TERMINOLOGY AND THE CURRENT LIMITATIONS OF TIME CAPNOGRAPHY: A BRIEF REVIEW

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Bhavani-Shankar K, Kumar AY, Moseley HSL, Ahyee-Hallsworth R. Terminology and the current limitations of time capnography: a brief review.

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ABSTRACT. The carbon dioxide (CO_2) trace versus time (time capnography) is convenient and adequate for clinical use. This is the method most commonly utilized in capnography. However, the current terminology in time capnography has not yet been standardized and is, therefore, a potential source of confusion. Standard terminology that is based on convention and logic to represent the various phases of a time capnogram is essential. The time capnogram should be considered as two segments: an inspiratory segment and an expiratory segment. The inspiratory segment is termed as phase 0; the expiratory segment is divided into phases I, II, III, and, occasionally, IV. Phase I represents the CO_2-free gas from the airways (anatomical dead space); phase II consists of a rapid S-shaped upswing on the tracing due to mixing of dead space gas with alveolar gas; and phase III, the alveolar plateau, represents CO_2-rich gas from the alveoli. The physiologic basis of phase IV, the terminal upswing at the end of phase III, which is observed in capnograms recorded under certain circumstances (such as in pregnant subjects and obese subjects) is discussed in detail. The clinical implications of the alpha angle, which is the angle between phases II and III, and the beta angle, which is the angle between phases III and the descending limb of phase 0, are outlined. The subtle but important limitations of time capnography are reviewed; its current status as well as its future potential are explored.

KEY WORDS. Measurement technique: capnography. Monitoring: carbon dioxide.

The CO_2 concentration ($F{CO_2}$) can be plotted against time (time capnogram) or expired volume (SBT-CO_2 curve—single-breath test for CO_2) during a respiratory cycle. Time capnography is convenient and this is the method most commonly utilized in capnographs. However, in recent literature, unlike in an SBT-CO_2 curve [1–6], there is little uniformity in the terminology used in a time capnogram. Numerous terms, such as PQRS, ABCDE, EFGHIJ, and phases I through IV, have been used to depict the various components of a time capnogram [2,6–14]. This results in unnecessary potential for confusion among the readers. For instance, "phase IV" has been used by some to designate the terminal upswing at the end of phase III, which is occasionally observed in capnograms recorded in pregnant subjects and obese subjects [2–4]. Others use phase IV to designate the descending limb of a time capnogram [6]. In much the same way that the nomenclature of the various segments of the ECG have been standardized, there is currently a need to define and standardize the nomenclature used to designate the various components of a time capnogram. Furthermore, time capnography, though more simple and convenient to use in clinical practice than "CO_2 versus expired volume capnography," has certain

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limitations. This brief review serves three purposes: (1) to redefine and clarify existing nomenclature in capnography, to suggest a standard terminology based on the prevailing literature, convention and logic, so that a uniform terminology can be used in the future to represent various components of a time capnogram; (2) to highlight the physiologic basis of phase IV that is observed occasionally in capnograms recorded in pregnant subjects and in subjects who are obese; and (3) to emphasize the limitations of time capnography as currently recorded, and suggest a possible direction of future research to overcome these limitations.

CAPNOMETRY

Capnometry is the measurement and display of CO_2 concentrations on a digital or analog indicator. Maximum inspiratory CO_2 concentrations (F_{ICO_2}) or tensions (P_{ICO_2}) and maximum expiratory CO_2 concentrations (F_{ETCO_2}) or tensions (P_{ETCO_2}) during a respiratory cycle are displayed.

CAPNOGRAPHY

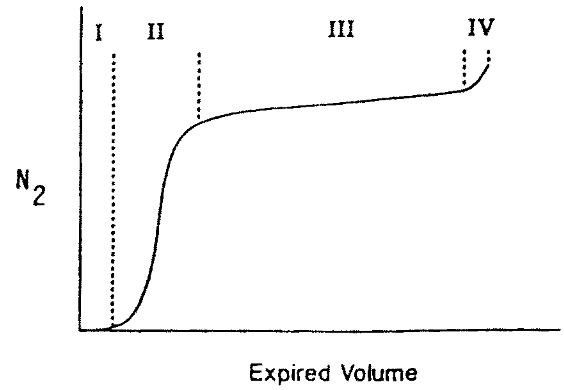
In addition to the display of CO_2 concentrations/tensions (capnometry), a plot of instantaneous CO_2 concentrations during a respiratory cycle is displayed (CO_2 waveform or capnogram).

CAPNOGRAMS

Capnograms can be of two types, depending on whether the F_{CO_2} is plotted against expired volume (SBT-CO_2 curve) or against time (time capnogram) during a respiratory cycle [2]. The latter is simpler and more practical for clinical use, because the former would require more elaborate equipment to generate expired volume versus CO_2 plots, where instantaneous CO_2 concentration is related to expired volume.

COMPONENTS OF SBT-CO_2 CURVE

In 1949, Fowler described SBT-N_2 (single-breath test for nitrogen) to study uneven ventilation in lungs where instantaneous nitrogen concentration is plotted against expired volume [15]. The resulting nitrogen curve is divided into four phases: phase I, phase II, phase III, and phase IV (Fig 1A). When the instantaneous CO_2 concentration is plotted against expired volume, the resulting curve resembles an SBT-N_2 curve in shape (Fig 1B), and is called an SBT-CO_2 curve. An SBT-CO_2 curve is also traditionally divided into three phases: I, II, and III, and, occasionally, a phase IV, if present [2,3–5,16]. Phase IV does not occur normally, but may be seen under certain circumstances, as described in the next section. The physiologic mechanism responsible for phases I, II, and III is similar in an SBT-N_2 as well as an SBT-CO_2 curve. However, the mechanism resulting in phase IV in SBT-CO_2 may be different from that in an SBT-N_2 curve, as explained in the next section.



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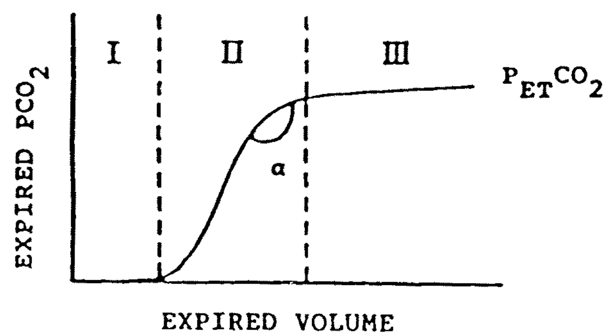

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Fig 1. (A) SBT-N_2 curve (single-breath test for N_2). N_2 concentration versus expired volume plot showing phases I through IV. (B) SBT-CO_2 curve (single-breath test for CO_2). CO_2 tension (P_{CO_2}) versus expired volume plot. Traditionally divided into phases I, II, and III. Phase IV may not be present under normal circumstances. P_{ETCO_2} = end-tidal CO_2 tension.

Phase I: Represents the CO_2-free gas from the airways (anatomical and apparatus dead space).

Phase II: Consists of a rapid S-shaped upswing on the tracing (due to mixing of dead space gas with alveolar gas).

Phase III: The alveolar plateau represents CO_2-rich gas from the alveoli. It almost always has a positive slope, indicating a rising P_{CO_2}.

An SBT-CO_2 curve can be related to the components of tidal volume. It can be used to determine physiologic

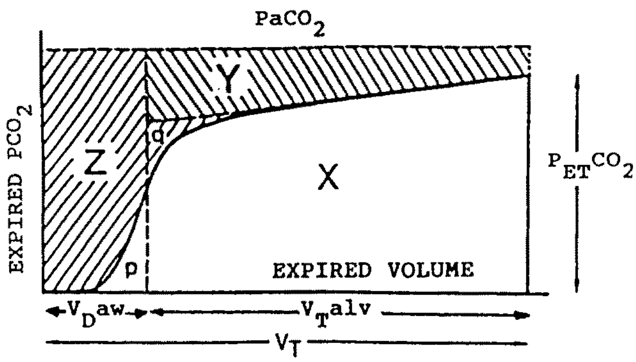

Fig 2. Relationship between the SBT-CO_2 curve and physiologic dead space and its subdivisions. Z = anatomical dead space; Y = alveolar dead space; Z + Y = physiologic dead space; X = effective tidal volume (VTalv); VT = tidal volume; VDaw = airway dead space. (Reproduced from Fletcher [3], with permission.)

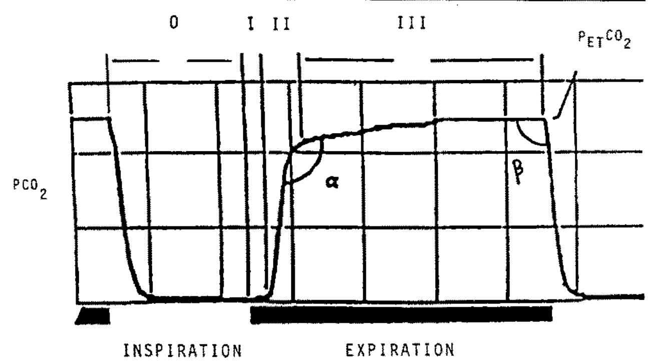

Fig 3. Time capnogram. Expired PCO_2 versus time plot: inspiratory segment (phase 0) and expiratory segment (phases I, II, III). Alpha angle: angle between phase II and phase III. Beta angle: angle between phase III and descending limb of phase 0.

dead space and its components [2,3,5]. A horizontal line (dotted line in Fig 2) representing arterial CO_2 tension ($PaCO_2$, arterial blood sampled during the plot of the SBT-CO_2 curve) is drawn on the SBT-CO_2 trace. The area under the curve, X, is the volume of CO_2 in the breath, and represents effective ventilation. The area below the horizontal dotted line (representing $PaCO_2$) and above the CO_2 curve depicts wasted ventilation (physiologic dead space). This area can be further divided into the components of physiologic dead space, namely anatomical and alveolar dead space. As phase II is the result of the mixing of dead space gas with alveolar gas, it is obligatory to divide phase II into two components. A vertical line is constructed through phase II, and the alveolar plateau (phase III) is extended to intersect the vertical line, so that the two areas, p and q, are equal. Area p is the effective ventilation component of phase II; area q is the anatomic dead space component. Area Z represents anatomic dead space (including phase I and q of phase II). Area Y, which is between the alveolar plateau and the dotted line ($PaCO_2$), represents alveolar dead space, and is due to temporal, spatial, and alveolar mixing defects in the normal lung. If ventilation/perfusion matching were ideal, the alveolar plateau would approach $PaCO_2$. Physiologic dead space is represented by area Z plus area Y [2,3,5]. Under normal circumstances, the end-tidal CO_2 (PCO_2 of the alveoli emptying last) is lower than $PaCO_2$ (average of all the alveoli) by 2 to 5 mm Hg [2,3,5].

COMPONENTS OF A TIME CAPNOGRAM

Unlike an SBT-CO_2 trace, a time capnogram has an inspiratory segment and an expiratory segment. There is no inspiratory segment in an SBT-CO_2 curve, as, by definition, an SBT-CO_2 trace is a plot of FCO_2 and expired volume. Various authors have used alphabetic names, such as PQRS, ABCDE, and EFGHIJ, to describe the inspiratory and expiratory components of a time capnogram [7–11,13,14], whereas Ward used phases I, II, and III to describe the expiratory segment of a time capnogram [12]. In a review on capnometry and anesthesia, our group also used phases I, II, and III to describe the expiratory segment of a time capnogram [2]. Good used phases I through III to describe the expiratory segment and phase IV to depict the inspiratory segment of a time capnogram [6]. Therefore, unlike an SBT-CO_2 curve, there is not yet standard terminology to represent various components of a time capnogram. We suggest that the following terminology, which is based on convention and logic, be used in the future to represent various components of a time capnogram (Fig 3).

For the purpose of this text, the expiratory segment will be considered before the inspiratory segment.

Expiratory Segment of Time Capnogram

The expiratory segment of a time capnogram resembles an SBT-N_2 curve and an SBT-CO_2 curve in shape. Hence, it is prudent to consider the expiratory segment of time capnogram as three phases: I, II, and III, as in an SBT-CO_2 curve or an SBT-N_2 curve. This is conventionally and logically appropriate because the physiologic mechanism responsible for phases I, II, and III in a time capnogram is similar to the phases seen in an SBT-CO_2 curve or an SBT-N_2 curve. Occasionally, at the end of phase III, a terminal upswing, phase IV, which resembles the terminal upswing (phase IV) seen in an SBT-CO_2 curve or an SBT-N_2 curve, may occur in a time capnogram. The details of phase IV are described in the next section.

Inspiratory Segment of Time Capnogram

After phase III of a time capnogram is complete, the descending limb makes an almost right-angle turn and rapidly descends to the baseline. This represents the inspiratory phase during which the fresh gas (CO_2 free) is inhaled and CO_2 concentration falls precipitously. The descending limb of the trace has been labeled differently by various authors as phase IV [6], segment RS [7,8,14], DE [9,10], and HIJ [11]. Using phase IV to depict this segment may be confusing to readers because phase IV conventionally represents the terminal upswing seen at the end of phase III in the SBT-N_2 curve, which may also occur in the SBT-CO_2 curve, as well as in the time capnogram, as stated below [3–5]. Therefore, we suggest that the segment on the time capnogram from the beginning of inspiration to the beginning of expiration, which includes the descending limb and the initial part of the horizontal baseline, may be appropriately designated phase 0. Designating the inspiratory segment "phase 0" may be logical, as inspiration precedes expiration (see Fig 3). Phase 0 represents the inspiratory phase of the respiratory cycle and, hence, the dynamics of inspiration.

Alpha Angle

The angle between phase II and phase III in an SBT-CO_2 curve (see Fig 1b) as well as in a time capnogram (see Fig 3) has been referred to as the alpha angle [14]. Normally, the alpha angle ranges between 100 and 110 degrees [14]. The alpha angle increases as the slope of phase III increases. The slope of phase III is dependent on the ventilation/perfusion (V/Q) status of the lung. Therefore, the alpha angle is an indirect indication of the V/Q status of the lung [14]. For instance, airway obstruction increases the slope of phase III, and the alpha angle increases from the normal value (108 degrees; Fig 4A) to a higher value (140 degrees; Fig 4B), depending on the degree of airway obstruction. Equipment and patient-related factors, such as response time of the capnometer, sweep speed of the device, and the respiratory cycle time of the patient, can produce changes in the alpha angle [2,17–20]. This effect can be minimized by using analyzers with rapid response time. The response time of CO_2 monitors has been considerably reduced in the newer units by (1) the use of more powerful amplifiers, (2) minimizing the volume of the sampling chamber and tubes, and (3) the use of relatively high sampling flow rates (150 ml/min^{-1}). In order to achieve predictable P_{ETCO_2} values and CO_2 waveforms, it is recommended that the response time of the analyzer be less than the respiratory cycle time of the patient [21]. Further, if the response time and the sweep speed of the analyzer are held constant, and there are no significant changes in the respiratory cycle time of the patient, a comparison of the alpha angle of a given curve with that of a baseline normal curve can be considered a good criterion for assessing any change in the V/Q ratio [14].

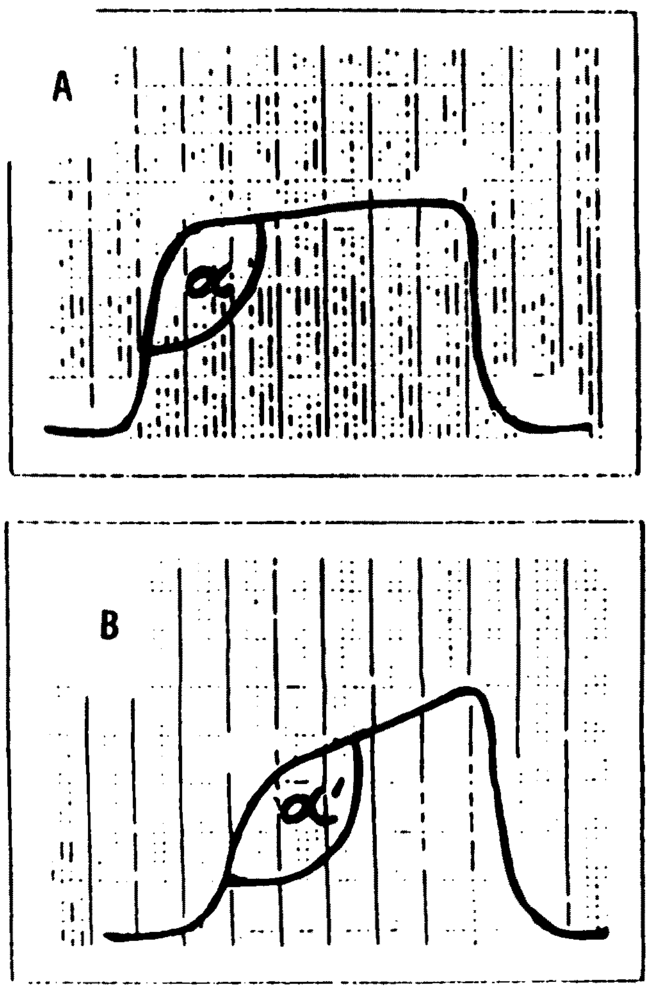

Fig 4. (A) Capnogram recorded during normal breathing, alpha angle = 108 degrees. (B) Capnogram recorded during bronchospasm, alpha' angle = 140 degrees. Note the increase in alpha' angle in (B) during bronchospasm compared to (A).

Beta Angle

The nearly 90-degree angle between phase III and the descending limb in a time capnogram (see Fig 3) has

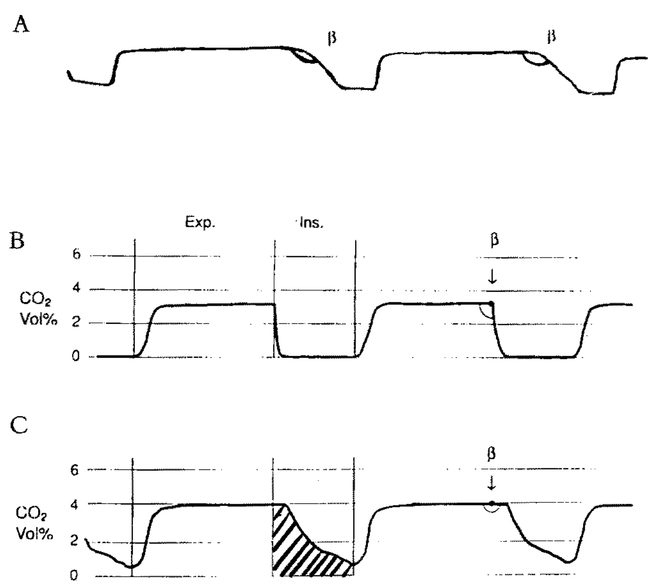

Fig 5. (A) Capnogram recorded during IPPV with excessive dead space. Note the increase in beta angle due to rebreathing. (B) Normal capnogram (recorded during anesthesia IPPV/circle system). Beta angle approximately equals 90 degrees. Ins = inspiration; Exp = expiration. (C) Abnormal capnogram recorded under the same circumstances as in capnogram (B), but with malfunction of the inspiratory unidirectional valve. The beta angle now is 180 degrees, and the shaded area represents rebreathing due to faulty inspiratory valve. (Reproduced from Kumar et al [22], with permission.)

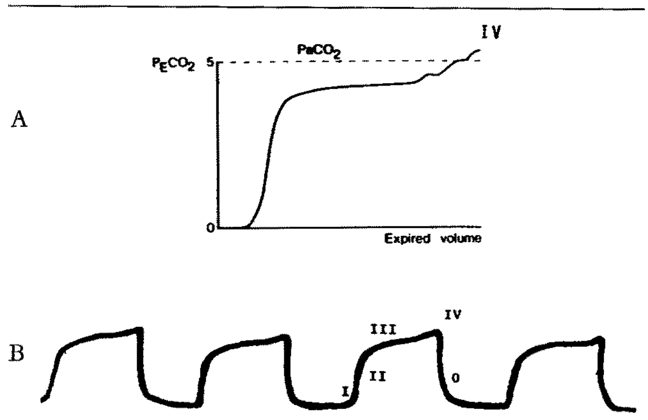

Fig 6. (A) SBT-CO_2 curve recorded in an obese patient during anesthesia/IPPV. (Reproduced from Fletcher [3], with permission.) (B) Time capnograms recorded during anesthesia/IPPV for caesarean section. Phase IV: Terminal upswing at the end of phase III in capnograms (A) and (B).

recently been designated the beta angle [22]. There is no beta angle in an SBT-CO_2 curve, as there is no inspiratory segment (see Fig 1B). This angle can be used to assess the extent of rebreathing [22]. During rebreathing, there is an increase in the beta angle from the normal 90 degrees (Fig 5A). As rebreathing increases, the horizontal baseline of phase 0 and phase I can be elevated above normal (Fig 5C) [2,22–25]. Occasionally, other factors, such as prolonged response time of the capnometer compared to respiratory cycle time of the patient, particularly in children, can produce increases in the beta angle with the elevation of the baseline of phase 0 and phase I, as observed during rebreathing [26]. As stated previously, these effects can be minimized by using faster CO_2 analyzers.

Phase IV

A terminal upswing is observed at the end of phase III in the SBT-CO_2 curve as well as the time capnogram recorded under certain circumstances, such as during anesthesia/IPPV in obese patients and in pregnant subjects (Fig 6A,B). The initial part of phase III is horizontal, or has a minimal slope, and lies below the level of $Paco_2$. The terminal part of phase III ascends steeply and may reach $Paco_2$. This terminal upswing, or rise, is known as phase IV because it resembles phase IV in the SBT-N_2 curve [3,4]. Phase IV of the SBT-N_2 is attributed to airway closure [27]. However, closure of dependent airways theoretically should cause a terminal downswing at the end of phase III in a capnogram, rather than an upswing. This downswing ought to occur because, consequent to the airway closure, the units in dependent regions (low V/Q units) containing high CO_2 relative to nondependent zones (high V/Q units) no longer contribute to the expired gas and, therefore, should result in a decline in the overall CO_2 concentration toward the end of expiration. The mechanism responsible for phase IV (terminal rise) in capnograms recorded in obese subjects as well as in pregnant subjects is complex. However, it may be explained on the basis of the expiratory characteristics of the fast and slow alveoli in these subjects (Fig 7).

Based on the lung model studies, it has been suggested that, in obese subjects with healthy lungs, there may be two lung compartments with different mechanical and V/Q properties (fast and slow compartments) [3,5]. Lung model studies were also used to study the alveolar CO_2 concentrations from fast and slow compartments during passive expiration where the expiratory flow pattern resembles a "die away" exponential function. Figure 7 shows alveolar Pco_2 curves obtained from fast and slow compartments.

From the fast alveolar compartments, there is a rapid initial emptying of gases. The high initial expiratory flow rate implies that most of the gas leaving the alveoli

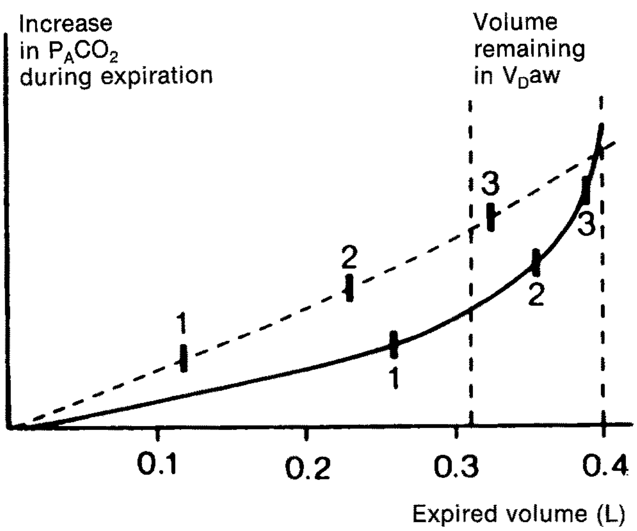

Fig 7. Lower tracing: Alveolar CO_2 curve from "fast alveoli." Time in seconds marked on tracing. Most of the expired gas leaves in the first second and, therefore, does so at an almost constant F_{CO_2}. As gas flow is reduced toward the end of expiration, F_{CO_2} rises steeply. Upper tracing: Alveolar CO_2 from a slow alveoli where the expiratory flow rate is more constant and, therefore, the increase in F_{CO_2} is spread more evenly over the tidal volume. V_{Daw} = airway dead space; P_{ACO_2} = alveolar P_{CO_2}; L = liters. (Reproduced from Fletcher [3], with permission.)

has a rather constant F_{CO_2} and is responsible for the near-horizontal initial part of phase III in CO_2 trace. However, as the expiratory flow decreases toward the end of expiration, the CO_2 content of the expired air increases markedly, producing a terminal steep rise or a "knee" in the F_{CO_2} tracing. This is because, in the latter part of expiration, the delayed alveolar emptying results in higher F_{CO_2} due to the continuous release of CO_2 into the alveoli. Normally, the alveolar gases with high CO_2 may remain within the airways (anatomical dead space) and are not analyzed by the CO_2 sensor at the mouth (see Fig 7). However, the use of large tidal volumes and low-frequency ventilation enables these gases to reach the mouth where the CO_2 sensor registers high F_{CO_2}.

The slow compartments empty at a more even pace, producing a positive slope from the beginning of phase III, as more time is allowed for CO_2 to accumulate in the alveoli. As the expiratory flow rate decreases toward the end of expiration, the slope of phase III increases steadily.

The combined effect of the emptying characteristics of different alveoli determines the shape of the alveolar plateau in an capnogram during IPPV.

The low total thoracic compliance of obese patients is associated with rapid initial emptying of the lungs and phase III of the resulting capnogram predominantly resembles the one produced by the fast compartments: a near-horizontal phase III, or phase III with minimal slope and a terminal upswing (phase IV) similar to phase IV of the SBT-N_2 curve.

Pregnant subjects resemble obese subjects in some features—namely, reduced functional residual capacity (FRC) and low total thoracic compliance. Additionally, CO_2 production is increased in pregnancy. Hence, phase IV may also occur in pregnant subjects during general anesthesia/IPPV with large tidal volumes [2,28]. The presence of phase IV also contributes to the negative (a-ET)CO_2 values, where end-tidal P_{CO_2} may exceed Pa_{CO_2}, which may be observed in obese and pregnant subjects (see Fig 6) [2,3,28–30].

LIMITATIONS OF TIME CAPNOGRAPHY

The time capnogram is convenient and adequate for clinical use; it is the method most commonly used by capnographs. More elaborate equipment is necessary for plotting an SBT-CO_2 trace. The CO_2 analyzer should be designed to operate with the ventilator, which provides a flow signal and a timing pulse. A computer relates the instantaneous CO_2 signals to expired volume and an SBT-CO_2 curve is plotted [3]. Further, the CO_2 analyzers used in SBT-CO_2 tracings are mainstream capnometers, where the cuvette containing the CO_2 sensor is inserted between the endotracheal tube and the breathing circuit. Hence, endotracheal intubation is required for plotting an SBT-CO_2 curve, whereas a time capnogram does not require a ventilator and can be used to monitor spontaneous ventilation without breathing through the ventilator. Further, time capnographs make use of mainstream sensors or sidestream sensors. Time capnographs with sidestream sensors have the sensor located in the main unit itself; the sample of gases is aspirated from the patient's airway, via a tiny pump through a 6-ft capillary tube, into the unit. This enables time capnography to monitor nonintubated patients, as a sampling of the respired gases can be obtained from the nasal cavity using nasal adapters. Furthermore, time capnography can be used to monitor the dynamics of expiration as well as inspiration, whereas the SBT-CO_2 curve monitors expiration exclusively, since it does not have an inspiratory component. There are, however, subtle but important limitations of a time capnography.

1. The V/Q status of the lung is more accurately reflected in the slope of phase III in an SBT-CO_2 trace than in that of a time capnogram, in which the gradient of the phase III slope is usually less obvious. This

may be because a smaller volume of expired gases (approximately the final 15%) occupies half the time available for expiration, so that a similar change in F_{CO_2} is distributed over a greater length of time in the time capnogram than in the SBT-CO_2 trace [3,5].
2. Unlike an SBT-CO_2 trace (see Fig 2), the physiologic dead space and CO_2 output cannot be determined from a time capnogram as currently recorded.
3. Presently, the available time capnographs do not distinguish the end of expiration from the beginning of inspiration. This drawback makes the analysis of time capnograms during inspiration difficult, and results in an inaccurate assessment of rebreathing, which is grossly underestimated. This is explained further below.

In a time capnogram, phase III continues until the end of the expiratory pause or the beginning of the next inspiration because, during this period, CO_2 is being sampled from the endotracheal tube. Therefore, in a time capnogram, phase III not only includes expiration, but also the expiratory pause. Thus, the end-tidal CO_2 in a nonrebreathing time capnogram is actually the end expiratory pause CO_2. Following the expiratory pause, the descending limb represents fresh CO_2-free gas flow during inspiration. It is usually assumed that the beginning of the descending limb corresponds to the start of the inspiration. The descending limb descends rapidly to zero and continues on the zero line until phase II starts. Once again, the time capnograph does not identify the end of inspiration or the beginning of expiration; therefore, phase I cannot be delineated accurately in a time capnogram. Inability to identify the various components of the respiratory cycle on a time capnogram can lead to incorrect determinations of the extent of rebreathing [22]. For instance, the capnogram in Figure 5B represents a normal capnogram recorded during anesthesia using IPPV/circle system. The beta angle in Figure 5B approximately equals 90 degrees, whereas the capnogram in Figure 5C represents an abnormal capnogram recorded under the same circumstances, but with a malfunctioning inspiratory unidirectional valve (same frequency of ventilation and I:E ratio as in Fig 5B). The beta point in Figure 5C represents the end of expiration and the beta angle now is 180 degrees, instead of the usual 90 degrees. The shaded area represents rebreathing resulting from the faulty inspiratory valve. Under these circumstances, the end-tidal F_{CO_2} actually refers to maximum inspiratory F_{CO_2}; the usual assumption that the beginning of the descending limb of phase 0 in a time capnogram corresponds to the start of next inspiration becomes invalid [22]. Therefore, the inability to detect precisely the end of expiration and the beginning of inspiration can lead to gross underestimation of rebreathing [22]. SBT-CO_2 tracings may not be effective in detecting rebreathing, as there is no inspiratory component in the SBT-CO_2 curve. Hence, in the future, there is a need to demarcate inspiration as well as expiration during a respiratory cycle in CO_2-versus-time capnography if it is to remain popular. This would not only enhance the safety of capnography in identifying a defective breathing circuit, but it would also widen the scope for further research. It would permit the identification of any differences between end-tidal CO_2 and end-expiratory pause CO_2, which are of particular importance in those time capnograms where the slope of phase III is steep. This distinction may result in a more accurate prediction of arterial P_{CO_2} from time capnography. Further, the demarcation of the end of expiration and the beginning of inspiration would permit more accurate estimation of rebreathing using time capnography.

CONCLUSIONS

In conclusion, we recommend standard terminology to represent various components of a time capnogram. The time capnogram should be divided into an inspiratory segment and an expiratory segment. The inspiratory segment should be called phase 0, which would include the descending limb and the initial part of the horizontal baseline; the expiratory segment should be divided into phases I, II, and III, and, if present, phase IV. The angle between phase II and III is the alpha angle; the angle between phase III and the descending limb of phase 0 is the beta angle. While time capnography is simpler and more convenient and versatile in clinical practice than the SBT-CO_2 curve, there is the need to obtain even greater and more accurate information with further improvements. Future research should explore the possibility of demarcating the end of expiration and the beginning of inspiration on a time capnogram. This would enable an accurate estimation of rebreathing and would enhance the efficacy of time capnography to identify potentially defective circuits. Furthermore, demarcating the inspiration and the expiration may allow the exploration of estimating physiologic dead space and its components utilizing a time capnogram, as is currently possible in an SBT-CO_2 curve.

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