—Originals—

External high-frequency oscillation for hypercapnia
after upper abdominal surgeryShinhiro Takeda¹⁾, Kazuhiro Nakanishi¹⁾, Teruo Takano¹⁾,
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Abstract

The purpose of this study was to evaluate the efficacy of external high-frequency oscillation (EHFO) in patients with hypercapnia following upper abdominal surgery. Seven patients were ventilated with EHFO for 2 hr at 60 oscillations/min, with cuirass pressures of 36 cm H₂O (−26 to +10), and an inspiratory to expiratory ratio of 1 : 1. Blood gases and cardiac functional parameters were examined during the 2 hr on EHFO. Pulmonary functional parameters were analyzed prior to the institution and after the termination of EHFO. PaCO₂ significantly decreased from 61 ± 8 mmHg to 48 ± 7 mmHg after 10 min on EHFO ($p < 0.01$). PaO₂ significantly increased from 74 ± 10 mmHg to 95 ± 26 mmHg after 1 hr on EHFO ($p < 0.01$). The heart rate decreased significantly from 108 ± 27 beats/min to 101 ± 24 beats/min after 30 min on EHFO ($p < 0.05$). The FEV₁ and FVC significantly increased from 1.09 ± 0.54 L to 1.50 ± 0.46 L ($p < 0.01$) and from 1.90 ± 0.74 L to 2.18 ± 0.60 L ($p < 0.05$), respectively. The other parameters of lung function also significantly improved after the termination of EHFO. The significant changes in all of the pulmonary functional parameters continued for 1 hr after the termination of EHFO. EHFO is an effective method of gas exchange which is associated with earlier return to preoperative lung function. (J Nippon Med Sch 1997 ; 64 : 440–445)

Key words: external high-frequency oscillation, hypercapnia, lung function, post-operative complications, upper abdominal surgery

Introduction

Pulmonary complications still play a major role in post-operative morbidity and mortality. Upper abdominal surgery is associated with a high risk for developing post-operative pulmonary complications^{1,2}. Continuous positive airway pressure delivered by mask has been shown to be effective for post-operative pulmonary complications³. However, some patients find this technique claustrophobic and difficult to tolerate either because of leakage from the mouth when using a nasal mask⁴, or because of

excessive pressure and difficulty in managing secretions when using a face mask⁵.

Effective gas exchange can be maintained without the need for endotracheal intubation using external high frequency oscillation (EHFO)^{6–8}. EHFO reduces end-tidal CO₂ concentration in patients with severe chronic obstructive pulmonary disease⁹. A recently developed approach to EHFO uses a cuirass system to oscillate the anterolateral area of the chest and abdomen with negative and positive pressures in combination with a continuous negative baseline pressure⁶. Oscillatory tidal volume as well as mean lung volume can be controlled,

a mouthpiece is unnecessary, and inspired air is warmed and humidified naturally.

The purpose of this study was to evaluate the efficacy of EHFO in patients with post-operative hypercapnia following upper abdominal surgery.

Materials and Methods

All subjects gave informed consent. There were seven adult patients with post-operative hypercapnia after upper abdominal surgery. All patients were classified as American Society of Anesthesiologists pre-anesthesia physical status classification I, without circulatory, respiratory, or metabolic disease. Anesthesia was induced with fentanyl, thiamylal sodium, and vecuronium bromide, and was maintained with isoflurane and nitrous oxide, combined with epidural analgesia. Extubation was performed in the operating room. A local anesthetic (1% mepibacaine, 1 to 3 ml/hr) and fentanyl (16 to 33 μ g/hr) were administered continuously through the epidural catheter to prevent post-operative pain.

All patients who had respiratory distress and PaCO_2 above 55 mmHg were enrolled. All patients received oxygen through a semi-rigid face mask at a flow rate of 8 or 12 L/min prior to study entry and during the study. The patients had undergone treatment with bronchodilators and mucokinetic agents using an ultrasonic nebulizer, antibiotics, and respiratory physiotherapy. Respiratory physiotherapy consisted of breathing exercises with a diaphragmatic breathing pattern (outward movement of abdomen and elevation of thorax during inspiration), pursed lip breathing and a forced expiration technique for bringing up expectoration (a few short forced expiratory efforts made with an open glottis from a high lung volume, followed by relaxed diaphragmatic breathing). This treatment was given once on the day of operation and twice daily post-operatively by the physician until study entry. The study was initiated at the least 4 hr after the last diuretic dose and when the arterial oxygen pressure and the dose of vasoactive medications had been stable for at least 4 hr.

A diagnosis of pneumonia was made when patients met two of the following three criteria: a change in the color or quantity of sputum, an oral temperature of $>38.5^\circ\text{C}$ for at least two days, and

an infiltrate on chest radiography. Chest radiography was interpreted by various radiologists as part of their clinical work. The same physician assessed lung sounds before and after surgery. A catheter was placed in the left radial artery to measure arterial blood pressure, and to obtain samples for blood gas analysis. Additional monitoring included electrocardiography (DS-1060, Fukuda Denshi, Tokyo, Japan) and pulse oximetry (N 180 pulse oximeter, Nellcor, Tokyo, Japan). Each patient was ventilated with EHFO using a Hayek Oscillator (Breasy Medical Equipment, London, England).

The oscillator consisted of a chest cuirass, a power unit, and a control unit. The cuirass was made of clear, flexible, lightweight plastic, and was covered in soft foam rubber. It was designed to fit snugly over the chest and upper abdomen. The cuirass was connected to the power unit with wide bore tubing. Within the power unit, there was a diaphragmatic pump with a maximum stroke of 3.5 L. The pump was able to operate over a wide range of frequencies (8 to 999 oscillations/min) to generate an oscillating pressure. An additional pump enabled this oscillation to be superimposed on a negative baseline, permitting the control of end-expiratory chamber pressure, and hence lung volume. The frequency, inspiratory pressure, expiratory pressure, and inspiratory to expiratory (I/E) ratio could be set on the automatic control unit, which then adjusted the performance of the power unit by negative feedback from a pressure transducer connected to the inside of the cuirass. Since both the inspiratory and expiratory phases were controlled, high frequencies could be achieved. Each patient was ventilated at 60 oscillations/min (high frequency) for 2 hr. Cuirass pressures were $-26 \text{ cmH}_2\text{O}$ (inspiratory) and $+10 \text{ cmH}_2\text{O}$ (expiratory). The I/E ratio was maintained at 1:1.

Blood gas values, arterial blood pressure, and heart rate were assessed with the patient in the supine position prior to EHFO (baseline), and at 10 min, 30 min, 1 hr, and 2 hr after EHFO, as well as at 5 min and 1 hr after the termination of EHFO. Forced expired volume in 1 sec (FEV_1), forced vital capacity (FVC), maximal flow at 50% of FVC ($\dot{V}_{50}$), maximal flow at 25% of FVC ($\dot{V}_{25}$), and respiratory rate were analyzed with the patient in the semi-sitting position prior to EHFO (baseline), and at 5

min and 1 hr after the termination of EHFO. In this study, lung function was tested using a dry rolling seal spirometer (Autospiro AS-500, Minato Medical Science, Osaka, Japan). The apparatus was chosen because the measurements were performed at the bedside. Pre-operative measurements were made using another type of spirometer (CHESTAC-55 V, Chest MI, Tokyo, Japan). Blood gas analysis was performed using standard blood-gas electrodes (ABL 300, Radiometer, Copenhagen, Denmark).

Statistical analysis

The results were expressed as the means $\pm$ SD. All results were examined using analysis of variance followed by the Dunnett multiple comparisons procedure. All p values less than 0.05 were considered statistically significant.

Results

All patients had undergone upper midline or paramedian incision for abdominal surgery (**Table 1**). Atelectasis was seen on chest radiography in four patients and another three patients were diagnosed with pneumonia prior to study entry. Two patients had received continuous intravenous aminophylline

(750 mg/day) prior to study entry. EHFO was undertaken 1.6 ± 0.8 days (range 1 to 3 days) post-operatively. All patients had complained of facilitation drainage of secretions after the termination of EHFO. Breathing sounds could be heard well throughout the lung fields after the termination of EHFO; as the crackles due to mucous retention also decreased. No patient complained of post-operative pain nor had an anastomotic or incisional breakdown during this study up to hospital discharge. No harmful side effects were observed with the use of the cuirass.

No hypoxemia (pulse oximetry $<90\%$) occurred during this study. The lowest level of PaO_2 was 61 mmHg, and the lowest level of oxygen saturation (pulse oximetry) was 92%. No adverse effects were seen during this study.

No patients had hypercapnia as compensation for metabolic alkalosis. The PaCO_2 was significantly lower at 10 min after EHFO than at baseline (**Table 2**). The PaCO_2 decrease of 20% (at 10 min) was the largest change in any of the parameters. The significant change in PaO_2 occurred later than the change in PaCO_2 (**Table 2**). The largest increase in PaO_2 was at 1 hr after the termination of EHFO. The significant changes in all of the parameters continued 1 hr after the termination of EHFO (**Table 2**).

All of the lung function tests were significantly higher prior to the operation than they were just prior to EHFO, and were significantly higher at 5 min and 1 hr after the termination of EHFO than at baseline (**Table 3**). Only the $\dot{V}_{25}$ returned to the pre-operative level after the termination of EHFO (**Table 3**).

Table 1 Patient characteristics

Case	Age (yr)	Sex	Smoking history	Surgical procedure
1	75	female	yes	Cholecystectomy
2	70	male	yes	Subtotal gastrectomy
3	75	male	yes	Total gastrectomy
4	57	female	yes	Right hemicolectomy
5	70	male	yes	Total gastrectomy
6	61	male	no	Total gastrectomy
7	72	male	yes	Total gastrectomy

Table 2 Changes in blood gas analysis and cardiac response

	Baseline	After institution of EHFO				After termination of EHFO	
		10 min	30 min	1 hr	2 hr	5 min	1 hr
PaCO_2 , mmHg	61 ± 8	$48 \pm 7^{**}$	$44 \pm 5^{**}$	$43 \pm 5^{**}$	$42 \pm 6^{**}$	$40 \pm 5^{**}$	$41 \pm 4^{**}$
PaO_2 , mmHg	74 ± 10	75 ± 12	83 ± 18	$95 \pm 26^{**}$	$93 \pm 22^{**}$	$99 \pm 25^{**}$	$108 \pm 24^{**}$
MAP, mmHg	82 ± 18	83 ± 14	82 ± 18	81 ± 18	78 ± 13	$73 \pm 14^{**}$	$75 \pm 15^{**}$
HR, beats/min	108 ± 27	106 ± 32	$101 \pm 24^*$	$98 \pm 20^{**}$	$96 \pm 19^{**}$	$94 \pm 19^{**}$	$95 \pm 19^{**}$

Each value represents the mean $\pm$ SD. Differences from baseline: * $p < 0.05$, ** $p < 0.01$. EHFO: external high-frequency oscillation; MAP: mean arterial pressure; HR: heart rate. Blood gas values, arterial pressure, and heart rate were assessed prior to EHFO (baseline) and at 10 min, 30 min, 1 hr, and 2 hr after EHFO, 5 min and 1 hr after the termination of EHFO.

Table 3 Changes in lung function and respiratory rate

	Pre-op	Baseline	After 5 min	After 1 hr
FEV ₁ , L	2.31±0.81	1.09±0.54 †	1.50±0.46 †	1.56±0.57 †**
FVC, L	2.88±1.02	1.90±0.74 †	2.18±0.60 †*	2.28±0.69 †**
FEV ₁ /FVC, %	80.5±4.4	58.1±13.9 †	69.0±10.0 †**	68.4±13.3 †**
$\dot{V}_{50}$, L/sec	3.06±1.61	0.88±0.61 †	1.36±0.42 †**	1.45±0.66 †**
$\dot{V}_{25}$, L/sec	1.03±0.39	0.52±0.32 †	0.96±0.42**	0.87±0.38**
RR, breaths/min	—	25.1±2.9	19.0±2.9**	18.4±2.6**

Each value represents the mean±SD. Differences from pre-op; † p<0.01. Differences from baseline; *p<0.05, **p<0.01. Pre-op: pre-operative state; Baseline: prior to EHFO; FEV₁: forced expired volume in 1 sec; FVC: forced vital capacity; $\dot{V}_{50}$: maximal flow at 50% of FVC; $\dot{V}_{25}$: maximal flow at 25% of FVC; RR: respiratory rate; EHFO: external high-frequency oscillation. Lung function was assessed 5 min and 1 hr after the termination of EHFO.

Discussion

Patients who undergo upper abdominal surgery have been reported to exhibit decreases in FEV₁ and FVC^{3,10}. It is difficult to improve lung function quickly by continuous positive airway pressure or respiratory physiotherapy. EHFO has compared well with high-frequency ventilation in animals with normal lungs, and may in fact be more effective in the presence of airway obstruction¹¹. EHFO may also be more effective than conventional ventilation in enhancing gas exchange in the presence of increased elastic recoil⁶. In our study, all lung functions were improved in all patients after the institution of EHFO. In particular, FEV₁/FVC and $\dot{V}_{25}$, which reflect airway obstruction, improved remarkably.

The decrease in mucus clearance and increased bacterial colonization seen after surgery may lead to infection^{2,12}. Respiratory physiotherapy is an important part of post-operative care in surgical patients. Drainage of secretions is one of its major components. In this study, it is remarkable that the patients expelled sputum far beyond that achievable by classic physiotherapy. EHFO may intermittently dilate the bronchi and alveoli, and improve inflation of poorly ventilated lung regions. As a method of ventilation for patients with post-operative hypercapnia, EHFO has potential advantages over continuous positive airway pressure delivered via a nasal or face mask. In particular, the oropharynx is easily accessible for the management of secretions. Clearance of mucus has also been shown to be enhanced

by high-frequency oscillation, possibly due to a reduction in sputum viscosity and enhancement of ciliary clearance¹³. The effectiveness of EHFO was shown to be advantageous to our patients.

Diminished expiratory lung volumes are associated with decreased lung compliance, which increases the elastic work of breathing. To minimize this work, patients take shallow, frequent breaths which may further decrease lung volume¹⁴. This explains the observation that patients who undergo upper abdominal surgery often have an increased respiratory rate during the post-operative period. The reduction in respiratory rate seen in normal subjects while maintaining gas exchange at frequencies of 30 to 60 oscillations/min implies that gas exchange was taking place during respiratory muscle rest⁷. One of the reasons why the respiratory rate decreased significantly may be the rapid improvement in PaCO₂. A decrease in heart rate was observed with continuous decreases in PaCO₂.

Fentanyl and mepibacaine were administered continuously through an epidural catheter to prevent post-operative pain. The side effects of epidural opioids are related to their rostral spread in the cerebrospinal fluid to supraspinal structures¹⁵. Continuous epidural infusion of fentanyl does not increase PaCO₂¹⁶.

It may be reasonable to use EHFO on a daily basis for short sessions in patients with severe chronic obstructive pulmonary disease to provide a rest period for fatigued respiratory muscles, relieving the patient's dyspnea for a few hours¹⁷. In our study, the significant changes in all parameters continued for 1 hr after the termination of EHFO. It

is not known whether this improvement persists. It may be preferable to continue EHFO until lung function improves to the pre-operative level.

Each patient was ventilated for 2 hr. In patients with chronic respiratory insufficiency, previous studies have shown that invasive positive pressure ventilation or external negative pressure ventilation for several hours a day leads to an improvement in arterial blood gases and clinical conditions that persists during the intervening hours¹⁷⁻²¹. Gutierrez et al. reported that external negative pressure ventilation for 8 hr improved blood gases in patients with chronic air-flow limitation and hypercarbia¹⁵. In our study, the frequency setting was 60 oscillations/min. In a previous study, it has been suggested that EHFO was equally effective at frequencies from 60 to 140 oscillations/min⁹. The frequency chosen should be determined in accordance with the comfort of the patient during application of the oscillator. On the other hand, the amplitude should be selected individually, based on the severity of the disease and compliance of the chest wall. Lean patients would require lower amplitudes than obese patients, and patients with less impairment would require a lower amplitude than severely impaired patients. In this study, a fixed amplitude was used for the purpose of uniformity. Further tests will establish the ranges that will allow adjustment to each individual patient. The I/E ratio used in our study was 1:1. Apparently, a lower I/E ratio, enabling a longer expiratory phase, would be more natural in patients with hypercapnia following upper abdominal surgery. The effect of the device is to create a negative distending pressure and a positive compression pressure that gives an amplitude of 36 cmH₂O (−26 to +10). This amplitude generates a respiratory cycle that is totally controlled by the device. The subject can occasionally use his own spontaneous drive to breathe, the effect of which is, however, negligible within the total framework of ventilatory output. Thus, the improved ventilation induced by the Hayek Oscillator is solely the effect of the device.

In conclusion, while the cuirass is attached, a pause in ventilation can easily be taken to allow patients to communicate with staff and to take fluids. EHFO opens a new range of applications in clinical chest medicine. It could be effectively used

in the management of hypercapnia in post-operative patients, particularly to prevent the need for endotracheal intubation and mechanical ventilation.

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