years to 71 years, with a mean of 35.2 years and SD of  $\pm 17.29$  years. There were 18 male patients and 12 female patients. Figure 4 shows the distribution of the medications used to treat the patients in the study. All patients were deemed fit for discharge after their treatment and were subsequently discharged. None of them returned to the ED during the next 24 h.

Paired samples analysis showed a significant difference in pre- and post-treatment PEFR values ( $p < 0.001$ ).

End-tidal carbon dioxide (EtCO<sub>2</sub>) levels were also recorded pre- and post-treatment. EtCO<sub>2</sub> levels pre-treatment ranged from 24 to 49 mm Hg, with a mean of 36.83 mm Hg and an SD of 4.96 mm Hg. This was essentially unchanged post-treatment (range 30–46 mm Hg; mean 36.7 mm Hg; SD  $\pm 4.49$  mm Hg). Paired *t*-test did not show any significant difference ( $p = 0.871$ ).

Gradient values for Phase II had a mean of 2.6174 (SD  $\pm 0.6156$ ) pre-treatment and a mean of 2.7448 (SD  $\pm 0.5143$ ) post-treatment (Figure 5); this difference was not significant ( $p = 0.35$ ). Gradient values for Phase III had a mean of 0.4419 (SD  $\pm 0.2361$ ) pre-treatment and a mean of 0.2301 (SD  $\pm 0.0945$ ) post-treatment

#### Treatment modalities for patients



**Figure 4. Treatment modalities for patients in the study population.**

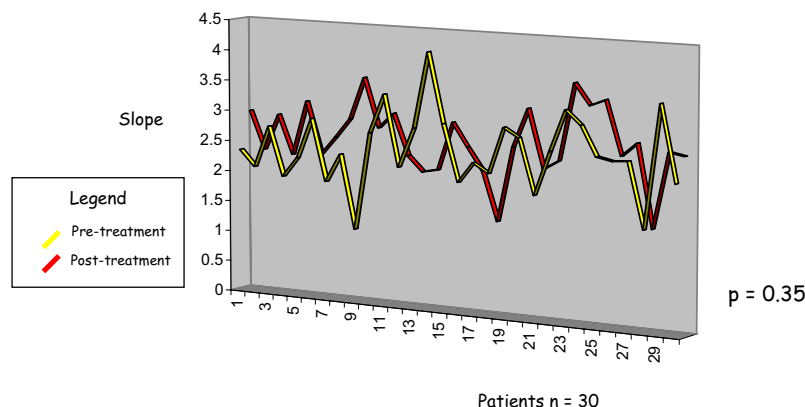


Figure 5. Phase II changes pre-treatment and post-treatment.

(Figure 6); this reduction was markedly significant ( $p < 0.001$ ). The angle Q was calculated from the observed gradients of Phase II and Phase III. The pre-treatment mean of 134.36 (SD  $\pm$  12.07) was significantly higher than the post-treatment mean of 123.27 (SD  $\pm$  6.41) ( $p < 0.001$ ) (Figure 7).

There were poor correlations between pre-treatment PEFR readings and graphical indices; that is, between PEFR and Phase II slope ( $r = 0.6026$ ), Phase III slope ( $r = -0.4328$ ), and Q ( $r = -0.5687$ ). Post-treatment, we also noted weak correlations between PEFR readings and graphical indices: Phase II ( $r = 0.2149$ ), Phase III ( $r = -0.3870$ ), and Q ( $r = -0.4809$ ). (Note: negative  $r$  values indicate inverse or negative correlation.) We also looked at the magnitude of change in PEFR and graphical indices pre- and post-treatment. We then conducted correlation studies after generating variables of differences. There was weak correlation between the magnitude of change in PEFR and Phase II pre- and post-treatment ( $r = 0.4875$ ). Similarly, there were only weak negative correlations between the magnitude of change in PEFR and Phase III ( $r = -0.2351$ ) and Q ( $r =$

$-0.3085$ ) pre- and post-treatments. In conclusion, there were poor correlations between the magnitudes of change in PEFR and change in graphical indices, pre-treatment and post-treatment.

## DISCUSSION

Many of the previous studies on capnography in asthmatics have been conducted in slightly more controlled situations, either with asthmatic patients in histamine challenge tests, or with asthmatic patients whose asthma status has been stable for a few hours (4,10,11). On the contrary, this study was conducted on asthmatic patients presenting to the ED with an acute attack of asthma. This study stands on one central pillar, that is, all patients within the study population were treated by the attending physicians according to departmental protocol without any influence from the researcher. All patients in our study group presented with an acute attack of asthma, were treated for it, and were deemed fit for discharge. We recorded the initial pre-treatment data after the diagnosis

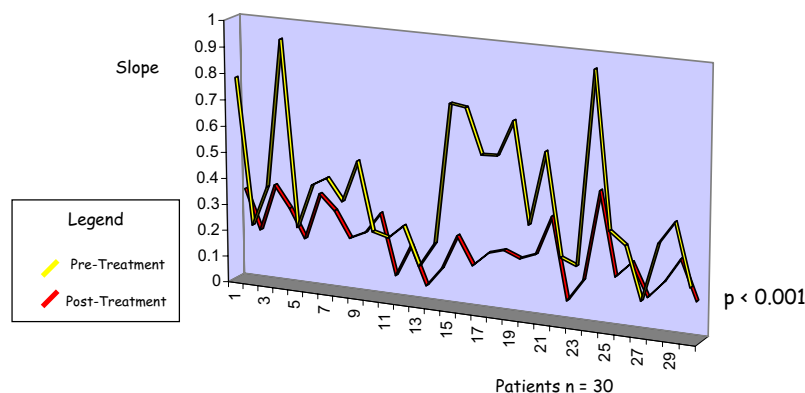
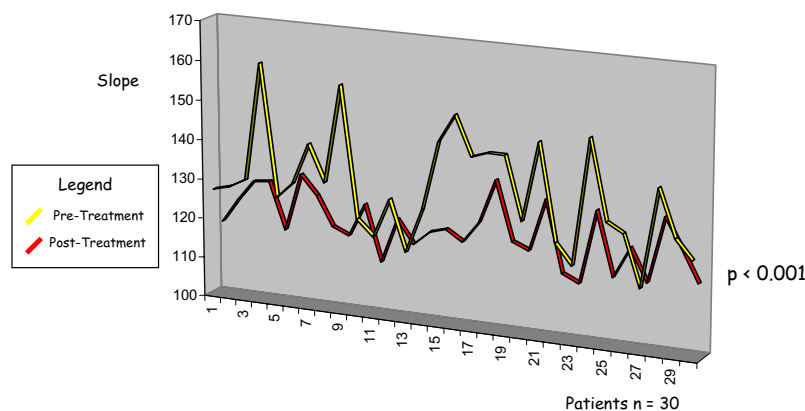


Figure 6. Phase III slope changes pre-treatment and post-treatment.



**Figure 7. Alpha angle (Q) changes pre-treatment and post-treatment.**

of acute asthma had been made, just before the onset of treatment. And we recorded the post-treatment data after the patient had completed the treatment and was deemed fit for discharge. In other words, the emergency physician decided if the patient had an asthmatic attack, and whether treatment was necessary. Treatment, usually with a wet nebulizer, was started according to the departmental protocol. The end-point of treatment was also decided by this doctor and recorded when the patient was deemed safe for discharge.

There are various options available for the assessment of airway obstruction in the acutely ill patient with asthma; clinical assessment and peak flow assessment are the most commonly used within the ED. There are obvious drawbacks to these methods. Most doctors rely on the presence of breathlessness and an expiratory wheeze to diagnose a patient with an acute attack of asthma, with improvement being defined as improvement of symptoms and absence of wheeze. Unfortunately, symptoms often tell us little about the severity of the disease, as many patients are unable to accurately assess the severity of their own disease (12). Even physicians may be found lacking in their judgment of degree of airway obstruction, as Quackenboss et al. so aptly pointed out in their study in 1991 (13). Symptomatic improvements are sometimes due to oxygen therapy alone and not improvements in airway obstruction. Physical findings help physicians better assess the patient's condition. Although findings like tachycardia, tachypnea, inability to speak in full sentences, presence of wheeze and pulsus paradoxus, tonic contractions of inspiratory muscles, and a low oxygen saturation level are indicative of severe asthma, the absence of the findings do not necessarily indicate improvement in the patient's status, and are thus of limited use.

Currently, peak flow measurement is the most widely used method of objectively monitoring patients with

acute asthma. Theoretically, peak flow rates are more a function of the diameter of the larger airways, whereas FEV<sub>1</sub> or FEV<sub>1</sub>/forced vital capacity (FVC) reflects the smaller airways. FEV<sub>1</sub> and FEV<sub>1</sub>/FVC are technically difficult to perform within the ED and involve cumbersome equipment. The major drawback is their effort-dependency. The patient's ability to perform these maneuvers is vital. Often in the ED, we see patients unable to perform these maneuvers. Some are unmotivated to perform any maneuver in the midst of their discomfort, anxiety, and breathlessness. Many, having performed such tests before, claim there is a worsening of symptoms, especially cough, after the maneuver. Some have such severe bronchospasm that they are totally unable to generate any significant flow at all. In the context of a study, this introduces bias and skewed results.

The capnographic waveform shows changes in bronchospasm that reflect the heterogeneity of the expired air. This is seen as a decrease in slope of Phase II, and increase of the slope of Phase III and the resultant increase in the alpha angle (angle Q). Whereas gross changes are visible to the naked eye, for example, "shark fin" appearance, more subtle changes require measurement of the slopes and angles. Because this is still a new concept, in all studies to date, this has been done manually (4,10,11). We have taken a slightly different approach. Keeping in mind that any future application of this concept would require computer analysis of the capnographic waveform, we set out by using indices that can be identified easily by computer algorithm. For the slope of Phase II, we obtained readings for a period of 0.2 s from the point when the capnographic waveform crosses the carbon dioxide reading of 4 mm Hg, because it is assumed that the carbon dioxide has to have come from the lungs to reach a level of 4 mm Hg. The second point identified was the end-tidal point, already a commonly identified point in all capnometers used today. We

measured the slope of Phase III by measuring for a period of 0.5 s from a point 0.25 s from the end-tidal point. These readings were then subjected to trend-line analysis, resulting in the slope. From the two slopes, the angle of alpha (Q) was calculated.

Kelsey and Oldham were among the first to report on shapes of the expiratory capnogram. In their report published in 1962, they described four kinds of shapes in normal and obstructive waveforms (14). Since their report, many attempts have been made to quantify these deformations, albeit mostly in patients with COPD (15–18). Most of them, however, were done in controlled situations and in intubated patients (19–21). Few studies have been conducted in asthmatics. Some of the initial studies conducted in children showed changes in Phase II and Phase III of the expiratory capnogram after a bronchial challenge (22,23).

You et al., in their series of studies, have shown that slopes of Phase II and III change demonstrably with improvements in airway diameter. In a continuation of their initial work, You et al. published a landmark article in 1994 describing eight capnographic indices and their correlations with spirometric measurements (4). They analyzed time durations of both inspiratory and expiratory phases of the capnogram, measured slopes of various parts of the curve, and derived areas under the slope at different parts of the slope. This study was groundbreaking in that they studied adult non-intubated patients with acute asthma using sidestream monitoring. In this study, they reported good correlations of all their indices with spirometric measurements. They also reported on the restrictions and criteria in selecting waveforms for analysis. However, this study too was performed manually in that all slope indices were measured manually and all derived data also were calculated manually. They again recognized the importance of computer analysis of the capnographic waveform and concluded that computerization of waveform indices may extend the use of capnography to continuously monitor non-intubated asthmatic patients within the ED (4). They concluded that indices based on the latter parts of the capnographic waveform are more sensitive and display a stronger correlation with spirometric indices (4,6).

You et al., in a landmark study on adult asthmatics, described various waveform indices such as slopes of different parts of the capnogram as well as areas subtended by different parts of the curve, and correlated these indices with different degrees of airway obstructions quantified by spirometric findings (4). They reported strong correlations of the capnographic indices with the spirometric parameters and suggested that capnographic waveform analysis may be used in the monitoring of asthma. Unfortunately, the analysis of the capnographic waveform is a concept still in its infancy.

Waveform indices that show satisfactory sensitivity (high correlation with spirometric parameters) are still being studied. Computer measurements of these indices, their memorization, and visualization in the form of trend curves could then constitute a useful tool for asthma monitoring. The computer analysis and display of capnographic waveform indices as numerical data would greatly simplify and thereby promote use of capnography for the purpose of monitoring asthmatic patients during an asthmatic attack.

In our study, we noted a similar trend, where Phase II slopes did not show any significant change pre-treatment vs. post-treatment ( $p = 0.35$ ). This is in contrast to the significant changes seen in Phase III ( $p < 0.001$ ) and alpha angle (angle Q) ( $p < 0.001$ ). This may be due in part to the mistaken selection of the point of 4 mm Hg, because in many patients this did not yet show the steep part of the Phase II slope. Another consideration is the inclusion of the terminal part of Phase I in the slope calculation. This may have occurred due to the slower changes in the transition from Phase I to Phase II seen in sidestream monitoring, mainly due to the delay during sampling. Theoretically, the initial parts of the expiratory capnographic waveform are most susceptible to change if the patient consciously attempts to control respiration. Finally, the slope of Phase II may be dependent on the end-tidal carbon dioxide level (the *height* of the expiratory capnographic waveform) and the respiratory rate (the *width* of the expiratory capnographic waveform), thereby adding another factor to the analysis. All these factors may explain why other studies, and ours, have found indices involving Phase II to be less sensitive. Future studies may avoid some of these problems by selecting a higher level of CO<sub>2</sub>.

We also identified a potential problem with the Phase III measurement criteria. In our study, Phase III was measured for a total of 0.5 s. In patients with higher respiratory rates, the duration of 0.5 s may bring part of the inflection curve into the reading, resulting in inaccuracies in calculation. This did not occur in this study due to the criteria of a minimum of 0.8 s duration of the waveform for analysis. Practically speaking, setting such criteria may exclude many waveforms for analysis and may not be ideal for future computer analysis. The duration of Phase III taken for analysis as a percentage of total duration would overcome this weakness. Future algorithms and studies may find this to be a more helpful method.

In this study, the Phase III slope and alpha angle (angle Q) changes were significantly different pre- and post-treatment. In other words, capnographic waveform indices were able to detect improvement in the patients' bronchospasm post-treatment, as could clinical parameters and peak flow measurements. Capnography pre-

sents some advantages. We know that these specific waveform changes indicate changes in airway obstruction. Capnography has the added advantage of being effort-independent, thereby reducing the influence of the patients' understanding and cooperation on monitoring parameters. This should provide a more objective evaluation of the patients' condition, an evaluation less influenced by patient factors. On the other hand, although we know of the specific waveform changes in asthma, we are still uncertain which capnographic waveform indices are most reflective of the situation in asthma. There are insufficient studies at the moment to determine this with any degree of certainty. Therefore, whether capnography is accurate at detecting changes in asthma can be answered only by further study. Nevertheless, we believe that capnography has great potential as a monitoring tool in asthma due to its properties of non-invasive, effort-independent, and continuous monitoring.

### LIMITATIONS

There are certain limitations to this study. First, the study population was small. In addition, distributions with respect to age and sex were not noted; however, there is no evidence to suggest that the shape of the capnogram is dependent on age or sex. Paired-sample analysis would reduce the influence of underlying medical conditions and other confounding factors.

Another potential source of bias was the selection of waveforms for analysis; waveforms were recorded when the morphology looked "similar" to the researcher, and analysis was conducted on waveforms that were not deformed by artifacts; this was a selection bias. Although this was a possible source of bias in this study, it also presents a problem for computer analysis in the future; the identification of waveforms suitable for analysis must be foremost on the mind of the researcher writing the algorithm. There are several possible approaches to this problem. Firstly, strict exclusion criteria may be imposed to select waveforms with artifacts. However, this runs the risk of analyzing waveforms that may not be indicative of the situation, or of having too few waveforms to analyze. Secondly, as Goldman and Landis have proposed, recognition of the different waveform morphologies, either through neural network algorithms or as clusters of morphologically similar waveforms, can be programmed (24,25). On the whole, this will reduce the influence of waveforms with artifacts or sub-optimal waveforms, and this may then form the basis of waveform selection for analysis. Thirdly, as with all single-source data, the problem of identification of artifacts needs to be addressed. The analysis of multi-source data

is usually easier and less susceptible to misdiagnosis of artifacts. An example in use today is the cardiac monitor. Movement artifacts often mimic ventricular fibrillation, but this is usually identified as artifact if normal readings of pulse rate and oxygen saturation are still being obtained (an unlikely event in the actual event of ventricular fibrillation). Here, multi-sources of data would avoid the misdiagnosis of an event. With regards to capnography, the addition of flow-directional information as proposed by Bhavani-Shankar et al., or perhaps simultaneous flow rate recording, might be helpful (26). Although these are possibilities in mainstream capnography, we cannot imagine their use in sidestream capnography. Again, this problem can be resolved only with further research.

Retrospectively, this study might be improved further by introducing some minor methodological changes. A greater number of study participants could be recruited by prolonging the study period. A multi-center study would represent a more diverse study population and assist the investigators in recruiting more patients. The study could also include all patients presenting with acute asthma regardless of the degree of severity, either intubated or non-intubated, as well as admitted patients. A validation study on the use of capnographic indices in acute asthma cases could be done by comparing them to standard assessment tools like peak flow meter and clinical parameters.

At the present time, research into capnography waveform analysis is still evolving. Multiple avenues are being explored. Although we are still unclear of the future direction of this research, and how capnographic waveform analysis will be conducted in the future, the potential for its use practically demands further research.

### CONCLUSION

In summary, the study provides some preliminary data showing that capnographic waveform indices can indicate improvements in airway diameter in acute asthmatics presenting to the ED, and that capnography potentially can be used in continuous monitoring of the asthmatic patient during an acute attack. The task now lies in the identification of ideal waveform indices, the computerization of waveform analysis, and the reporting of such indices in an easily understood and reproducible form. The production of a suitable algorithm, perhaps followed later by the development of capnometers able to report these indices as numerical values, would greatly enhance the field of asthma monitoring. The ultimate hope is that this will bring with it a better understanding of asthma, improved management, and eventually a decrease in its associated morbidity and mortality.



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