Effects of high frequency chest compression on respiratory system mechanics in normal subjects and cystic fibrosis patients

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RL JONES, RT LESTER, NE BROWN. Effects of high frequency chest compression on respiratory system mechanics in normal subjects and cystic fibrosis patients. Can Respir J 1995;2(1):40-46.

OBJECTIVE: To investigate the short term effects of high frequency chest compression (HFCC) on several indices of respiratory system mechanics in normal subjects and patients with cystic fibrosis (CF).
DESIGN: Comparative physiological approach. Subjects were blinded to 10 randomized HFCC settings (5, 10, 15, 20 and 25 Hz) with each applied at the lowest and at the highest background vest pressure.
SETTING: Pulmonary function and lung mechanics laboratory, University of Alberta.
PARTICIPANTS: Ten normal male volunteers (24.2±3.8 years) and 11 clinically stable CF patients (23.4±6.7 years). Normal subjects were nonsmokers who had normal lung function. The CF patients had a wide range of airway obstruction.
INTERVENTIONS: HFCC was supplied by oscillating a pneumatic vest that covered the entire torso. Balloon tipped catheters were used to measure esophageal (Pes) and external chest wall (Pcw) pressures. Changes in end-expiratory lung volume (EELV) during HFCC were measured from a spirogram and were compared with baseline functional residual capacity (FRC). The HFCC induced air movement at the mouth, oscillated tidal volume (Vosc), was measured by reverse plethysmography.
RESULTS: Both normals and CF patients had similar changes in Pes and EELV. At the highest background vest pressure and at the higher oscillation frequencies, EELV decreased approximately 30% from the no-HFCC baseline FRC. Vosc decreased with increasing oscillation frequency but normals had higher Vosc than CF patients at each frequency. Conversion of Vosc to flow ($\dot{V}$osc) revealed that the highest $\dot{V}$osc occurred between 10 and 15 Hz for both normals and CF patients. Also, $\dot{V}$osc was dependent on the overall airway function. Low forced expired volume in 1 s resulted in low $\dot{V}$osc, especially when $\dot{V}$osc was measured during spontaneous expiration.
CONCLUSIONS: CF patients with moderate or severe airway obstruction may gain maximal benefit from HFCC therapy when low vest pressure is used at an oscillation frequency of 10 to 15 Hz. The low vest pressure minimizes the decrease in EELV and 10 to 15 Hz maximizes $\dot{V}$osc. *(Pour résumé, voir page 41)*

Key Words: *Cystic fibrosis, Esophageal pressure, High frequency chest compression, Lung function*

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Effets d'une compression thoracique à haute fréquence sur la mécanique du système respiratoire chez des sujets sains et chez des patients atteints de fibrose kystique

Objectif : Étudier les effets à court terme d'une compression thoracique à haute fréquence sur plusieurs indices de la mécanique du système respiratoire chez des sujets sains et chez des patients atteints de fibrose kystique (FK).
Modèle : Approche physiologique comparative. Étude en aveugle sur des sujets soumis à 10 niveaux de compression thoracique à haute fréquence randomisés (5,10,15,20,25 Hz), chacun appliqué à la pression de référence la plus basse et la plus haute d'un gilet.
Contexte : Laboratoire d'explorations fonctionnelles et de mécanique pulmonaire de l'Université d'Alberta.
Participants : Dix hommes volontaires sains (24,2±3,8 ans) et 11 patients atteints de fibrose kystique cliniquement stable (23,4±6,7 ans). Les volontaires sains étaient des non-fumeurs et démontraient une fonction pulmonaire normale. Les patients atteints de FK présentaient une obstruction bronchique de degré variable.
Interventions : La compression thoracique à haute fréquence a été appliquée en oscillant un gilet pneumatique recouvrant le thorax. Des cathéters à extrémité gonflable ont été utilisés pour mesurer la pression oesophagienne et les pressions à l'extérieur de la paroi thoracique. Les changements dans le volume pulmonaire en fin d'expiration pendant la compression thoracique à haute fréquence ont été mesurés d'après un spirogramme et comparés avec la capacité résiduelle fonctionnelle (CRF) de base. Le mouvement d'air à la bouche induit par la compression thoracique à haute fréquence, volume courant obtenu par oscillation, était mesuré par pléthysmographie inversée.
Résultats : Les patients sains et ceux atteints de FK présentaient des changements similaires dans la pression oesophagienne et dans le volume pulmonaire en fin d'expiration. À la pression de référence la plus haute du gilet et aux fréquences d'oscillations les plus hautes, le volume pulmonaire en fin d'expiration chutait approximativement de 30 % par rapport à la CRF de base non soumise à la compression thoracique de haute fréquence. Le volume courant obtenu par oscillation chutait lors d'une augmentation de la fréquence des oscillations, cependant, à chaque fréquence, les sujets sains présentaient un volume courant obtenu par oscillation plus élevé que celui des patients atteints de FK. La conversion du volume courant obtenu par oscillation en débit a révélé qu'on obtenait le débit le plus élevé entre 10 et 15 Hz à la fois pour les sujets sains et ceux atteints de FK. De même le débit obtenu par oscillation était dépendant de la fonction respiratoire dans son ensemble. Un volume expiratoire maximum/seconde faible résultait en un débit obtenu par oscillation faible, en particulier quand le débit obtenu par oscillation était mesuré au cours d'une expiration spontanée.
Conclusions : Les patients atteints de FK et présentant une obstruction modérée ou grave des voies aériennes pourraient largement bénéficier d'une thérapie par compression thoracique à haute fréquence lorsque une faible pression est appliquée à l'aide d'un gilet à une fréquence d'oscillations de 10 à 15 Hz. La faible pression du gilet minimise la chute du volume pulmonaire en fin d'expiration tandis que 10 à 15 Hz maximalisent le débit obtenu par oscillation.

High frequency chest compression (HFCC) reportedly increases mucus clearance in normal animals (1-3) and in patients with lung disease (4-6). In patients, HFCC can be delivered by a pneumatic vest that surrounds the thorax. The vest is inflated to a positive background pressure over which pressure oscillations of 5 to 25 Hz are superimposed. The patient can either breathe spontaneously during continuous HFCC or HFCC can be activated during expiratory breathing manoeuvres. Enhanced mucociliary clearance has been attributed, at least in part, to high oscillated air flow in the airways (1-3).

The concept of HFCC was first described in 1966 by Beck (4). He described the use of a belt-like bladder that surrounded the upper abdomen and lower thorax which was inflated to 30 cm H_2O and the air oscillated at 30 Hz. Increases in mucus expectoration, vital capacity and maximal voluntary ventilation were reported for a patient with chronic obstructive pulmonary disease. Then in the mid-1980s, King et al (1,2) reported that HFCC enhanced tracheal and peripheral mucociliary clearance in normal dogs. The cuff and pump system used by King et al produced peak oscillatory cuff pressures of up to 100 cm H_2O, and 13 Hz was found to be the most effective mucus clearance frequency. Since then, HFCC studies on cystic fibrosis (CF) patients have demonstrated increased short term sputum production (5-6) and improved peripheral ventilation (6). Furthermore, Warwick and Hansen (6) reported improved lung function in 15 of 16 CF patients after 22 months of daily HFCC use.

In view of its reported effectiveness and the availability of a commercially available device, the clinical use of HFCC is likely to increase. However, studies investigating the short term effects of HFCC on respiratory system mechanics in human subjects have not been reported.

We studied normal subjects and CF patients to determine the effects of HFCC on external chest wall pressure (Pcw), pleural pressure, end-expiratory lung volume (EELV), oscillated tidal volume (Vosc) and oscillated air flow (Vosc). Some important differences were found between normal subjects and CF patients.

PATIENTS AND METHODS

Subjects: This study was approved by the local ethics committee and signed informed consent was obtained from all subjects. Ten normal subjects and 11 CF patients were studied. The normal subjects comprised nonsmoking volunteers 24.2±3.8 years old with normal lung function. The CF patients averaged 23.4±6.7 years, with forced expiratory volume in 1 s (FEV_1) ranging from 21 to 111% of predicted values (7). All of the CF patients were in a clinically stable phase of their disease and daily routine and medical treatments were unaltered for this study.

Lung function: Pulmonary function tests were done within 1 h before the HFCC study. Baseline lung function, which included spirometry and lung volumes, was determined in all subjects. For the CF patients, lung volumes were measured with both the helium dilution and body plethysmograph

TABLE 1
Anthropometric and baseline lung function for all subjects*

	Normals	Cystic fibrosis patients
Age (years)	24.2±3.8	23.4±6.7
Height (cm)	177.3±4.8	175.0±7.1
Weight (kg)	78.2±8.7	63.9±6.8
FEV_1 (% predicted) (range)	100.8±10.7 (85-123)	63.7±26.9 (21-111)
FEV_1/FVC (%)	82.3±5.8	55.2±16.3
FRC_{He} (% predicted)	118.4±12.3	123.9±14.5
RV_{He} (% predicted)	89.0±18.1	122.4±51.5
TLC_{He} (% predicted)	101.0±7.4	104.0±17.3
TLC_{Pl} (% predicted)	–	119.8±43.6

**All subjects were male. Data presented as mean ± SD. FEV_1 Forced expiratory volume in 1 s; FRC Functional residual capacity; FVC Forced vital capacity; He Helium dilution; Pl Body plethysmography; TLC Total lung capacity. Predicted values are from references 7 and 8*

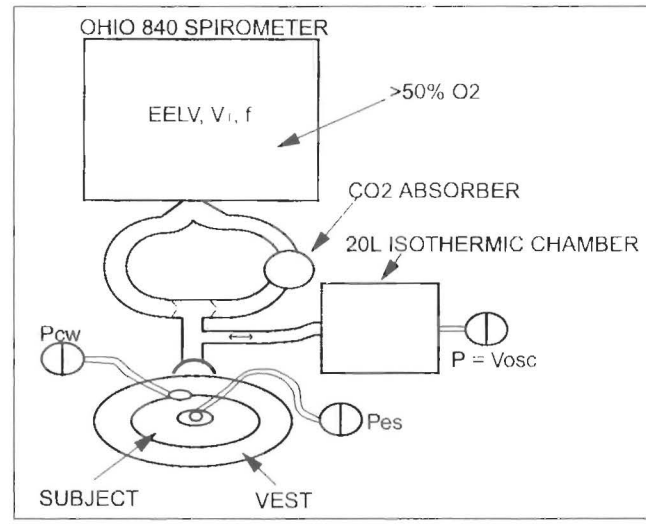

Figure 1) *Diagram of the system used to measure simultaneously external chest wall pressure (Pcw), esophageal pressure (Pes), oscillated tidal volume (Vosc), end-expiratory lung volume (EELV), tidal volume (V_T) and frequency (f). The ThAIRapy air pulse generator is not shown but connects to the vest via two flexible hoses*

methods, but only helium dilution values were obtained for the normals. A Gould 2400 PFT system and a Gould 2800 Autobox were used (Gould, Ohio). Baseline helium dilution functional residual capacity (FRC) measurements were taken in triplicate with at least 5 mins between measurements. The average of these three values was used to determine the EELV during HFCC. Anthropometric and baseline lung function data for the two study groups are presented in Table 1 with normal values for spirometry and lung volumes obtained from Morris et al (7) and Crapo et al (8), respectively.

HFCC system: The ThAIRapy system (American Biosystems, Minnesota) was used for HFCC. The system contains an air-pulse generator consisting of a high volume regenerative blower that provides a constant background pressure and a rotary valve that produces alternating positive and zero-gauge pressures. These pressures are applied to a pneumatic vest via two flexible hoses. The deflated vest covers the entire thorax and extends to the iliac crest. In this study, the vest was fitted to each subject by having the subject inhale to total lung capacity and then securely fastening the vest in place. This allowed for subjects to take deep breaths without being restricted by the noncompliant vest.

The vest's background pressure can be regulated and the frequency of the pulse pressures is controllable between 5 and 25 Hz. Ten of a wide range of possible pressure and frequency combinations were investigated: 5, 10, 15, 20 and 25 Hz oscillation frequencies and the lowest (LP) and highest (HP) background pressure settings. Activation of the HFCC system is controlled by a 'dead man's' switch designed for control by the patient, but in this study it was controlled by the investigator.

Lung mechanics measurements during HFCC: To study the short term effects of HFCC, a system capable of simultaneously measuring several indices of respiratory system mechanics was devised (Figure 1). These included Pcw, esophageal pressure (Pes), changes in EELV, spontaneous tidal volume (V_T), spontaneous breathing frequency (f) and the HFCC induced volume change at the mouth, Vosc. Both pulse pressure (amplitude of the pressure wave) and mean pressure (pressure at midpulse) were obtained for Pcw and Pes (Pcw-pp, Pes-pp, Pcw-m, and Pes-m, respectively). All measurements were recorded on a four-channel Gould strip chart recorder and values for Pcw, Pes and EELV were obtained at the end of a spontaneous expiration. Two measurements of Vosc were made during HFCC for each of the 10 frequency-pressure combinations: one Vosc was measured at the middle of a spontaneous inspiration and the other was measured at the middle of expiration for the same spontaneous breath to ensure a constant lung volume for the two measurements.

Pcw was measured via a 120 cm long and 0.20 cm inner diameter catheter with a latex balloon covering its tip. The balloon was 4 cm long and 2 cm in diameter and partially inflated with 1.5 mL of air. The catheter was taped to the external chest wall so that the balloon was 2 to 4 cm below the left pectoral muscle and under the vest. A Validyne MP 45 (±50 cm H_2O) (Validyne Engineering Corp, California) pressure transducer was used and the frequency response of the chest wall balloon system was flat through 25 Hz.

Pes was measured using the method described by Milic-Emili et al (9). An esophageal balloon was connected to a Validyne MP 45 (±50 cm H_2O) transducer via a 90 cm long and 0.15 cm inner diameter catheter. This was then connected to a 60 cm long 0.50 cm inner diameter catheter. The response of the Pes measurement system was frequency dependent and correction factors were used to account for this. The correction factors ranged from 1.00 to 1.15 at 5 Hz and 25 Hz, respectively.

The immediate HFCC induced changes in EELV, V_T and f were measured by a rebreathing system (Figure 1) with separate inspiration and exhalation pathways (Ohio 840,

TABLE 2
Short term ventilation response to HFCC

	$V_{T,b}$ (L)	$V_{T,HFCC}$ (L)	f_b (beats/min)	f_{HFCC} (beats/min)	$\dot{V}_{E,b}$ (L/min)	$\dot{V}_{E,HFCC}$ (L/min)
Normal subjects	0.59±0.04	0.66±0.11	15.3±0.7	16.4±1.3	8.2±0.5	10.0±1.8
Cystic fibrosis patients	0.95±0.06	1.08±0.06	11.3±0.4	11.9±0.7	10.1±0.7	12.2±1.0
P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01

Data presented as mean ± SD; n=100 for both groups. b Baseline (no HFCC); f Frequency; HFCC High frequency chest compression; $\dot{V}_E$ Total ventilation; VT Tidal volume

TABLE 3
Mean values for the various measurements during HFCC

	Pcw-m (cmH_2O)		Pcw-pp (cmH_2O)		Pes-m (cmH_2O)		Pes-pp (cmH_2O)		EELV (%FRC)		$Vosc_I$ (mL)		$Vosc_E$ (mL)	
	LP	HP	LP	HP	LP	HP	LP	HP	LP	HP	LP	HP	LP	HP
Normals	n=10	n=10	n=10	n=10	n=10	n=10	n=10	n=10	n=10	n=10	n=10	n=10	n=10	n=10
B	0	0	0	0	−4.8	−4.8	0	0	100	100	0	0	0	0
5 Hz	14.0	28.3	11.0	19.2	−2.6	−1.6	4.9	7.5	91.4	82.6	53.8	78.0	38.8	61.9
10 Hz	14.2	31.2	6.3	10.9	−2.7	−0.4	3.7	6.5	91.1	83.4	33.6	42.3	29.0	42.5
15 Hz	16.7	38.7	8.4	12.7	−2.6	0.5	4.2	6.9	91.3	79.9	23.5	26.8	19.5	22.9
20 Hz	22.0	43.0	8.8	13.3	−2.3	0.4	4.4	6.3	88.3	79.1	12.3	16.5	10.7	14.6
25 Hz	23.2	46.0	8.2	10.9	−2.6	0.3	4.5	5.7	88.2	78.2	8.8	10.4	8.3	9.3
CF	n=11	n=11	n=11	n=11	n=7	n=7	n=7	n=7	n=11	n=11	n=11	n=11	n=11	n=11
B	0	0	0	0	−2.7	−2.7	0	0	100	100	0	0	0	0
5 Hz	13.0	31.5	12.4	21.6	0.4	2.5	5.8	9.4	91.3	84.5	42.9	62.2	30.9	30.1
10 Hz	16.6	37.2	8.2	14.0	0.6	4.0	4.6	7.5	91.1	80.5	24.3	33.7	14.3	17.4
15 Hz	20.4	41.5	8.9	14.3	0.5	4.3	4.6	7.4	88.8	79.9	17.0	22.6	10.6	9.5
20 Hz	22.9	51.5	9.2	12.7	0.9	3.9	4.3	5.9	87.9	78.9	11.2	12.7	5.5	4.6
25 Hz	25.1	53.4	8.3	11.2	1.8	5.2	3.2	5.3	87.9	76.5	7.9	9.7	4.4	4.4

B Baseline; BTPS Body temperature, ambient pressure and saturated with water vapour; CF Cystic fibrosis; EELV End-expiratory lung volume; FRC Functional residual capacity; HFCC High frequency chest compression; HP Highest HFCC background pressure; LP Lowest HFCC background pressure; Pcw-m Mean chest wall pressure; Pes-m Mean esophageal pressure; Pcw-pp Chest wall pulse pressure; Pes-pp Esophageal pulse pressure; $Vosc_I$ Oscillated tidal volume (BTPS) during spontaneous inspiration; $Vosc_E$ Oscillated tidal volume (BTPS) during spontaneous expiration

Ohio Medical Products, Wisconsin). Carbon dioxide was removed and the initial fraction of inspired oxygen (F_IO_2) was set at approximately 0.5 to allow several minutes of rebreathing. Each of the 10 combinations of background pressure and oscillation frequency required 3 mins of rebreathing with the F_IO_2 restored between each combination. Oxygen saturation (Ohmeda Biox 3700, Ohmeda, Colorado) was monitored as a safety measure in the CF patients but oxygen saturation remained between 97 and 100% in all patients.

The subjects breathed for 1 min from the closed circuit without superimposed HFCC to obtain the baseline spirogram. Then, when HFCC was started, the increased external chest wall pressure caused a shift in the spirogram to a new and stable position which was measured as EELV. HFCC continued for 2 mins. EELV during HFCC (expressed as %FRC) was obtained by use of the baseline helium dilution FRC and the HFCC induced change in EELV.

The exhalation pathway acted as a low pass filter so that rapid volume changes at the mouth caused by HFCC (Vosc) could be recorded as pressure changes in a 20 L isothermic chamber located near the mouth (Figure 1). The Vosc measurement was frequency dependent and correction factors were used to obtain the true Vosc. These correction factors ranged from 1.00 to 1.55 at 5 Hz and 25 Hz, respectively. The correction factors were obtained by oscillating the isothermic chamber with a Matrix oscillator connected either at the mouth piece or directly to the chamber with a short piece of wide bore tubing. Airflow through the breathing system, either inspiration or expiration, had no effect on Vosc measurement.

Since Vosc approximated a sinusoidal wave, the mean Vosc during HFCC was calculated by multiplying the Vosc by half the oscillation frequency at which it was measured.

Correlation coefficients were calculated and analysis of variance (ANOVA) tests were done to test for differences between groups and within groups. Post-hoc comparisons were then done using the least significant difference test. Significant differences were taken at the $P<0.05$ level.

RESULTS

Esophageal pressure was obtained for all of the normal subjects but for only seven of the 11 CF patients. Four patients were unable to tolerate the esophageal balloon. In this study, a wide range of pressures was delivered to the chest wall due to the different background pressure settings (LP and HP) and the five different oscillation frequencies used.

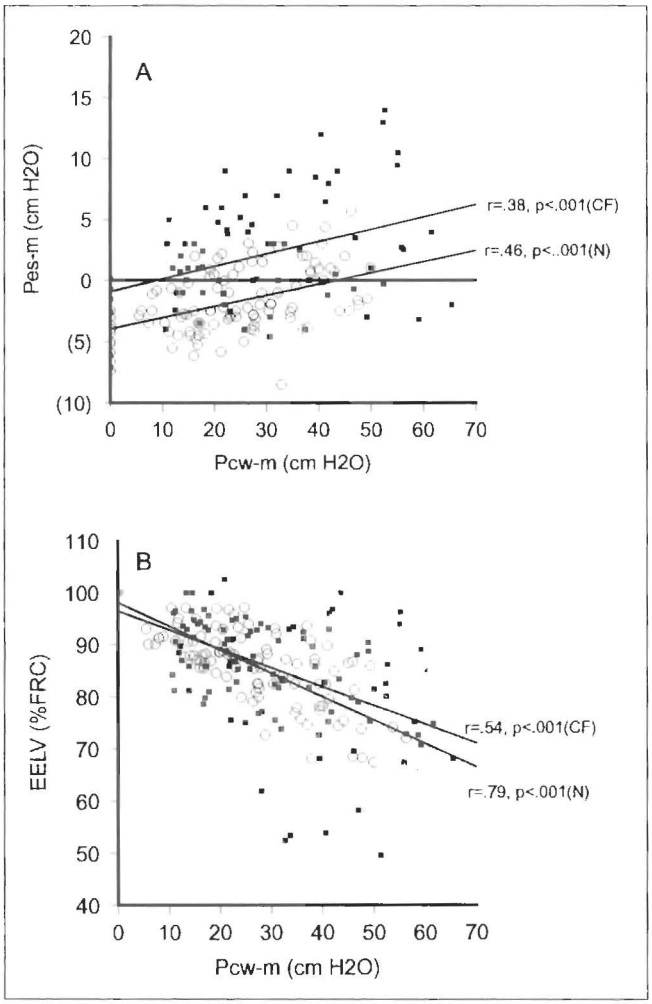

Figure 2) *Effects of mean chest wall pressure (Pcw-m)* **A** *on mean esophageal pressure (Pes-m), and* **B** *on end-expiratory lung volume (EELV).* ○ *Normals (N);* □ *Cystic fibrosis (CF) patients; FRC Functional residual capacity*

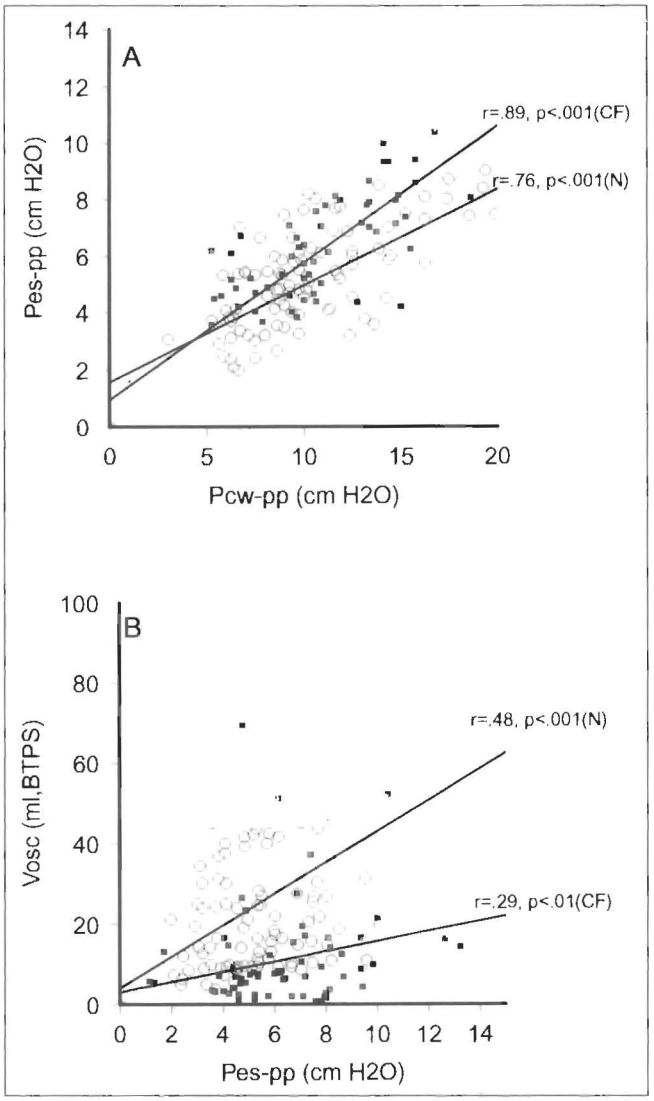

Figure 3) **A** *Effects of chest wall pulse pressure (Pcw-pp) on esophageal pulse pressure (Pes-pp).* **B** *The effects of Pes-pp on oscillated tidal volume (Vosc).* ○ *Normals (N);* □ *Cystic fibrosis (CF) patients; BTPS Body temperature, ambient pressure and saturated with water vapour*

The effect of HFCC on V_T, f and total ventilation (V_E) are shown in Table 2. The CF patients breathed with significantly larger V_T, lower frequencies and larger ventilation rates than the normal subjects, and HFCC caused significant increases in all of these variables in both normals and CF patients. The HFCC data represent the mean for all 10 pressure-frequency combinations but the changes in breathing pattern were similar for all of the combinations.

Table 3 shows the mean values for the other measurements made before and during HFCC. For all subjects, the LP setting resulted in Pcw-m being approximately half the value obtained during HP. Compared with LP at the same oscillation frequency, HP always resulted in higher values for Pcw-pp and Pes-pp, more positive Pes-m and lower EELV. In the normal subjects, Vosc was always higher during HP, regardless of whether Vosc was measured during spontaneous inspiration or expiration. For the CF patients, Vosc was also higher during HP when it was measured during spontaneous inspiration, but the differences in Vosc between LP and HP were insignificant when it was measured during spontaneous expiration. For both normals and CF patients, Vosc decreased exponentially as frequency increased.

The transmission of pressure from outside the chest to the pleural space is shown in Figure 2A. At FRC, without HFCC, Pes-m averaged –4.8 cm H_2O in the normal subjects and –2.7 cm H_2O in the CF patients. During HFCC, the changes in Pes-m were similar for the normals and CF patients, averaging 0.092 cm H_2O/cm H_2O and 0.103 cm H_2O/cm H_2O, respectively.

As expected, increasing Pcw-m decreased EELV (Figure 2B). EELV decreased similarly for both normal subjects and CF patients. The lowest EELV seen in the normal group was 66% of the pre-HFCC FRC and in the CF group it was 50%. In both instances the lowest EELV occurred at the HP 25 Hz setting. The lowest six values for EELV, seen in Figure 2B, came from the same CF patient.

The ability to transmit HFCC pulse pressures through the

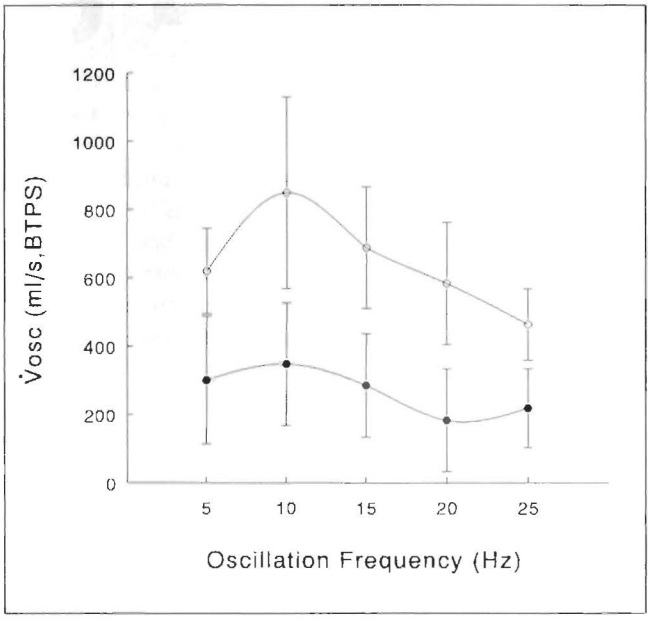

Figure 4) *Effects of oscillation frequency on oscillated tidal flow (V̇osc) during spontaneous expiration using the highest background pressure. ○ Normals (N); ● Cystic fibrosis (CF); BTPS Body temperature, ambient pressure and saturated with water vapour. The two groups were significantly different at all frequencies (P<0.005)*

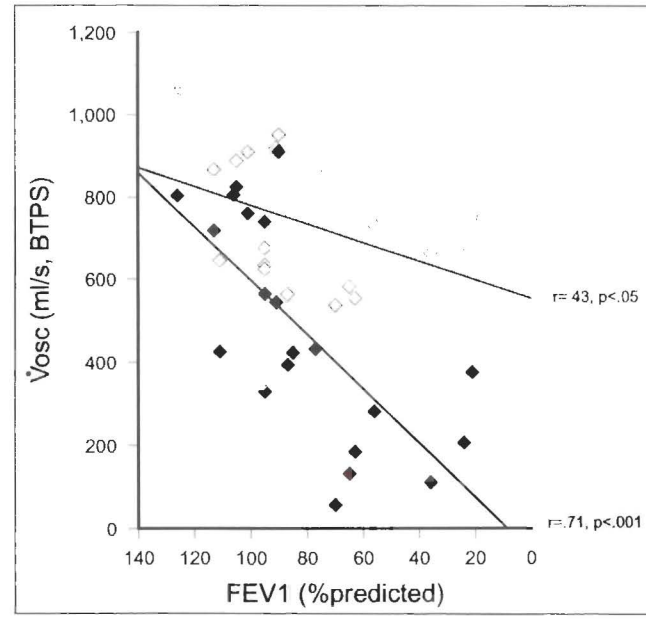

Figure 5) *Effect of airway obstruction, depicted by forced expiratory volume in 1 s (FEV_1) on oscillated tidal flow (V̇osc) at the high pressure 15 Hz setting measured at midexpiration (◆) and mid-inspiration (✧). Normal and cystic fibrosis patient data are included. The results obtained during expiration were significantly (P<0.05) lower than during inspiration. All other pressure-frequency combinations were qualitatively similar. BTPS Body temperature, ambient pressure and saturated with water vapour*

chest wall to the pleural space is indicated in Figure 3A. Increasing Pcw-pp was associated with higher Pes-pp in both the normal and CF groups. On average for the 10 experimental HFCC settings, Pes-pp was 50±6% of Pcw-pp in normals and 50±5% of Pcw-pp in CF patients. Each of the regressions in Figure 3A was significant (P<0.001) but they were not significantly different from each other.

The effects of Pes-pp on Vosc are shown in Figure 3B. Although there was a large scatter of points for both the normal subjects and CF patients the linear regressions were significant (r=0.48 and r=0.29, respectively). For a given Pes-pp the Vosc, measured during spontaneous expiration, was approximately three times greater in normals than in CF patients.

The effects of oscillation frequency on oscillated tidal flow rate in normals and CF patients during spontaneous expiration are shown in Figure 4. Although the normals had much higher V̇osc than the CF patients, the highest V̇osc occurred at 10 Hz in both groups. A similar pattern was seen for V̇osc measured during spontaneous inspiration except that V̇osc peaked at 15 Hz and that V̇osc, like Vosc, was higher during spontaneous inspiration than during expiration, especially for the CF patients.

Figure 5 shows the effect of airway obstruction, as assessed by FEV_1, on V̇osc at HP and 15 Hz. Regardless of whether V̇osc was measured during spontaneous inspiration or spontaneous expiration, decreasing FEV_1 decreased V̇osc. This effect was larger during spontaneous expiration even though the measurements were made at the same lung volume as during spontaneous inspiration. A similar effect of FEV_1 on V̇osc was observed for all of the other HFCC pressure and frequency combinations investigated in this study.

DISCUSSION

We found that both normal subjects and CF patients had decreases in EELV during HFCC. At HP and at the higher oscillation frequencies, EELV decreased to less than 80% of the baseline FRC. We also found that transmission of HFCC induced pulse pressure across the chest wall to the pleural space was similar for normals and CF patients. However, conversion of Pes-pp to Vosc and to V̇osc was less efficient in CF patients than in normal subjects, especially during spontaneous expiration.

Patients with airway obstruction tend to breathe at an elevated FRC, which minimizes the degree of airway closure (10) and it is generally considered undesirable for them to decrease EELV. Since HFCC decreases EELV one might expect widespread airway closure in CF patients who have significant airway obstruction. Although we did not observe a decrease in arterial oxygen saturation during short term HFCC, it should be recalled that F_IO_2 was kept at approximately 0.5 during the studies. Typically, HFCC treatments are conducted over 30 mins while the patients breathe room air so it is possible that hypoxemia could develop in that instance. On the other hand, V_T increased during HFCC and it is possible that, at end-tidal inspiration, any airway closure is overcome and gas exchange may be reasonably well preserved. Also, HFCC, especially at the lower frequencies where Vosc is highest, may be beneficial to gas exchange

(11,12). However, animal studies suggest that any beneficial effects of chest wall oscillation on gas exchange require larger, and not smaller, lung volumes (11). Studies during HFCC should be done to determine whether the decreased EELV causes any significant effects on gas exchange.

We showed (Figure 4) that $\dot{V}osc$, measured during spontaneous expiration, was considerably lower in CF patients than in normal subjects and there was a less well defined 'best frequency' for $\dot{V}osc$ in the CF patients. We believe this difference in $\dot{V}osc$ between the two groups is related to the higher airway resistance in CF patients. Increased airway resistance causes a larger time constant and, at a given Pes-pp, $\dot{V}osc$ will be lower. The decrease in EELV would be expected to cause a further increase in time constant (13) and this may contribute to the lower $\dot{V}osc$ that occurs with increasing HFCC frequency in both normals and CF patients (Table 3).

Figure 5 shows that $\dot{V}osc$ changes with FEV_1 and with the phase of spontaneous breathing. During inspiration $\dot{V}osc$ was, without exception, higher than during expiration for both normals and CF patients. Also, the lower the FEV_1 the greater was the disparity in $\dot{V}osc$ between inspiration and expiration. We believe this illustrates the influence of pleural pressure on airway resistance. The measurements in Figure 5 were obtained at the midpoints of inspiration and expiration when lung volume and elastic pressure were similar. Therefore, differences in pleural pressure between midinspiration and midexpiration represent the pressure required to overcome resistance (14). For instance, at high background pressure and at 15 Hz, this resistive pressure, obtained from Pes-m, averaged 5.9 cm H_2O in the normal subjects and 12.2 cm H_2O for the CF patients. The higher airway resistance, augmented by a more positive pleural pressure, causes $\dot{V}osc$ to be lower during expiration in CF patients than in normals. This effect is greater when the degree of airway obstruction is greater.

If HFCC-induced increases in mucus clearance depend on $\dot{V}osc$, then our results suggest that CF patients with moderate or severe airway obstruction may be less beneficially affected by HFCC treatment than patients with less airway obstruction. However, this may be an oversimplistic view of the factors that affect mucus clearance. It is possible that the lower $\dot{V}osc$ in CF patients with severe airway obstruction, when accompanied by the decreased EELV that should further narrow the small airways (13), may increase airflow velocity more than would be predicted from the low $\dot{V}osc$. Recently, Arens et al (16) showed that daily HFCC therapeutic sessions given over a two-week period did improve lung function in CF patients with severe airway obstruction.

Although we did not assess the effects of HFCC on mucus clearance, the highest $\dot{V}osc$ occurred at either 10 or 15 Hz in the normal subjects and CF patients. This is similar to the frequency found most effective in enhancing mucus clearance in normal canine lungs (1).

In summary, we found that HFCC caused a decrease in EELV in both normal subjects and CF patients and that the magnitude of decrease in EELV was dependent on external chest wall pressure. The combination of inherently high airway resistance, decrease in EELV and positive pleural pressure during spontaneous expiration causes the oscillated flow rate to be low in CF patients, especially in those with moderate or severe decreases in FEV_1.

ACKNOWLEDGEMENTS: This study was supported in part by a grant from American Biosystems Inc.

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