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The effect of airway narrowing and dead space on the shape of the capnogram

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Abstract: We have investigated the effects of incomplete obstruction of the endotracheal tube and the amount of additional dead space between the endotracheal tube and the capnographic sampling adapter on the shape of the capnogram. A 9.0-mm endotracheal tube was connected to a 3-L reservoir bag filled from the bottom with 5% carbon dioxide and 95% oxygen. The narrowed adapter (internal diameter: 3.0, 4.0, 6.5, and 9.0 mm), the capnographic sampling adapter, and a semiclosed respiratory system were successively connected to this endotracheal tube. Additional dead space (0, 30, 62, 92, 124, or 154 ml) was inserted between the narrowed adapter and the capnographic sampling adapter. The reservoir bag was ventilated with the anesthesia ventilator (fresh gas flow, 6 L·min^{-1}; tidal volume, 500 ml; respiratory rate, 10 min^{-1}, and inspiratory-expiratory ratio, 1:2). The capnogram from each initial ventilation was recorded and the peak carbon dioxide tension (P_{peak} CO_2) was also measured. The $T_{90\%}$ value was defined as the time it took for the capnograph output to respond from 0% to 90% of the P_{peak} CO_2. The $T_{90\%}$ value seen in a 3.0-mm adapter did not change compared with the value in a 9.0-mm adapter, when no additional dead space was connected between the endotracheal tube and the capnographic sampling adapter. Further, the slanting upstroke of the capnogram occurred only when the endotracheal tube narrowing and a large amount of dead space between the endotracheal tube and the capnographic sampling adapter coexisted. Thus, it is unlikely that incomplete obstruction of the endotracheal tube can easily be detected by the slanting upstroke of the capnogram.

Key words: Airway, Capnography, Capnogram, Carbon dioxide tension, Dead space

Introduction

Early detection of endotracheal tube accidents are accomplished by capnography [1–3]. The absence of ventilation, which may result from esophageal intubation, accidental tracheal extubation, disconnection of the endotracheal tube from the mechanical ventilator, or obstruction of the endotracheal tube, is diagnosed by sudden disappearance of the capnographic waveform [1–3]. Further, partial obstruction of the endotracheal tube shows some change in the shape of the capnogram, i.e., the shape of the slanting expiratory upstroke phase and/or the upsloping on reaching the respiratory plateau [2,3]. Murray and Modell [3] reported similar changes in the shape of the capnogram in the dog when the endotracheal tube was kinked 90° or more without total obstruction. However, it has not been clarified whether the degree of airway narrowing related to the endotracheal tube affects the shape of the capnogram.

On the other hand, the dead space between the patient and the capnographic sampling adapter is one of the factors responsible for widening of the arterial to end-tidal carbon dioxide differences [2,4]. Carbon dioxide-free air in the dead space causes dilution of carbon dioxide contents in the exhaled gas [2,4]. Thus, dead space between the endotracheal tube and the capnographic sampling adapter may influence the shape of the capnogram during incomplete obstruction of the endotracheal tube.

Therefore, we have investigated the effects of airway narrowing related to the endotracheal tube and the amount of additional dead space between the endotracheal tube and the capnographic sampling adapter on the shape of the capnogram in an experimental system that uses a reservoir bag as a model lung.

Materials and methods

After the recommended warm-up time, the capnograph (POET II; Criticare Systems, Waukesha, WI, USA) was calibrated with a gas mixture containing 5% carbon dioxide and 95% oxygen. Gas samples were then aspi-

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rated through a 2-m sampling line, and with the sampling rate of the capnograph set at 150 ml·min^{-1}. The time it took for the capnograph output to respond to a step change from 5% to 95% of the peak carbon dioxide concentration was 125 ms. The experimental system of this study is shown in Fig. 1. In brief, the endotracheal tube, with an internal diameter of 9.0 mm, was connected to the 3-L reservoir bag. The cuff of the endotracheal tube was sufficiently inflated with air so that no air leakage occurred when the bag was ventilated via the endotracheal tube. Then, narrowed adapters (10 cm in length with an internal diameter of 3.0, 4.0, 6.5, or 9.0 mm), the capnographic sampling adapter, the semiclosed anesthetic system, and the anesthesia machine were successively connected to the endotracheal tube. Next, additional dead space (0, 30, 62, 92, 124 or 154 ml) was inserted between the tested narrowed adapter and the capnographic sampling adapter. Additional dead space was made up of the heat and moisture exchanger (Thermovent 600, Portex, Hythe, England) and the Flex Tube of HME 15-22F (Heat and moisture exchanger, Pall, Glen Cove, NY, USA). Then, the reservoir bag was filled from the bottom with mixed air, containing 5% carbon dioxide and 95% oxygen and the inflow rate was maintained at 2 L·min^{-1} throughout the measurement.

After the experimental system was set up, the reservoir bag was ventilated by the anesthesia ventilator (KMA-1300 F, Acoma, Tokyo, Japan). The ventilator was set up as follows: the fresh gas flow, 6 L·min^{-1}; F_IO_2, 1.0; tidal volume, 500 ml; respiratory rate, 10 min^{-1}; and inspiratory-expiratory ratio, 1:2. The airway pressure and expiratory tidal volume was monitored by the airway pressure monitor and the respirometer (Ohmeda, West Yorkshire, England) built into the anesthesia machine. Each capnogram of initial ventilation was recorded with a Think Jet printer (Hewlett Packard, Andover, MD, USA) and simultaneously, each peak carbon dioxide tension ($P_{peak}CO_2$) was measured. The time for the capnograph output to respond to a step change from 0% to about 90% of the $P_{peak}CO_2$ indicates the time from the beginning to the end of upstroke in the normal capnogram. Furthermore, the time from 10% to 63% or 70% of the $P_{peak}CO_2$, is considered to represent the dynamic response time of the capnograph itself [5,6]. Thus, in the present study, the $T_{90\%}$ was defined as the time that it took for the capnogram to respond from 0% to 90% of the $P_{peak}CO_2$. In this manner, the $T_{90\%}$ value was obtained for each recorded capnogram and then used to estimate the degree of slanting upstroke of the capnogram.

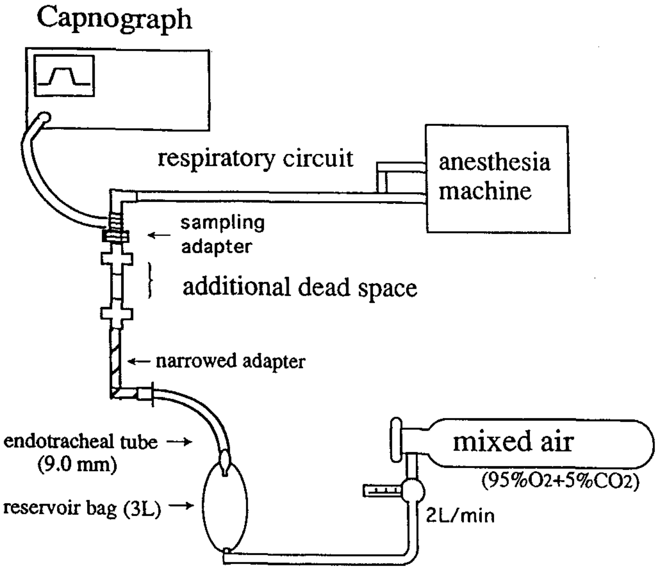

Fig. 1. Diagram of the experimental system setup

Values expressed in the text are means ± SD. The statistical analysis was performed by a one-way ANOVA, followed when appropriate by Scheffe's F-test for the measurement of the $T_{90\%}$ value and the P_{peak} CO_2 value in each narrowed adapter and for the measurement of the $T_{90\%}$ value and the $P_{peak}CO_2$ value in each additional dead space. A linear regression analysis was also performed between the $T_{90\%}$ value and the internal diameter of the narrowed adapter, and between the $T_{90\%}$ value and the amount of additional dead space. A value of $P < 0.05$ was considered statistically significant.

Results

Representative capnograms of each adapter and of each additional dead space are shown in Fig. 2. The typically slanted upstroke and upsloping plateau seen in capnograms occurred when a 3.0-mm adapter was connected to the experimental system and the additional dead space amounted to 124 ml or 154 ml.

The effect of the diameter of the narrowed adapter and the additional dead space on the $T_{90\%}$ value is shown in Fig. 3. The $T_{90\%}$ value significantly increased when a 9.0, 6.5, 4.0, or 3.0 mm adapter was connected and additional dead space of 154 ml (1.25 ± 0.07, 1.23 ± 0.06, 1.35 ± 0.08, 1.69 ± 0.03 s, respectively), compared with the $T_{90\%}$ value when there was no additional dead space with same adapters (0.43 ± 0.03, 0.44 ± 0.02, 0.43 ± 0.02, 0.5 ± 0.03 s, respectively). Further, the $T_{90\%}$ value seen in a 3.0-mm adapter was the same as that seen in a 9.0-mm adapter when no additional dead space was connected.

The linear regression between the $T_{90\%}$ value (Y_1, s) and the internal diameter of the adapter (X_1, mm) was calculated as follows: dead space, 0 ml: $Y_1 = -0.009X_1 + 0.495$ ($r = 0.337$, not significant); dead space, 30 ml:

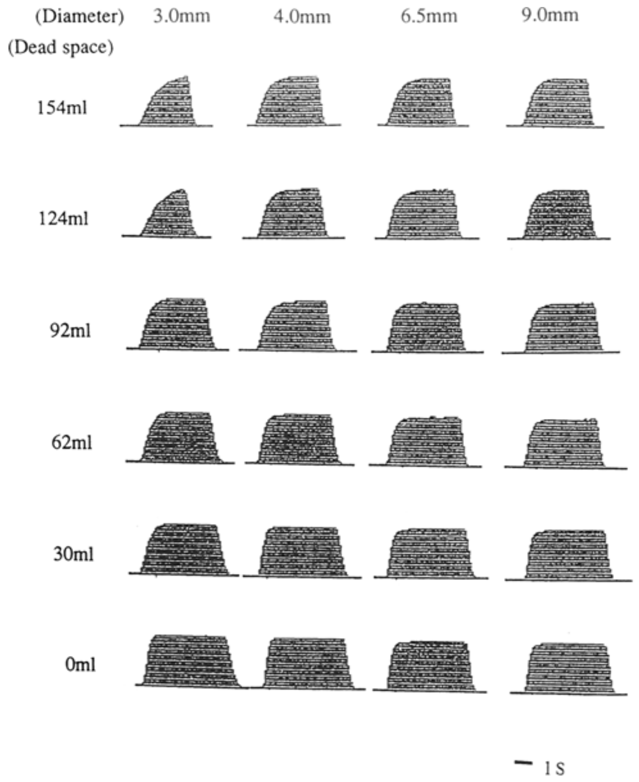

Fig. 2. Representative capnographic tracings of each adapter and each additional dead space are shown. Both a sharply slanted upstroke and upsloping plateau were seen when a 3.0-mm adapter and 124 ml or 154 ml of additional dead space were tested

$Y_1 = -0.014X_1 + 0.642$ ($r = 0.259$, not significant); dead space, 62 ml: $Y_1 = -0.022X_1 + 0.834$ ($r = 0.474$, $P < 0.05$); dead space, 92 ml: $Y_1 = -0.024X_1 + 1.088$ ($r = 0.297$, not significant); dead space, 124 ml: $Y_1 = -0.071X_1 + 1.484$ ($r = 0.546$, $P < 0.01$); dead space, 154 ml: $Y_1 = -0.061X_1 + 1.724$ ($r = 0.609$, $P < 0.01$). When 62, 124, or 154 ml of additional dead space were present in the system, the $T_{90\%}$ value and the internal diameter value were significantly correlated.

However, in spite of being statistically significant, these regression coefficients were much smaller than the regression coefficients between the $T_{90\%}$ value and the amount of additional dead space.

The linear regression between the $T_{90\%}$ value (Y_1, s) and the amount of additional dead space (X_2, ml) was calculated as follows: 9.0-mm adapter: $Y_1 = 0.005X_2 + 0.377$ ($r = 0.876$, $P < 0.01$); 6.5-mm adapter: $Y_1 = 0.005X_2 + 0.428$ ($r = 0.927$, $P < 0.01$); 4.0-mm adapter: $Y_1 = 0.006X_2 + 0.377$ ($r = 0.889$, $P < 0.01$); and 3.0-mm adapter: $Y_1 = 0.008X_2 + 0.414$ ($r = 0.924$, $P < 0.01$). Thus, the $T_{90\%}$ value and the amount of additional dead space were well correlated in the linear regression analysis.

The effect of the narrowed adapter and additional dead space on the P_{peak} CO_2 value is shown in Fig. 4. When a 3.0-mm adapter was used and with additional dead space of 154 ml, the P_{peak} CO_2 value significantly decreased compared with no additional dead space. With connections involving a 3.0-mm adapter and additional dead space of 0, 30, 62, or 92 ml, and a 4.0-mm adapter and additional dead space of 0 or 30 ml, the P_{peak} CO_2 values significantly increased compared with the 9.0-mm adapter.

The peak airway pressure values when 9.0-, 6.5-, 4.0-, or 3.0-mm adapters were used were approximately 8, 11, 35, and 55 cm H_2O, respectively. Further, the expiratory tidal volume when each adapter was used amounted to approximately 500, 500, 450, and 400 ml, respectively.

Discussion

This study has found that the slanting expiratory upstroke phase of the capnogram occurs only when endotracheal tube narrowing and a large amount of dead space between the endotracheal tube and the capnographic sampling adapter coexist.

The $T_{90\%}$ value seen in a 3.0-mm adapter, whose cross-sectional area was about 7.0 mm^2, did not change compared with a 9.0-mm adapter, when no additional dead space was connected between the endotracheal tube and the capnographic sampling adapter. Thus, it is unlikely that incomplete obstruction of the endotracheal tube is easily detected by the slanting upstroke of the capnogram. Murray and Modell [3] showed the slanting upstroke of the capnogram sampled from a sideport of the Y-connector where the endotracheal tube was connected to it. However, in their study, the endotracheal tube was kinked 90° or more without total obstruction [3]. More severe airway narrowing might exist in their study than that in the present study. Thus, more severe airway narrowing than occurred in the present study may be needed to slant the upstroke phase of the capnogram. In contrast, the peak inspiratory pressure markedly increased with a decrease in the size of the internal diameter of the adapter. It appears that airway pressure monitoring is more reliable than capnography during airway narrowing.

In the present study, the slanting upstroke phase of the capnogram occurred only when a smaller narrowed adapter and a large amount of dead space between the endotracheal tube and the capnographic sampling adapter coexisted. Furthermore, the $T_{90\%}$ value and the amount of additional dead space were well correlated in the linear regression analysis. Thus, to detect incomplete obstruction of the endotracheal tube caused by changes in the shape of the capnogram, it seems necessary to locate the capnographic sampling adapter at a distance from the endotracheal tube. However, dilution

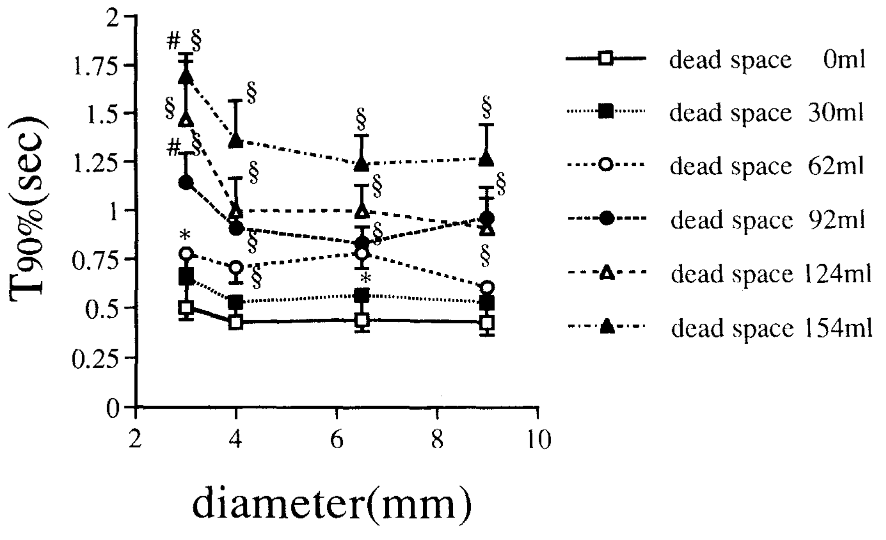

Fig. 3. Graph showing the correlation of the time the capnograph took to reach 90% of peak CO_2 tension ($T_{90\%}$) and airway narrowing and the varying amount of additional dead space ($n = 6$). $*P < 0.05$, $\#P < 0.01$, vs. 9.0-mm diameter; §$P < 0.01$ vs. 0 ml of dead space

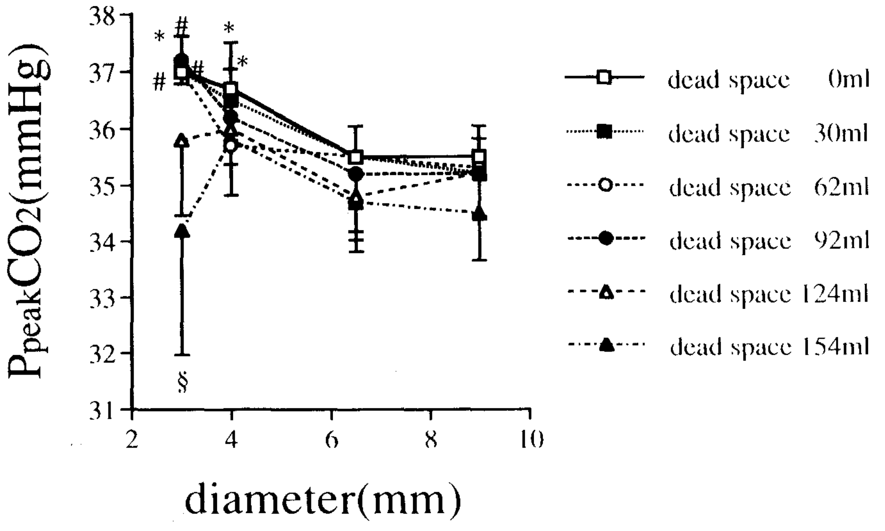

Fig. 4. Graph showing the effects of airway narrowing and additional dead space ($n = 6$) on peak CO_2 tension ($P_{peak}CO_2$). $*P < 0.05$, $\#P < 0.01$ s 9.0mm diameter; §$P < 0.01$ vs 0 ml of dead space

of the end-tidal gas in addition to dead space ventilation appears to be responsible for inaccuracies during end-tidal carbon dioxide tension measurement [2,4]. It is recommended that the exhaled gas is sampled from the proximal end of the endotracheal tube and sometimes from the distal end, particularly in infants and children [4]. Therefore, we usually sample the exhaled gas for capnography near the proximal end of the endotracheal tube. It might help to explain why changes in the shape of the capnogram during incomplete obstruction of the endotracheal tube are rarely seen in clinical practice.

No change in the P_{peak} CO_2 was noted in most adapters when the amount of additional dead space increased, the exception being the 3.0-mm adapter. Thus, changes in the shape of the capnogram may be more sensitive than end-tidal carbon dioxide tension during airway narrowing related to the endotracheal tube.

Several limitations of this study should be mentioned. In the present study, the reservoir bag was not equally ventilated by the anesthesia ventilator because the expiratory tidal volume varied with the adapter diameter: decreases in the expiratory tidal volume of 5%–10% occurred in both 4.0- and 3.0-mm adapters compared with the set tidal volume, though no decrease in expiratory tidal volume occurred with either the 9.0- or 6.5-mm adapters. These differences may account for the changes in the P_{peak} CO_2 values when a smaller amount of additional dead space is connected to the system. Thus, our findings should be interpreted cautiously and limited to the situation when incomplete obstruction of the endotracheal tube occurs during ventilation with an anesthesia ventilator.

The present results suggest that it is unlikely that incomplete obstruction of the endotracheal tube is easily detected by the slanting upstroke of the capnogram.

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