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Respiration and the Airway

Capnogram slope and ventilation dead space parameters: comparison of mainstream and sidestream techniques

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Abstract

Background: Capnography may provide useful non-invasive bedside information concerning heterogeneity in lung ventilation, ventilation–perfusion mismatching and metabolic status. Although the capnogram may be recorded by mainstream and sidestream techniques, the capnogram indices furnished by these approaches have not previously been compared systematically.

Methods: Simultaneous mainstream and sidestream time and volumetric capnography was performed in anaesthetized, mechanically ventilated patients undergoing elective heart surgery. Time capnography was used to assess the phase II ($S_{II,T}$) and III slopes ($S_{III,T}$). The volumetric method was applied to estimate phase II ($S_{II,V}$) and III slopes ($S_{III,V}$), together with the dead space values according to the Fowler (V_{DF}), Bohr (V_{DB}), and Enghoff (V_{DE}) methods and the volume of CO_2 eliminated per breath (V_{CO_2}). The partial pressure of end-tidal CO_2 (PET_{CO_2}) was registered.

Results: Excellent correlation and good agreement were observed in $S_{III,T}$ measured by the mainstream and sidestream techniques [ratio=1.05 (SEM 0.16), R^2=0.92, P<0.0001]. Although the sidestream technique significantly underestimated V_{CO_2} and overestimated $S_{III,V}$ [1.32 (0.28), R^2=0.93, P<0.0001], V_{DF}, V_{DB}, and V_{DE}, the agreement between the mainstream and sidestream techniques in the difference between V_{DE} and V_{DB}, reflecting the intrapulmonary shunt, was excellent [0.97 (0.004), R^2=0.92, P<0.0001]. The PET_{CO_2} exhibited good correlation and mild differences between the mainstream and sidestream approaches [0.025 (0.005) kPa].

Conclusions: Sidestream capnography provides adequate quantitative bedside information about uneven alveolar emptying and ventilation–perfusion mismatching, because it allows reliable assessments of the phase III slope, PET_{CO_2} and intrapulmonary shunt. Reliable measurement of volumetric parameters (phase II slope, dead spaces, and eliminated CO_2 volumes) requires the application of a mainstream device.

Key words: capnography; carbon dioxide; intraoperative monitoring; mechanical ventilation; ventilation-perfusion ratio

Capnography is a non-invasive method for the numerical and graphical analysis of the exhaled CO_2 concentration,[1–5] and a valuable tool for the improvement of patient safety.[6] Although assessment of capnogram shape factors is not yet a standard part of patient monitoring, it has the promise to provide routine information concerning pathophysiological processes of lung ventilation, such as airway patency[7–10] and lung recoil tendency.[8 9] Furthermore, combination of capnography with expired gas volume

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Editor's key points

- It is not clear which factors sidestream capnography can indicate as accurately as mainstream capnography.
- Mainstream and sidestream time and volumetric capnography were performed to compare several factors in anaesthetized, mechanically ventilated patients undergoing elective heart surgery.
- Sidestream capnography provides adequate quantitative bedside information about uneven alveolar emptying and ventilation–perfusion mismatch, but mainstream capnography is required for a reliable measurement of volumetric parameters.

monitoring allows the assessment of ventilation–perfusion matching and the metabolic status of the body.[3 5 10 11]

In clinical practice, two techniques are available, based on the measurement site of CO_2. Mainstream capnography applies an infrared sensor located proximally to the patient between the tracheal tube and the Y-piece, and thus, allows a rapid and accurate analysis of the CO_2 concentration of the exhaled gas.[12–14] However, this method is used mainly in intensive care units, because of the disadvantages posed by the local heating of the head and the weight of the sample cell, which increases the risk of tracheal tube dislocation.

As an alternative, sidestream capnography is often used in the operating theatre because it is easily manageable and allows the monitoring of other gases.[7–9 15] These devices analyse the gas sample distally from the patient, and therefore, have the drawbacks of a prolonged total response time,[16–18] the occurrence of axial mixing,[2 10 11 19] and a variable suction flow rate.[20] All these processes result in a dynamic distortion of the CO_2 concentration curve, and thus, have a potential to bias the derived capnographic parameters.

There have been a few previous attempts to compare capnographic parameters obtained by sidestream and mainstream techniques, but they were the manufacturer's educational material,[21] focused only on the end-tidal CO_2 value in experimental[22] and clinical studies,[23–25] or were limited to a small cohort of infants.[26] However, there is a lack of information about the relationship between capnographic indices obtained by sidestream and mainstream techniques in mechanically ventilated adults. Therefore, the aim of the present study was to validate the ability of the sidestream technique to provide adequate quantitative bedside information about uneven alveolar emptying and ventilation–perfusion mismatching. Therefore, we determined which of the capnogram parameters (shape factors, respiratory dead space) can be assessed reliably by applying the sidestream technique. We hypothesized that sidestream capnography is suitable to measure indices obtained from the quasi-static phases of the capnogram, whereas phases with transient CO_2 concentration changes are exposed to measurement bias.

Methods

Patients

Twenty-nine patients [female/male: 13/16, 71 (57–85) yr old] undergoing elective cardiac surgery were enrolled into the study in a prospective consecutive manner. The study protocol was approved by the Human Research Ethics Committee of the University of Szeged, Hungary (no. WHO 2788). Written informed consent was obtained from each patient. Patients with severe cardiopulmonary disorders (pleural effusion >300 ml, ejection fraction <30%, BMI >35 kg m^{-2}, or intraoperative acute asthma exacerbation) were excluded.

Anaesthesia and surgery

Anaesthesia was induced with i.v. midazolam (30 µg kg^{-1}), sufentanil (0.4–0.5 µg kg^{-1}), and propofol (0.3–0.5 µg kg^{-1}), and was maintained by an i.v. propofol infusion (50 µg kg^{-1} min^{-1}). Neuromuscular block was achieved by i.v. boluses of rocuronium (0.2 mg kg^{-1} every 30 min).

After tracheal intubation, the patients' lungs were mechanically ventilated in volume-controlled mode with descending flow (Dräger Zeus, Lübeck, Germany) by setting the tidal volume to 7 ml kg^{-1}, the ventilator frequency to 9–14 bpm, and the PEEP to 4 cm H_2O, and maintaining the inspired oxygen fraction at 0.5.

Recording and analyses of the expiratory capnogram

The measurement set-up was designed to allow the sampling of the mainstream (Capnogard®; Novametrix, Andover, MA, USA) and sidestream (Ultima™; Datex/Instrumentarium, Helsinki, Finland) capnographs from the same sampling site in the ventilator circuit. This was achieved by connecting the sampling port of the sidestream capnograph next to the mainstream sensor between the Y-piece and the tracheal tube. A screen pneumotachograph (Piston Ltd, Budapest, Hungary) was used to record the central airflow at the same point of the ventilator circuit. Simultaneous 15 s recordings of the CO_2 signals of the mainstream and sidestream capnographs and the ventilation flow were digitized (sampling frequency 102.4 Hz) and analysed with custom-made software. Volumetric capnograms were constructed from the time capnograms and the integrated flow data. To compensate for the transport delay caused by the suction of the gas into the sample cell, the sidestream time capnograms were shifted by −1.65 s. This value was determined by analysing the time delay between the mainstream and sidestream capnogram curves during stepwise changes in CO_2 concentration, in a similar manner to an earlier approach.[17]

The slopes of phase III of the time and volumetric capnograms determined by mainstream ($S_{III,T,MS}$ and $S_{III,V,MS}$) and sidestream ($S_{III,T,SS}$ and $S_{III,V,SS}$) capnography were assessed by fitting a linear regression line to the last 60% of phase III.[7 8 12] Likewise, regression lines were fitted to the points around the inflexion point of phase II within 20% of the time or volume of phase II, to determine their slopes in the mainstream ($S_{II,T,MS}$ and $S_{II,V,MS}$) and sidestream ($S_{II,T,SS}$ and $S_{II,V,SS}$) measurements. The angles formed by the phase II and III limbs of the expiratory time mainstream (α_{MS}) and sidestream (α_{SS}) capnograms were calculated from the phase II and phase III slopes using a monitoring speed of 1.67 kPa s^{-1} (12.5 mm Hg s^{-1}).

Additionally, dead space fractions were calculated from volumetric capnograms. Fowler's dead space, reflecting the volume of the conducting airways,[27] was determined by taking the volume expired up to the inflexion point of phase II from the mainstream and sidestream capnograms ($V_{DF,MS}$ and $V_{DF,SS}$). The physiological dead space according to Bohr ($V_{DB,MS}$ and $V_{DB,SS}$), reflecting the alveolar volume with decreased or no perfusion, was calculated from the mainstream and sidestream capnograms as follows:[28]

$$V_{DB,MS}/V_T = (Pa_{CO_2,MS} - P\bar{E}_{CO_2,MS})/Pa_{CO_2,MS}$$
$$V_{DB,SS}/V_T = (Pa_{CO_2,SS} - P\bar{E}_{CO_2,SS})/Pa_{CO_2,SS}$$

where $Pa_{CO_2,MS}$ and $Pa_{CO_2,SS}$ are the mean alveolar partial