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TECHNICAL NOTE

Expiratory flushing of airways: a method to reduce deadspace ventilation

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Expiratory flushing of airways: a method to reduce deadspace ventilation. B. Jonson, T. Similowski, P. Levy, N. Viires, R. Pariente.
ABSTRACT: **A jet of fresh gas entering the trachea during the last part of expiration, expiratory flushing of airways (EFA), may during mechanical ventilation bring the fresh gas interface into the trachea to reduce deadspace. EFA, delivered in a variety of modes, was tested in healthy dogs. EFA allowed tidal volume, peak and mean airway pressure to be reduced by about 25%. EFA was administered in the form of pulses with frequencies 2–8 Hz, and as a continuous flow. The mode was of little importance. EFA was found to be efficient and should be clinically tested.**
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In mechanically ventilated patients with severe lung disease adequate elimination of CO_2 may be difficult to achieve without using deleteriously high airway pressures. During expiration the airways are filled with alveolar gas rich in CO_2. This gas can be partly eliminated by flushing the upper airways with CO_2-free gas. At the start of the following inspiration, the interface between alveolar and fresh gas will then be situated in the trachea or the main bronchi. This implies a reduction of deadspace that should allow smaller tidal volumes and lowering of airway pressures.

Expiratory flushing of airways (EFA), is a simple approach. The principle has been recognized [1, 2], but not systematically evaluated.

The goal of the present study was to investigate the technical feasibility of EFA and to evaluate some modes of its administration in an animal model.

Materials and methods

Five healthy beagle dogs, weighing 11–18 kg, were anaesthetized with pentobarbital (a bolus 15 $mg \cdot kg^{-1}$ and infusion 3 $mg \cdot kg^{-1} \cdot h^{-1}$). They were intubated and curarized with pancuronium bromide (0.1 $mg \cdot kg^{-1}$+0·06 $mg \cdot kg^{-1} \cdot h^{-1}$). Body temperature was kept constant by covering the dogs with aluminum foil and heating the operating table. An arterial catheter was used for sampling of blood for gas analysis (Radiometer, Copenhagen, Denmark).

The dogs were intubated with a Mallincrodt Hi-Lo Jet tracheal tube, size 8 or 9. They were ventilated with a ServoVentilator 900C (Siemens Elema, Sweden). Volume controlled ventilation was given with a square inspiratory flow pattern, at 20 $breaths \cdot min^{-1}$. The minute ventilation was adjusted to give an arterial carbon dioxide tension (Pa_{CO_2}) of about 4.7 kPa (35 mmHg). Inspiratory time was 25% of the respiratory cycle and post-inspiratory pause 10%. This regular mode of ventilation is denoted (RMV).

Expiratory CO_2 concentration was measured with a CO_2 Analyzer 930 (Siemens Elema AB) that integrates the CO_2 signal and the flow signal to a continuous display of CO_2 elimination per minute. The signals were analysed in a personal computer (IBM) to yield the single-breath test for CO_2, (SBT-CO_2) (fig. 1) [3].

EFA was administered *via* the jet port inside the tracheal tube 60 mm from its tip. A high frequency jet ventilator operating under control of the ServoVentilator was used (a prototype from Siemens Elema AB, Sweden). The jet ventilator is set to deliver pulses of gas during any period of the ventilatory cycle of the ServoVentilator. The jet flow rate can be determined as well as the frequency and duration of pulses.

EFA was started after 50% of the expiratory phase had elapsed and was continued until 10% remained. In this way the last portion of the flushing gas had time to be expired (fig. 2). The flushing was delivered as

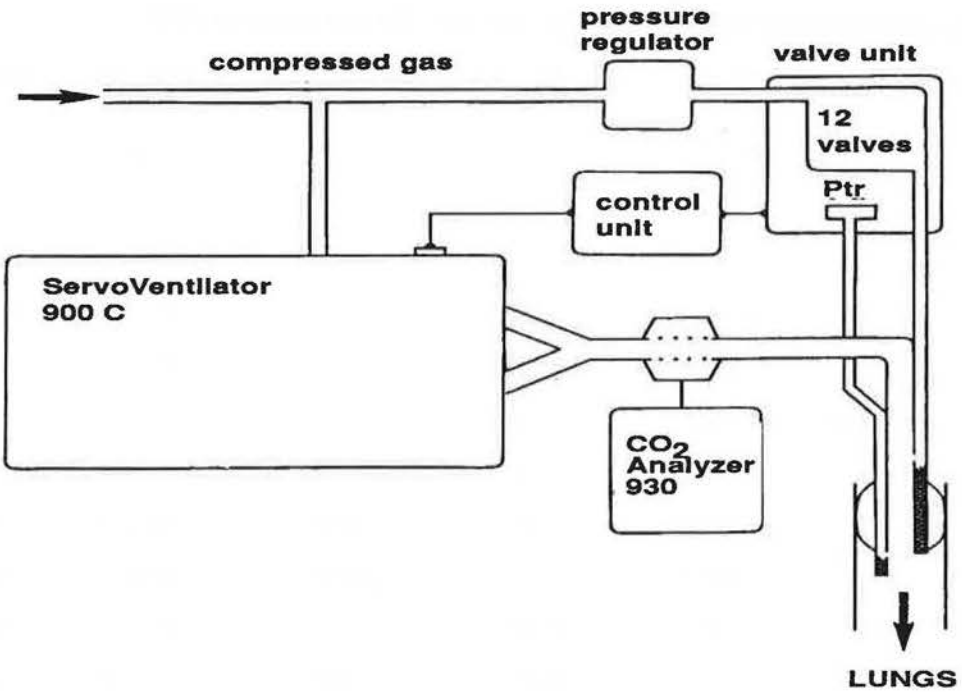

Fig. 1. – The unit for high frequency ventilation comprised a pressure regulating valve, a valve unit and an electronic control unit. The latter allows control of the jet pulses with respect to the phase of the ServoVentilator 900C. The airway pressure was measured *via* the pressure lumen of the jet tracheal tube. Retrograde flow caused by entrainment during the jet pulses was hindered by a one way valve in the expiratory line within the ventilator.

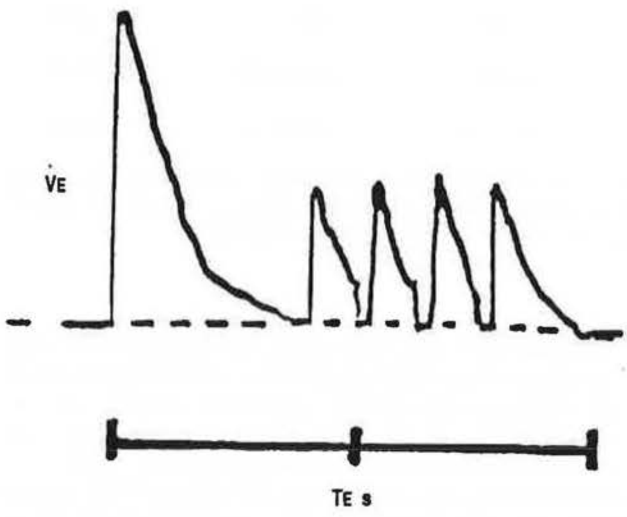

Fig. 2. – Expiratory flow pattern during EFA. The time period for expiration (TE) starts with a regular free expiration followed by a train of four mini-expirations, each corresponding to a prior jet pulse. The pulse frequency was in this case 4 Hz. V̇e: minute ventilation; EFA: expiratory flushing of airways.

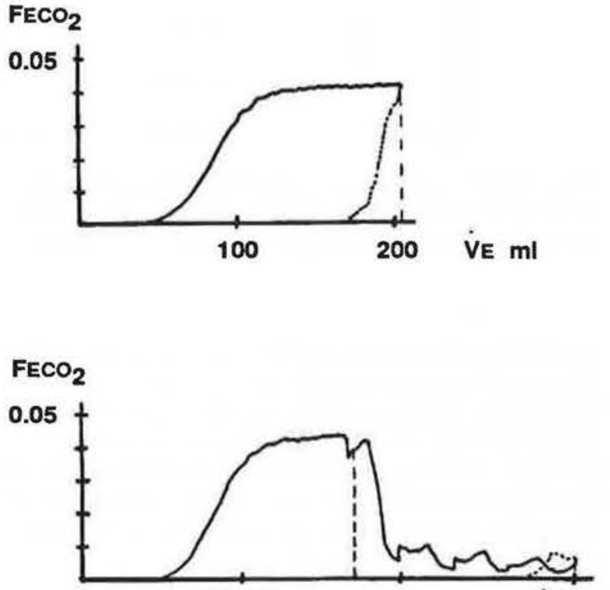

Fig. 3. – Upper panel: The SBT-CO_2 during RMV, *i.e.* fraction of CO_2 plotted *versus* expired volume is shown by the drawn curve. The area under this curve corresponds to expired volume of CO_2. The dotted curve represents the following inspiration. A certain volume of CO_2 is reinspired (area under the dotted curve). Lower panel: During EFA expiration starts as during RMV. The reduced tidal volume from the ordinary ventilator (interrupted line) was reduced compared to RMV (upper panel). Each EFA pulse, in this case four, conveyed a certain volume of CO_2, that rapidly declined with the number of pulses. The reinspired volume of CO_2 (area under the dotted curve) was reduced compared to RMV. SBT-CO_2: single-breath test for carbon dioxide; RMV: regular mode of ventilation; F_{ECO_2}: fraction of expired CO_2. For further abbreviations see legend to figure 2.

pulses with a frequency of 2, 4 and 8 Hz, or as a constant flow (cf). The flushing period was close to one second. This means that 2, 4 and 8 pulses were produced per breath when EFA was given as pulses. The time for the flushing flow (Ti), was either 25 or 50% of the total pulse cycle time. The volume used for EFA was selected to be about 1.5 and 2.5 times larger than the airway deadspace (VDaw), determined from SBT-CO_2.

Table 1. – Data demonstrating homeostasis during RMV and EFA and effects of EFA

Pattern of ventilation	frequency	Ti	$Paco_2$ kPa	Pao_2 kPa	Tidal volume ml	Peak pressure kPa	Mean pressure kPa
RMV			4.5±0.1	13.3±1.3	196±19	1.22±0.17	0.32±0.07
EFA							
V_{EFA} = 1.5	2	0.25	4.4±0.3	12.5±1.1	134±21	0.96±0.18	0.24±0.07
		0.50	4.4±0.3	12.5±1.3	144±30	1.05±0.15	0.28±0.04
	4	0.25	4.4±0.3	12.9±1.6	144±31	0.98±0.18	0.25±0.07
		0.50	4.5±0.4	12.7±1.5	150±27	1.01±0.16	0.28±0.07
	8	0.25	4.5±0.3	12.7±1.3	144±29	0.98±0.16	0.26±0.07
		0.50	4.6±0.4	12.4±1.5	143±27	1.02±0.17	0.28±0.07
	cf		4.5±0.2	12.7±1.1	150±32	1.09±0.17	0.29±0.05
V_{EFA} = 2.5	2	0.25	4.5±0.2	13.3±1.3	123±29	0.86±0.17	0.20±0.08
		0.50	4.5±0.4	12.2±0.9	143±36	1.09±0.20	0.26±0.07
	4	0.25	4.4±0.2	12.1±1.3	146±9	1.04±0.13	0.25±0.05
		0.50	4.4±0.2	12.3±1.2	169±20	1.14±0.20	0.29±0.05
	8	0.25	4.6±0.2	12.3±1.6	149±17	1.06±0.17	0.26±0.05
		0.50	4.7±0.4	12.1±1.1	153±27	1.06±0.24	0.29±0.05
	cf		4.4±0.4	12.5±1.2	142±30	1.08±0.14	0.28±0.04

V_{EFA} signifies the volume used for flushing per breath, *i.e.* 1.5 or 2.5 times the airway deadspace. Frequency is in Hz and Ti in % of the jet cycle. cf: constant flow; $Paco_2$ and Pao_2: arterial carbon dioxide and oxygen tension, respectively; RMV: regular mode of ventilation; EFA: expiratory flushing of airways; Ti: time for flushing flow. mean±SD.

In all dogs each mode of EFA was tested in random order and compared to the average of three observations made at RMV. At each new mode the ventilation was immediately adjusted to keep CO_2-elimination constant. As metabolism is stable a constant arterial partial pressure of CO_2, ($Paco_2$), was expected.

Statistical analysis was performed with Student's t-test for paired observations.

Results

Figure 2 shows a typical expiratory flow pattern at EFA in the dogs. During each jet pulse the flow in the expiratory line fell to zero. Each jet pulse was followed by a "mini-expiration". The SBT-CO_2 during RMV and EFA is shown in figure 3. During RMV the typical three phases of expiration are observed, namely the absolute space followed by mixed airway and alveolar gas, and the alveolar plateau. At the start of the following inspiration the CO_2 in the mouthpiece and in the adjacent ventilator tubes is reinspired [3].

During EFA the first parts of the SBT-CO_2 was similar to that observed at RMV. After expiration of the reduced tidal volume, additional volumes of gas corresponding to the EFA pulses were exhaled. The pulses conveyed extra volumes of CO_2. The CO_2 concentration in exhaled gas fell toward zero during EFA, showing that little CO_2 remained in the main airways at the end of EFA. Accordingly the first EVA pulses were more effective than later pulses. A further effect of EFA was that the volume of reinspired CO_2 was reduced.

$Paco_2$ was unchanged, (table 1). Pao_2 showed a nonsignificant tendency toward slightly lower values during EFA compared to RMV. Tidal volume(V_T), delivered by the ServoVentilator was during EFA 63–86% of that observed during RMV ($p<0.01$), (table 1). Peak and mean airway pressures were reduced in nearly the same proportions as V_T. The reductions of V_T and peak airway pressure were slightly larger at the shorter Ti (25%) ($p<0.05$). When various pulse frequencies were compared, no significant differences were found. The larger flushing volumes (2.5 times

VDaw) were not more efficient than the smaller ones (1.5 times VDaw).

Discussion

EFA was found to allow reduction of tidal volume and airway pressure at mechanical ventilation, under preservation of isocapnic conditions. The recordings of expired CO_2 demonstrate that a considerable volume of CO_2 is eliminated by the flushing. Previous observations of enhanced CO_2 elimination during combined high frequency and ordinary mechanical ventilation [4] can be explained by its effect on airway deadspace.

The degree of VT reduction, about 25%, reflects the volume of airways which was reached by the flushing jet. The exact mode in which EFA was produced was of little importance. The shorter jet pulses, Ti 25%, were slightly more efficient, which is in agreement with the finding that a high instant flux of gas promotes gas exchange in high frequency jet ventilation [5]. The jet probably penetrates deeper into the airways when it is delivered at a high linear velocity. In this context, one may remember that the geometry of the jet orifice and its position in the airway is important. The tube used in this study provides a standardization of these factors.

If the gas volume delivered as EFA pulses would not as a whole have been exhaled during the particular breath an auto-positive end-expiratory pressure (PEEP) effect or hyperinflation would result. A certain time was allowed for free expiration after the last EFA pulse. During that period the expiratory flow fell close to zero. EFA did, accordingly, not produce any important auto-PEEP effect. Another indication that EFA did not cause hyperinflation is that peak pressure fell to about the same extent as did VT. The slightly lower Pao_2 during EFA compared to RMV suggests the same conclusion, as this tendency is compatible with a reduction of mean lung volume during the respiratory cycle, rather than the opposite.

In this study a "first order effect" of EFA was demonstrated. The reduction of deadspace and VT achieved may make it suitable to increase breathing frequency and so gain a "second order advantage" as concerns reduction in airway pressure.

Clinical usefulness of EFA remains to be explored. In particular, we expect EFA to be useful in patients with severe lung disease and CO_2 retention. EFA may also be useful in cases without significant lung pathology. During neurosurgery hyperventilation and low venous pressure are desired in order to minimize arterial and venous bleeding, respectively. Deadspace reduction may then be important. In severe metabolic acidosis hyperventilation may also be desirable without resorting to high tidal volume and airway pressure.

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Rinçage expiratoire des voies aériennes. Une méthode pour réduire la ventilation de l'espace mort. B. Jonson, T. Similowski, P. Levy, N. Viires, R. Pariente.

RÉSUMÉ: Comme une bouffée de gaz frais pénètre dans la trachée au cours de la dernière partie de l'expiration, un rinçage expiratoire des voies aériennes (EFA) peut, pendant la ventilation mécanique, amener l'interface de gaz frais dans la trachée pour réduire l'espace mort. EFA, adminstré de diverses façons, a été testé chez des chiens bien portants. EFA a permis une réduction d'environ 25% du volume courant, de la pression de pointe et de la pression moyenne des voies aériennes. EFA a été administré sous forme de vibrations de fréquence de 2 à 8 Hz, ainsi que sous forme d'un flot continu. Le mode d'administration s'avère de faible importance. EFA s'avère donc efficace et devrait être testé en clinique.

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