

# Effects of changes in lung volume on oscillatory flow rate during high-frequency chest wall oscillation

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**SJ Butcher, MP Pasiorowski, RL Jones.** Effects of changes in lung volume on oscillatory flow rate during high-frequency chest wall oscillation. *Can Respir J* 2007;14(3):153-158.

**BACKGROUND:** The effectiveness of high-frequency chest wall oscillation (HFCWO) in mucolysis and mucous clearance is thought to be dependant on oscillatory flow rate (Fosc). Therefore, increasing Fosc during HFCWO may have a clinical benefit.

**OBJECTIVES:** To examine effects of continuous positive airway pressure (CPAP) on Fosc at two oscillation frequencies in healthy subjects and patients with airway obstruction.

**METHODS:** Five healthy subjects and six patients with airway obstruction underwent 12 randomized trials of HFCWO (CPAP levels of 0 cm H<sub>2</sub>O, 2 cm H<sub>2</sub>O, 4 cm H<sub>2</sub>O, 6 cm H<sub>2</sub>O, 8 cm H<sub>2</sub>O and 10 cm H<sub>2</sub>O at frequencies of 10 Hz and 15 Hz) within a body plethysmograph, allowing measurements of changes in lung volume. Fosc was measured by reverse plethysmography using a 20 L isothermal chamber near the mouth. At the end of each randomized trial, an inspiratory capacity manoeuvre was used to determine end-expiratory lung volume (EELV).

**RESULTS:** EELV increased significantly ( $P<0.05$ ) with each level of CPAP regardless of oscillation frequency. Fosc also significantly increased with CPAP ( $P<0.05$ ) and it was correlated with EELV ( $r=0.7935$ ,  $P<0.05$ ) in obstructed patients but not in healthy subjects ( $r=0.125$ ,  $P=0.343$ ). There were no significant differences in perceived comfort across the levels of CPAP.

**CONCLUSIONS:** Significant increases in Fosc with CPAP-induced increases in lung volume were observed, suggesting that CPAP may be useful as a therapeutic adjunct in patients who have obstructive airway disease and who require HFCWO.

**Key Words:** Chronic obstructive pulmonary disease; Continuous positive airway pressure; Cystic fibrosis; End-expiratory lung volume; High-frequency chest wall oscillation

For over 40 years, chest physiotherapy has been used as the primary technique for airway clearance in patients with cystic fibrosis (CF) (1-3). Unfortunately, skill in application and compliance with prescribed home regimens is often poor due to the time-consuming, technically complicated and often uncomfortable nature of the therapy (4-6). Consequently, newer therapies have been developed in an attempt to provide increased airway clearance, increased independence, enhanced lifestyle and better compliance with home regimens (7).

High-frequency chest wall oscillation (HFCWO) uses a pneumatic vest to compress and oscillate the chest wall, and is a relatively new method of facilitating airway clearance. Over the past decade, studies have demonstrated HFCWO to be as

## Effets de la variation du volume pulmonaire sur le débit oscillatoire durant l'oscillation de la paroi thoracique à haute fréquence

**CONTEXTE :** On croit que l'efficacité de l'oscillation de la paroi thoracique à haute fréquence (OPTHF) dans la mucolyse et l'élimination du mucus dépend du débit oscillatoire (DO). Ainsi, le fait d'augmenter le DO pourrait se révéler avantageux sur le plan clinique.

**BUT :** L'étude avait pour but de vérifier l'effet d'une pression aérienne positive continue (PAPC) sur le DO, à deux fréquences d'oscillation, chez des sujets en santé et chez des patients atteints d'une obstruction des voies aériennes.

**MÉTHODE :** Cinq sujets en santé et six patients atteints d'une obstruction des voies aériennes ont été soumis à 12 essais d'OPTHF (PAPC : 0 cm H<sub>2</sub>O, 2 cm H<sub>2</sub>O, 4 cm H<sub>2</sub>O, 6 cm H<sub>2</sub>O, 8 cm H<sub>2</sub>O, 10 cm H<sub>2</sub>O; fréquence : 10 Hz et 15 Hz) répartis au hasard, dans un pléthysmographe corporel permettant de mesurer la variation du volume pulmonaire. Le DO a été mesuré par pléthysmographie inversée à l'aide d'une enceinte isothermique de 20 litres, placée près de la bouche. À la fin de chaque essai hasardisé, nous avons procédé à une manœuvre de capacité inspiratoire afin de déterminer le volume pulmonaire en fin d'expiration (VPFE).

**RÉSULTATS :** Le VPFE a augmenté de façon significative ( $P<0.05$ ) à chaque degré d'intensité de la PAPC, indépendamment de la fréquence d'oscillation. Le DO a aussi augmenté de façon significative en fonction de la PAPC ( $P<0.05$ ) et il était en corrélation avec le VPFE chez les patients atteints d'une obstruction des voies aériennes ( $r=0.7935$ ;  $P<0.05$ ) mais pas chez les sujets en santé ( $r=0.125$ ;  $P=0.343$ ). Aucune différence sensible n'a été relevée entre les différents degrés d'intensité de la PAPC en ce qui concerne le confort.

**CONCLUSION :** Nous avons observé une augmentation significative du DO associée à une augmentation du volume pulmonaire liée à la PAPC, ce qui donne à penser que la PAPC pourrait se révéler un traitement d'appoint utile chez les patients qui sont atteints d'une obstruction des voies aériennes et qui ont besoin d'OPTHF.

effective as standard physiotherapy in terms of patient tolerance (8), length of hospital stay (9), improvement in lung function (8,9) and degree of sputum expectoration (8,9).

Several studies have characterized the effects of HFCWO on breathing mechanics in humans and animals. HFCWO has been demonstrated to decrease end-expiratory lung volume (EELV) to as much as 50% of the functional residual capacity (FRC) in patients with airway disease (10) due to the increased load applied to the chest wall (11). The decreased EELV was found to have a secondary effect on decreasing the HFCWO-induced oscillated volume in humans (10,12) and in dogs (11,13), but this effect can be reversed with the use of positive expiratory pressure (PEP) in combination with HFCWO. Dosman et al (12) and Perry et

**TABLE 1**  
**Subject demographics**

	Patients (n=6) mean ± SD	Controls (n=5) mean ± SD
Age (years)	56.7±16.3	27.0±4.9
Height (cm)	178.8±7.0	165.8±12.3
Weight (kg)	82.4±10.9	66.1±15.3
FEV <sub>1</sub> (% predicted)	52.8±23.8	116.9±13.9
FVC (% predicted)	78.6±30.3	97.6±10.1
FEV <sub>1</sub> /FVC	0.49±0.13	0.95±0.10

FEV<sub>1</sub>, Forced expiratory volume in 1 s; FVC Forced vital capacity

al (14) found that a small amount of PEP, between 2 cm H<sub>2</sub>O and 3.7 cm H<sub>2</sub>O, maintained EELV at the level of FRC and it increased mean oscillated volume measured at the mouth in pediatric patients with CF (12) and in older patients with chronic obstructive pulmonary disease (COPD) (14). It was concluded that decreases in airway resistance, due to the PEP-induced increase in EELV (15), accounted for the increases in oscillated volume. By decreasing airway resistance, PEP also decreases expiratory airflow limitation (16) and increases collateral airflow in peripheral airways obstructed by secretions (17). The net effect is an increase of oscillatory flow rate (Fosc) during HFCWO. Because increased flow velocity in the airways, where mucous has accumulated, is thought to be responsible for the enhanced mucolytic and mucous clearance effects of HFCWO (18), PEP may improve these as well. Although previous studies used PEP to increase EELV back to FRC (12,14), the optimal EELV during HFCWO may exceed the FRC.

In the present investigation, we examined the effects of adding between 2 cm H<sub>2</sub>O and 10 cm H<sub>2</sub>O of continuous positive airway pressure (CPAP) on lung mechanics and Fosc during HFCWO. Because increased levels of CPAP may cause significant patient discomfort, we postulated that an optimal level of CPAP would occur when the ratio of Fosc to the level of discomfort was highest.

## METHODS

On arrival to the laboratory, subjects performed baseline spirometry using a dry rolling seal spirometer (SensorMedics, USA). Subjects then underwent 12 randomized trials of HFCWO (CPAP levels of 0 cm H<sub>2</sub>O, 2 cm H<sub>2</sub>O, 4 cm H<sub>2</sub>O, 6 cm H<sub>2</sub>O, 8 cm H<sub>2</sub>O and 10 cm H<sub>2</sub>O at frequencies of 10 Hz and 15 Hz) as described below.

## Subjects

The present study was approved by the University of Alberta (Edmonton, Alberta) Health Research Ethics Board and signed informed consent was obtained from each subject. Five healthy subjects (three men and two women) and six patients with obstructive airway disease (four COPD and two CF patients; five men and one woman) participated in the present study (Table 1). The patients were selected from the outpatient Cystic Fibrosis and Pulmonary Clinics at the University of Alberta Hospital, and the control subjects were undergraduate and graduate students. Spirometry was performed before beginning the HFCWO protocol. Predicted values for forced vital capacity (FVC) and forced expiratory volume in 1 s were obtained from Morris et al (19). All patients were clinically

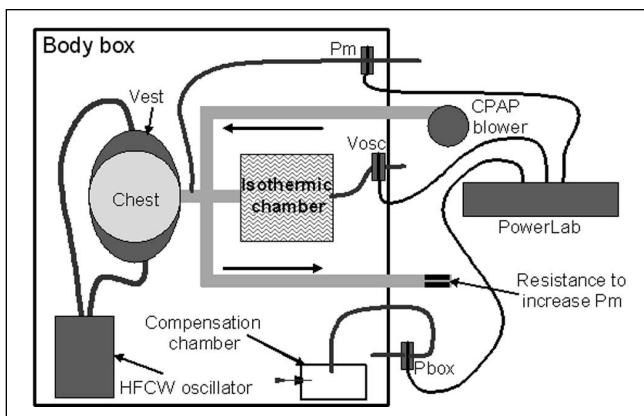
stable and were taking their usual medications while participating in the study.

## Instrumentation

A pneumatic vest system (The Vest Airway Clearance System, Hill-Rom Inc, USA) was used to administer HFCWO. The background pressure of the vest was set to a dial pressure of four (a common setting used by patients, which produces a pressure on the chest of approximately 10 cm H<sub>2</sub>O without oscillation), and the oscillation frequency was set at either 10 Hz or 15 Hz. The study was conducted with the subjects seated within a custom-built body plethysmograph to measure changes in lung volume. Use of the body plethysmograph was required to obtain inspiratory capacity (IC) because IC measurements taken at the mouth during CPAP are technically difficult to obtain. The body plethysmograph (2.13 m high, 1.22 m long and 0.76 m wide, creating an internal volume of approximately 2700 L) was constructed of 1.91 cm thick plywood and 1.27 cm thick acrylic glass. Electromagnets were used to seal the door and to permit rapid access to the subject. Several airtight ports in the box wall allowed tubes to be connected for breathing and for taking pressure measurements. Because the subjects inhaled and exhaled air from the room outside the box, the changes in box pressure were used to obtain the changes in thoracic displacement, ie, the volume changes during breathing and IC manoeuvres. When the body plethysmograph was emptied and sealed, the time constants for air leakage were longer than 2 min for both positive and negative box pressures.

When the box was sealed, changes in box pressure were measured by a pressure transducer (MP45, ±50 cm H<sub>2</sub>O; Validyne Engineering; USA) and converted to changes in lung volume using a calibration factor. One side of the box pressure transducer was connected to a compensation chamber, which was connected to the box using a 22-gauge needle. This compensation chamber cancelled any slow box pressure changes, such as those caused by body heat. With subjects in the box and breathing at varying rates and volumes from a spirometer (Model 1022, SensorMedics, USA) located outside the box, the volume changes measured by the box were found to be highly correlated with those measured by the spirometer ( $r=0.998$ ,  $P<0.001$ ).

Figure 1 shows the breathing circuit set-up used to obtain the physiological measurements of the subjects. Subjects breathed room air through a tube connected to a commercial air blower (Advanced Respiratory Inc, USA) to administer CPAP. The tube for expiration had a lumen of 15 mm to maintain pressure within the breathing circuit. The tubes for inspiration and expiration, the isothermic chamber and the mouthpiece used by the subject were connected via a four-way polyvinyl chloride connector. Mouth pressure was measured through a port in the polyvinyl chloride connector via a pressure transducer. Another pressure transducer was used to measure the pressure oscillations in a 20 L isothermic chamber filled with copper wool, which was used to obtain the oscillatory volumes at the mouth produced by HFCWO. The isothermic chamber was calibrated by rapidly injecting 50 mL of air into the sealed chamber and recording the resultant pressure change. Because the mouth and isothermic chamber pressure transducers were located within the body box, the negative ports on both transducers were ducted to the exterior of the box. Oscillatory volume was differentiated to obtain oscillatory flow, which was recorded at mid-tidal volume expiration over several tidal breaths for all conditions. The



**Figure 1)** Top diagrammatic view of the experimental set-up. CPAP Continuous positive airway pressure; HFCW High-frequency chest wall; Pbox Plethysmograph pressure; Pm Mouth pressure; PowerLab Data acquisition system; Vosc Oscillated volume

oscillated flow was superimposed onto the slower expired tidal flow rate measured with the body box during the same tidal breath to obtain the actual expiratory flow rate, both the fast and slow components. This was then positioned on the volume axis of the standard spirometer-derived flow-volume loop using the IC data from the body box (Figure 2). All pressure, volume and flow data were recorded digitally (PowerLab 8SP, Chart version 4.2; ADInstruments Inc; Australia) at 200 Hz.

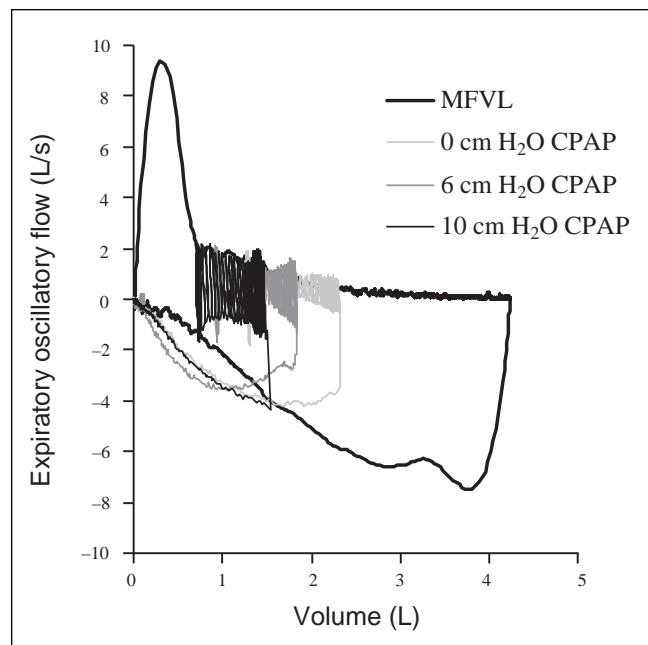
#### Protocol

Each subject was fitted with an appropriately sized vest and seated within the body box for 5 min following door closure to allow for temperature equalization. The subject then started the blower on the vest unit, which inflated the vest to a preset dial pressure of four (background pressure). The CPAP blower was turned on and adjusted so that mouth pressure, during a brief breath-hold, was at the desired level of CPAP (0 cm H<sub>2</sub>O to 10 cm H<sub>2</sub>O). At 0 cm H<sub>2</sub>O CPAP, the blower was turned on to produce a low airflow past the mouth to prevent rebreathing of expired air, but the resistance in the expiration tube was removed so that mouth pressure remained at atmospheric pressure.

The first 2 min of each trial allowed the subject to become accustomed to the CPAP and to establish a stable EELV. The next 3 min combined CPAP with HFCWO, after which the oscillation was stopped, the vest was deflated and the subject was cued to complete an IC manoeuvre. The IC was determined from the level of inspiration above the average EELV obtained from three tidal breaths before stopping HFCWO. Subjects scored the perceived comfort of each combination of CPAP and HFCWO on a 100 mm visual analogue scale, ranging from very comfortable (0 mm) to moderately uncomfortable (50 mm) to unbearable (100 mm). The average values for Fosc were divided by the comfort level for each trial to create an effectiveness index.

#### Analysis

The present study was designed to compare Fosc and EELV in patients and control subjects, as well as effectiveness index scores within six levels of CPAP across two oscillation frequencies commonly used by patients. As such, a two by six (frequency by CPAP level) repeated-measures ANOVA was used. When a



**Figure 2)** The expiratory oscillatory flow tracings superimposed on the tidal expiratory flow-volume curve and placed within the maximal flow-volume (MFVL) envelope for one cystic fibrosis patient at 0 cm H<sub>2</sub>O, 6 cm H<sub>2</sub>O and 10 cm H<sub>2</sub>O continuous positive airway pressure (CPAP). This figure demonstrates that as lung volume increases with increasing CPAP levels, the oscillatory tidal expiratory flow rates increase to correspond closely with the available maximal flow rates. The data shown are from a patient at the upper limit for the range of end-expiratory lung volumes observed

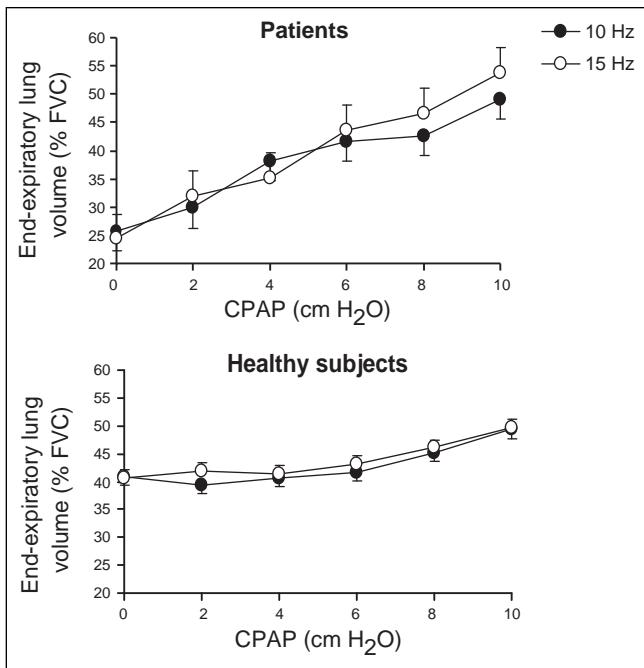
significant effect was observed, Tukey's post hoc analysis was used to discern when the effect occurred. To assess the relationship between Fosc and EELV, a Pearson's rho correlation analysis was used. Alpha was set at 0.05 for all analyses. All analyses examined patients and healthy subjects separately.

## RESULTS

In patients, EELV increased significantly ( $P<0.05$ ) with each level of CPAP regardless of oscillation frequency, with the greatest increases occurring at 15 Hz (Figure 3). At 10 Hz, EELV averaged 49.0% FVC at 10 cm H<sub>2</sub>O CPAP compared with 25.8% FVC at 0 cm H<sub>2</sub>O CPAP. At 15 Hz, EELV averaged 53.8% FVC at 10 cm H<sub>2</sub>O CPAP compared with 24.4% FVC at 0 cm H<sub>2</sub>O CPAP. In the healthy subjects, at 10 Hz, EELV increased to 49.3% FVC at 10 cm H<sub>2</sub>O CPAP from 40.8% FVC at 0 cm H<sub>2</sub>O CPAP. Similar values were obtained at 15 Hz.

Oscillated flow rate increased significantly as EELV increased for each frequency in patients ( $r=0.79$ ,  $P<0.05$ , Figure 4). Compared with a CPAP of 0 cm H<sub>2</sub>O, Fosc was significantly greater at all CPAP levels for both frequencies ( $P<0.05$ ). As well, the 15 Hz condition produced greater Fosc values than the 10 Hz condition at CPAP levels of 6 cm H<sub>2</sub>O, 8 cm H<sub>2</sub>O and 10 cm H<sub>2</sub>O ( $P<0.05$ ). In contrast, there was not a significant correlation between EELV and Fosc in healthy subjects ( $r=0.125$ ,  $P=0.343$ ), but, similar to the patients, Fosc was higher at 15 Hz than at 10 Hz for all levels of CPAP.

Our effectiveness ratio was dependant on Fosc and on the score for discomfort (0 mm to 100 mm scale). There were no

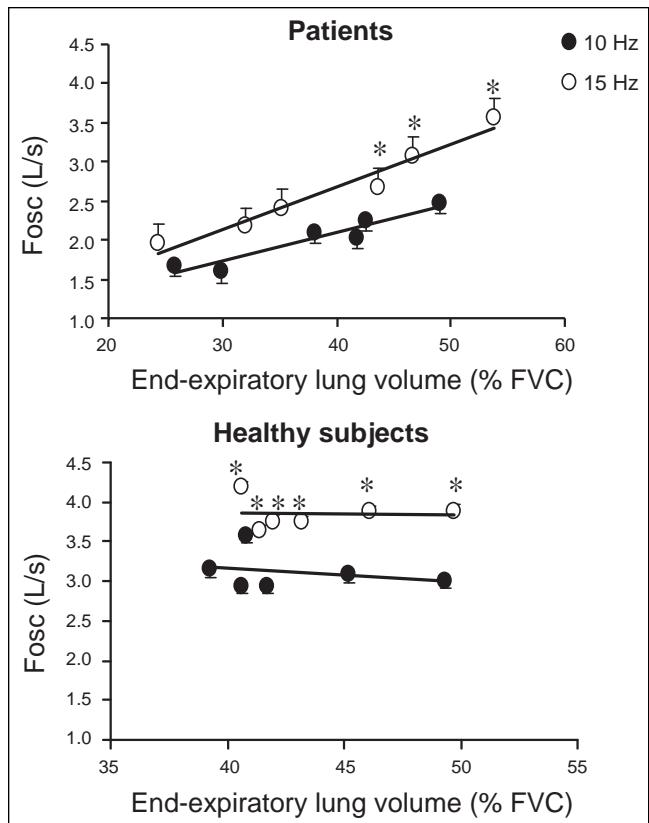


**Figure 3**) End-expiratory lung volumes at different levels of continuous positive airway pressure (CPAP) in patients (top) and in healthy subjects (bottom) at oscillation frequencies of 10 Hz (solid dots) and 15 Hz (open dots). Values are expressed as mean  $\pm$  SD. FVC Forced vital capacity

significant differences between the levels of discomfort within either group of subjects for the two oscillation frequencies. The mean discomfort ratings were 22.9 mm versus 17.9 mm at 0 cm H<sub>2</sub>O CPAP for the control subjects and patients, respectively. At 10 cm H<sub>2</sub>O CPAP, the discomfort ratings were 48.6 mm and 21.8 mm, respectively. Therefore, the patients felt nearly as comfortable at 10 cm H<sub>2</sub>O CPAP as they did without CPAP, but the control subjects felt much more uncomfortable at 10 cm H<sub>2</sub>O CPAP than the patients. There were no significant differences in the effectiveness indexes for the two oscillation frequencies, and the results for the patient group are shown in Figure 5. The highest level of effectiveness occurred at 15 Hz with 10 cm H<sub>2</sub>O CPAP (26.1 mL/s/mm versus 11.7 mL/s/mm at 0 cm H<sub>2</sub>O CPAP) due to a systematic increase in Fosc as CPAP increased, without a corresponding increase in level of discomfort.

## DISCUSSION

The novel finding of this research is that increasing EELV above the FRC using CPAP during HFCWO significantly increases Fosc in patients with chronic airflow obstruction. Also, breathing at lung volumes above the FRC does not significantly increase the level of discomfort during HFCWO in the patients we studied. Compared with the study by Perry et al (14), in which mild levels of PEP were used to return EELV to the FRC during HFCWO, our study used higher mouth pressures to increase EELV above the FRC with the expectation of further reducing airway resistance and augmenting Fosc. Patients, who are expiratory flow-limited due to increased airway resistance, responded to CPAP with significantly increased Fosc as EELVs increased. Because breathing at a higher lung volume allows for more flow availability, it



**Figure 4**) Oscillatory flow rate (Fosc) plotted against end-expiratory lung volume for patients (top) and healthy subjects (bottom) at oscillation frequencies of 10 Hz (solid dots) and 15 Hz (open dots). For patients, all levels of continuous positive airway pressure (CPAP) produced greater Fosc than 0 cm H<sub>2</sub>O CPAP. Values are expressed as mean  $\pm$  SD. \*P<0.05 between 10 Hz and 15 Hz at matched CPAP results. FVC Forced vital capacity

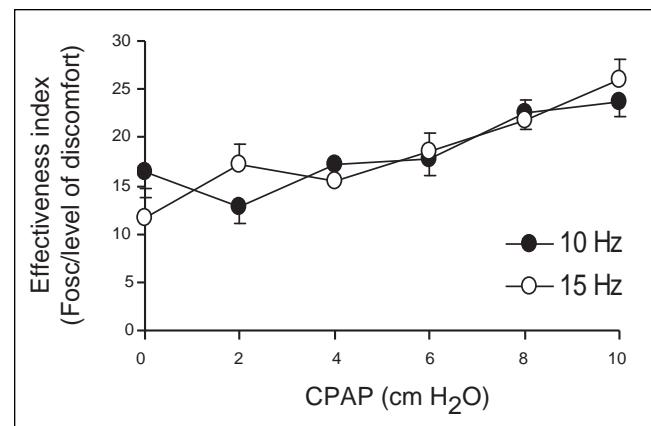
is not surprising that Fosc, at mid-tidal volume expiration, increased with increasing CPAP, as illustrated in Figure 2. It is likely that CPAP levels higher than 10 cm H<sub>2</sub>O would continue to produce increased Fosc because there was no tendency for either EELV or Fosc to level off at 10 cm H<sub>2</sub>O CPAP.

The effect of increased Fosc with the addition of CPAP is consistent with previous data (14). The results of our study demonstrated that the increase in Fosc from 0 cm H<sub>2</sub>O CPAP to 10 cm H<sub>2</sub>O CPAP was 48% at 10 Hz and 83% at 15 Hz. Dosman et al (12) found a 14% increase in oscillatory volume with about 2 cm H<sub>2</sub>O PEP in children with CF, but those children had near-normal airway function when they were studied; thus, relatively smaller effects are expected. Using a similar technique as that used by Dosman et al (12), Perry et al (14) found a 57% increase in oscillatory volume in severe COPD patients. Given that in vitro studies have shown Fosc to act as a physical mucolytic, enhancing mucous clearance (18), there is the potential for a clinical benefit of CPAP when added to HFCWO. However, it is important to note that we measured Fosc at the mouth, not at the site of actual mucous accumulation, and we did not measure mucous clearance. As such, we do not know whether mucous clearance would be increased with added CPAP. However, Hofmeyr et

al (17) have shown a clinical benefit of PEP, without HFCWO, on mucous clearance. Therefore, increasing lung volume is important clinically, and when this benefit is combined with the demonstrated clinical benefit of HFCWO (8,9), there is a potential for synergism. Still, our demonstration of increased Fosc at the mouth may not translate into increased airflow velocity at the site of mucous accumulation in the periphery, which is thought to be responsible for the important effect of airflow in altering mucous rheology (18). However, it is reasonable to believe that the increased Fosc does, in fact, represent an increase in airflow velocity in the peripheral airways. Figure 2 shows that our severely obstructed patients were breathing in the lung volume range when laminar flow occurred (20), and laminar flow is proportional to the airway radius to the fourth power. If the radius of a peripheral airway was doubled by CPAP, then, at the same alveolar-to-mouth driving pressure, the airflow would increase 16-fold. The cross-sectional area in that theoretical airway is proportional to its radius to the second power. The end result of doubling the radius of an airway would be a four-fold increase in the velocity of airflow, mainly due to decreasing the airway's resistance. Also, it stands to reason that mucous cannot be cleared from closed airways, and CPAP should help to open airways.

In contrast to the patients, no corresponding increase in Fosc was seen in healthy subjects (Figures 4 and 5). However, such a result is not surprising, because tidal expiratory flow rate at rest is not flow limited. As well, the healthy subjects did not increase their lung volume with increasing CPAP until the 8 cm H<sub>2</sub>O CPAP level (Figure 4). Because the healthy subjects tended to find the testing procedures more uncomfortable than the patients, it is possible that they attempted to maintain EELV by exerting increased expiratory pressure against the CPAP. It is also important to note that Fosc in healthy subjects was greater at all levels of CPAP than in patients, however, at 10 cm H<sub>2</sub>O CPAP in patients, Fosc approached the levels observed in the control subjects. This is an important finding, and it relates to the discussion above about Fosc and airflow velocity. The fact that Fosc at the mouth was similar between the patients and the control subjects during 10 cm H<sub>2</sub>O CPAP, suggests that airflow velocity in the peripheral airways of patients was considerably higher than in the control subjects, because, even at 10 cm H<sub>2</sub>O CPAP, the patients most certainly had a much higher airway resistance than the control subjects (see the flow-volume loop in Figure 2). Our findings for control subjects may have clinical significance too, because HFCWO is used in a variety of mucous clearance disorders, such as in neuromuscular disease (21), in which airway resistance can be normal. Our results suggest that CPAP would be of little or no benefit to these patients.

Furthermore, the level of discomfort from HFCWO did not increase across the levels of CPAP in patients. As such, higher levels of CPAP (10 cm H<sub>2</sub>O or less) can be tolerated as well as lower levels, with the potential benefit of increased oscillated flow rate. We evaluated the effects of increased CPAP on Fosc during mid-expiration because previous work from our laboratory had demonstrated that Fosc during inspiration is less influenced by increased levels of PEP (12,14). We speculate that the limitation to Fosc is due to the reduced maximal expiratory flow rate and the flow limitation in patients with airway obstruction.



**Figure 5**) Effectiveness index scores (oscillatory flow rate [Fosc]/level of discomfort) for patients at oscillation frequencies of 10 Hz (solid dots) and 15 Hz (open dots). No significant differences were observed between frequencies or across all levels of continuous positive airway pressure (CPAP)

## CONCLUSIONS

Our study found that, during HFCWO, oscillated flow rate increases with CPAP, and that the addition of CPAP to HFCWO does not significantly decrease patient comfort compared with HFCWO alone. Therefore, in patients with airway obstruction, the combination of CPAP with HFCWO may add to the effectiveness of HFCWO, but this needs to be tested clinically.

**FUNDING:** Grant support was provided by Hill-Rom Inc. The authors have no financial interest in Hill-Rom Inc, the company that produces the high-frequency chest compression vest. Dr Richard L Jones received grant support from the manufacturer for this research and for previous research.

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