# High-frequency chest compression: A summary of the literature

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The purpose of the present literature summary is to describe high-frequency chest compression (HFCC), summarize its history and outline study results on its effect on mucolysis, mucus transport, pulmonary function and quality of life. HFCC is a mechanical method of self-administered chest physiotherapy, which induces rapid air movement in and out of the lungs. This mean oscillated volume is an effective method of mucolysis and mucus clearance. HFCC can increase independence. Some studies have shown that HFCC leads to more mucus clearance and better lung function compared with conventional chest physiotherapy. However, HFCC also decreases end-expiratory lung volume, which can lead to increased airway resistance and a decreased oscillated volume. Adding positive end-expiratory pressure to HFCC has been shown to prevent this decrease in end-expiratory lung volume and to increase the oscillated volume. It is possible that the HFCC-induced decrease in end-expiratory lung volume may result in more mucus clearance in airways that remain open by reducing airway size. Adjunctive methods, such as positive end-expiratory pressure, may not always be needed to make HFCC more effective.

**Key Words:** *Chest physiotherapy; End-expiratory lung volume; High-frequency chest compression; Mucus clearance; Positive end-expiratory pressure*

## Vibrations mécaniques de haute fréquence : Sommaire de la littérature

Le but du présente résumé de la littérature est de décrire la technique de vibrations mécaniques de haute fréquence, d'en résumer l'historique et de donner un aperçu des résultats d'une étude ayant mesuré ses effets sur la mucolyse, le dégagement du mucus, la fonction pulmonaire et la qualité de vie. Les vibrations mécaniques de haute fréquence sont une technique de physiothérapie pulmonaire auto-administrée qui accélèrent l'entrée et la sortie de l'air durant la respiration. Cette technique stimule efficacement la mucolyse et l'élimination du mucus et peut de ce fait favoriser l'autonomie. Certaines études ont montré qu'elle favorise l'expectoration et améliore la fonction pulmonaire comparativement à la physiothérapie pulmonaire classique. Par contre, elle réduit également le volume pulmonaire télé-expiratoire et peut entraîner une résistance respiratoire accrue et une baisse du volume oscillatoire. L'ajout d'une pression télé-expiratoire s'est révélée susceptible d'atténuer la baisse du volume pulmonaire télé-expiratoire et d'accroître le volume oscillatoire. Il est possible que la diminution du volume télé-expiratoire induite par les vibrations mécaniques de haute pression favorise une plus grande élimination du mucus dans les voies aériennes qui restent ainsi dégagées, en réduisant le calibre des voies respiratoires. Des méthodes d'appoint, comme la pression positive télé-expiratoire ne seraient pas toujours nécessaires pour rendre cette technique plus efficace.

Patients with cystic fibrosis have excessively thick lung mucus, which tends to plug the small peripheral airways. The cycle of hypersecretion, infection (1), inflammation and impaired mucus clearance (2,3) leads to progressive airway obstruction and destruction, especially in the lung periphery where cough and conventional chest physiotherapy are less effective at clearing mucus (3,4).

High-frequency chest compression (HFCC) is a patient-delivered form of chest physiotherapy, which causes mucolysis (5,6), as well as increased mucus clearance (7-10) and improvement in pulmonary function (1,10,11) compared with that achieved by conventional chest percussion and postural drainage. Also called high-frequency oscillation, HFCC was initially administered only to patients with cystic fibrosis, but is now starting to be used for a wide range of pulmonary, neurological and neuromuscular disorders (12).

## DESCRIPTION AND HISTORY OF HFCC

HFCC is a portable mechanical method of self-administered chest physiotherapy (13), and is analogous to frequent repetitive coughing (7). Cough generates a shear stress at the air-mucus interface (14), which increases mucus flow rate (15). Repetitive cough induces significantly more mucus clearance than a single cough, and even more clearance with an increased frequency of repetitive cough or air flow oscillations (14,16). Therefore, it follows that rapid air movement may also enhance mucus clearance.

HFCC is delivered by a pneumatic vest that surrounds the thorax. The vest is inflated to a nearly constant (11) positive background pressure with a superimposed frequency of air pressure oscillations (17). These oscillations induce rapid air movement in and out of the lungs, which is measured at the mouth as mean oscillated volume. Mean oscillated volume increases mucus clearance (11), particularly from the periphery of the lung (18). The volume of mucus moved has been thought to be greatest at frequencies between 10 Hz and 20 Hz, which can be alternated to maximize the volume of air and rate of air flow (19). HFCC may be advantageous in patients with cystic fibrosis in which plugging of the peripheral airways is a major problem and in patients with other obstructive lung disease where peripheral mucociliary clearance is impaired and cough is less effective (18).

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In 1966, high-frequency vibration of the chest was first used to effectively relieve respiratory airway obstruction due to retained secretions, thereby increasing vital capacity (20). A cycled external vibrocompressor applied pressure to the upper abdomen and lower thorax during expiration (20). The ThAIRapy Vest for high-frequency chest wall compression was developed in the 1980s by Hansen and Warwick, and was approved for use and met all the criteria for airway clearance therapy published by the American Association for Respiratory Care (21). This modality is now called The Vest (Advanced Respiratory, USA) (12). The pressure pulse frequency is adjustable from 5 Hz to 25 Hz.

In 1983, King et al (7,8) found that, in anesthetized dogs, a modified blood pressure cuff placed around the lower thorax, providing high-frequency chest wall oscillations at 5 Hz to 17 Hz and of the same magnitude as used for ventilation, led to the enhancement of the tracheal mucus clearance rate (8). The tracheal mucus clearance rate was frequency-dependent, with a maximal effect at 13 Hz (340% of spontaneously breathing control) (7). Their hypotheses for how HFCC increased the mucus clearance included cephalad bias of air flow, reduction of mucus crosslinking, which decreases mucus viscosity, and enhanced ciliary beating. Both chest wall compression and oscillated volume are thought to be necessary (7-9). Increased depth of airway mucus or excessive airway narrowing are necessary for mucus-air flow interaction to have an effect. More recently, HFCC with a pulse frequency of 3 Hz and of 16 Hz alternating with 1.5 Hz was shown to have comparable effects on the weight of expectorated sputum in human patients with cystic fibrosis compared with the effects from conventional chest physiotherapy (22). A 2004 short-term crossover study by Phillips et al (23), using the Hayek Oscillator 1000 (Flexico Medical Instruments AG, Switzerland) for HFCC with a frequency of 10 Hz, found no significant change in sputum volume or pulmonary function post-treatment, in contrast to active cycle of breathing techniques. In another study (10), the use of HFCC with a pulse frequency of 6 Hz to 19 Hz led to significantly more sputum expectoration than during conventional chest physiotherapy.

HFCC has also been found to be an effective method of physical mucolysis (5), because its high-frequency oscillations disentangle mucus gel by reducing its crosslinkages (6). The physical disruption of mucus gel decreases its viscoelasticity and spinnability (thread-forming ability of mucus), which would be predicted to increase the cough clearability of the mucus after 30 min of oscillation (5). Majaesic et al (24) found a greater decrease in sputum viscosity from HFCC than with conventional chest physiotherapy. They speculated that physically disrupting the mucus network could enhance the delivery of chemical agents such as recombinant human deoxyribonuclease I throughout the mucus. Oscillations may also break up the DNA molecules of mucus (6), and, therefore, enhance the action of recombinant human deoxyribonuclease I in cleaving the DNA molecules and reducing the viscoelasticity (25).

## EFFECTS OF HFCC COMPARED WITH CONVENTIONAL CHEST PHYSIOTHERAPY ON MUCUS CLEARANCE AND PULMONARY FUNCTION

Although there have been some studies with equivocal results (13,22,23), and there have not yet been meta-analyses of HFCC, the weight of current opinion (1,10,11,26-29) suggests that HFCC has a beneficial effect on mucus clearance and pulmonary function compared with conventional chest physiotherapy. In their papers, Oermann et al (27) and Donahue (30) suggest that the various airway clearance modalities (conventional chest physiotherapy, HFCC and positive expiratory pressure breathing) presently appear to be more or less equivalent in efficacy. More definitive, long-term comparative studies are needed (27,28,30), and such a multicentre study is apparently currently underway (30).

In one study (13), HFCC and conventional chest physiotherapy were reported to have similar effects on mucus clearance, improvement of pulmonary function and clinical status during acute pulmonary exacerbation in patients with cystic fibrosis. There was, however, a significant increase in wet sputum production during the first hour after HFCC than after conventional chest physiotherapy (13). Conventional chest physiotherapy primarily affects the large airways, whereas HFCC increases peripheral mucus clearance when applied at 13 Hz. The effect of HFCC may indeed be stronger in the lung periphery than in the central airways (4), and, therefore, more effective than conventional chest physiotherapy at mucus clearance.

In their 1998 prospective, randomized trial, Scherer et al (22) found that using HFCC with a frequency of 16 Hz alternating with 1.5 Hz in patients with stable cystic fibrosis produced a comparable expectorated sputum weight compared with conventional chest physiotherapy, and was equally tolerated, with no treatment-induced changes in $O_2$ saturation or pulmonary function. They noted that an increased weight of sputum may or may not reflect a reduction in the amount of lower airway secretions. In a 1996 crossover trial, Kluft et al (10) found that hospitalized patients with cystic fibrosis expectorated more sputum (as determined by both the wet and dry measurements) during HFCC using a pulse frequency ranging from 6 Hz to 19 Hz than during conventional chest physiotherapy.

In a 1994 prospective, randomized controlled trial (13) involving patients with cystic fibrosis and pulmonary exacerbations, a two-week treatment with HFCC or conventional chest physiotherapy yielded similar significant improvements in pulmonary function. In other studies, HFCC increased mucus clearance (10,11) and significantly improved lung function outcome (1,11,29) compared with standard chest physiotherapy. In 1990, Hansen and Warwick (11) demonstrated improved peak flow and forced vital capacity (FVC), to a level equal to that of five years earlier, and showed restored ventilation to previously nonventilated areas of the lung in a 48-year-old man with cystic fibrosis superinfected with *Pseudomonas aeruginosa* after a year of using the HFCC vest. In 1996, patients with cystic fibrosis treated with HFCC over a 30-month period showed improved small airway function (26).

Another long-term study (1) was performed in adolescents and young adults with cystic fibrosis using 30 min of daily HFCC therapy for 22 months. Before beginning the study, when the group was receiving conventional chest physiotherapy, the group mean showed deteriorating FVC and forced expiratory volume in 1 s ($FEV_1$). During the HFCC phase, those who were younger and had mild obstructive disease showed a significant improvement in FVC and $FEV_1$; the group with moderate-severe obstructive disease showed a significant change in $FEV_1$. In 2000, Tecklin et al (29) reported a relatively large,

12-month, retrospective study in children with cystic fibrosis who used either HFCC or conventional chest physiotherapy twice daily for 60 min. They concluded that HFCC is an adequate alternative to conventional chest physiotherapy for long-term care, because both yielded similar changes in FVC, $FEV_1$, forced expiratory flows at 25% to 75% of the exhaled vital capacity, residual volume:total lung capacity, and changes in the number of days hospitalized during the study.

In the pediatric population, HFCC is most widely used in children with cystic fibrosis. However, children with developmental disorders involving neuromuscular dysfunction also have impaired airway clearance with or without ventilator dependence. HFCC has been effective in improving mucus clearance in these children (31). Preliminary data from a randomized control trial (32) suggest that HFCC is more effective in promoting airway secretion clearance and liberating patients from the ventilator than conventional chest physiotherapy in ventilator-dependent patients. Large, long-term studies are needed examining HFCC in the patients with developmental disorders (31).

There are methodological limitations in the studies examining secretion clearance techniques, which have been described by Hess (33) in his 2001 literature review. He outlined that there is a lack of evidence that secretion clearance, in general, improves the course of respiratory disease, but that this did not mean there was a lack of benefit seen in clinical practice.

## HFCC DECREASES FUNCTIONAL RESIDUAL CAPACITY AND MEAN OSCILLATED VOLUME

With the use of HFCC, end-expiratory lung volume decreases; it has been shown to decline to 50% of the pre-HFCC functional residual capacity in humans (17,34). In dogs receiving HFCC at frequencies of 5 Hz and 11 Hz, the mean oscillated volume declined over 30 min secondary to the increased load applied on the chest wall (34), decreasing lateral chest wall displacement (4). Jones et al (17) found that patients with the most severe airway obstruction had the lowest mean oscillated volume, and it is in these patients that a decrease in end-expiratory lung volume may be least desirable, because HFCC is most likely to decrease end-expiratory lung volume below closing volume (35).

Patients with cystic fibrosis tend to breathe at an elevated functional residual capacity, which minimizes the degree of airway closure (18,36). A decrease in end-expiratory lung volume may aggravate an already increased resistance in the narrowed airways of patients with cystic fibrosis (35). Because these patients tend to breathe just above their residual volume, any decrease in end-expiratory lung volume may cause airway closure and additional obstruction, further compromising mucus clearance.

The more the vest-induced chest wall pressure decreases mean oscillated volume, the less air-mucus interaction might occur. Decreased linear velocity in the airways could diminish the shear stress exerted on the mucus for movement (30) in the cephalad direction. However, it is conceivable that the reduction in cross-sectional area of the airways caused by HFCC may actually result in increased linear airway velocities despite a reduction in oscillated volumes at the airway opening. Thus, reduced lung volume from HFCC might result in more mucus mobilization, especially in people whose baseline functional residual capacity is not elevated, such as in patients with neuromuscular dysfunction.

## EFFECTS OF POSITIVE END-EXPIRATORY PRESSURE ON MUCUS CLEARANCE AND PULMONARY FUNCTION

Positive expiratory pressure is thought to increase collateral air flow to peripheral airways obstructed by secretions (37) by increasing end-expiratory lung volume through the expansion of the small airways. Khirani et al's (38) mathematical model shows positive end-expiratory pressure decreasing airway resistance and expiratory air flow limitation. No harmful effects have been reported from positive expiratory breathing (39). Although there have been some contradictory reports (37,39) and there have not yet been meta-analyses of the use of positive end-expiratory pressure for people with cystic fibrosis, chronic obstructive pulmonary disease or neuromuscular disorders, the majority of clinical studies (27,28,35,40-45) have described benefits of positive expiratory pressure on mucus clearance and pulmonary function.

In one study (37), sputum clearance was found to be less effective when positive expiratory pressure was used compared with the forced expiration technique (huffing). Another study (40) found positive expiratory pressure to significantly increase sputum production in patients with cystic fibrosis. In another study (41), a positive expiratory pressure mask was used as an adjunct to the forced expiration technique, and this combination had a longer lasting effect on mucus clearance than the forced expiration technique alone. In a related study (42), nasal positive pressure ventilation at night in patients with cystic fibrosis with advanced lung disease subjectively improved their quality of life, despite not changing pulmonary function.

A study in 1991 (39) showed no significant change in the volume of trapped gas with positive expiratory pressure mask breathing compared with the use of productive coughing (lung volumes returned to baseline immediately after positive expiratory pressure breathing); however, this study showed promising effects of positive expiratory pressure on functional residual capacity. Functional residual capacity increased in patients with cystic fibrosis after 2 min of positive expiratory pressure breathing using an expiratory pressure of either 5 cm $H_2O$ or 15 cm $H_20$, with a greater effect from 15 cm $H_20$. Positive expiratory pressure was provided using a face mask containing a one-way valve leading to an expiratory resistance. Positive expiratory pressure was used with the hypothesis that mucus in the small peripheral airways is mobilized by coughing or forced expiration if alveolar pressure is increased, and positive expiratory pressure increases alveolar pressure. In pediatric patients with cystic fibrosis, McIlwaine et al (46) found that long-term use of a positive expiratory pressure mask with a midexpiratory pressure of 10 cm $H_20$ to 20 cm $H_20$ resulted in significantly improved FVC and $FEV_1$ than in patients treated with conventional chest physiotherapy, whose pulmonary function declined. They also suggested that positive expiratory pressure therapy may help mobilize peripheral lung secretions more than conventional chest physiotherapy.

Braggion et al (28) performed a two-day crossover study in patients with cystic fibrosis admitted for a pulmonary exacerbation. They found that similar sputum weight was

produced using twice daily 50 min sessions of positive expiratory pressure of 10 cm $H_20$ to 20 cm $H_20$ (provided by the patient breathing through a mask with a one-way valve and an expiratory resistor), an HFCC device (ThAIRapy Bronchial Drainage System) using compression frequencies of 6 Hz to 19 Hz or postural drainage. Sputum weight is thought to reflect mucus clearance by coughing (28). None of the systems changed pulmonary function during this short-term study. A 2001 crossover study by Oermann et al (27) examined the use of the Flutter device (VarioRaw SA, Switzerland), which provided a positive expiratory pressure of 15 cm $H_2O$ to 25 cm $H_2O$ combined with airway vibration, and the use of the ThAIRapy Vest system for HFCC with cycle frequencies at 5 Hz to 25 Hz. Both modalities resulted in similar improvements in pulmonary function in 24 patients with cystic fibrosis over four weeks of two or three times daily therapy. This pilot study indicated that either oscillated positive expiratory pressure or HFCC offered acceptable alternatives to conventional chest physiotherapy.

In their 1996 and 1998 studies, Perry et al (35,43) showed that adding a modest amount of positive end-expiratory pressure (3.7±1.0 cm $H_20$ through a three-way valve in the pneumatic vest system) to HFCC use in older patients with chronic obstructive pulmonary disease prevented the decrease in end-expiratory lung volume and significantly increased the mean oscillated volume during both inspiration and expiration. They proposed that the increased mean oscillated volume resulted from the decreased airway resistance associated with the increased end-expiratory lung volume. Guerin et al (45) indicated that inspiratory airway resistance decreased with increasing lung volume from positive end-expiratory pressure. In 2003, Dosman et al (47) found that the addition of a small amount of positive end-expiratory pressure (2.0±0.3 cm $H_2O$) during HFCC prevented the HFCC-induced decrease in end-expiratory lung volume and significantly increased the mean oscillated volume during expiration in pediatric patients with cystic fibrosis.

Controlling positive end-expiratory pressure may also be critical as an adjunct to HFCC therapy in people with neuromuscular disorders. The use of external positive end-expiratory pressure may reduce respiratory muscle workload for inspiratory air flow (48); however, the effects of HFCC on respiratory muscle tone are not known. In addition, for people with weak chest wall muscles, a slight lowering of end-expiratory lung volume may actually be beneficial, because it is possible that a lower functional residual capacity and narrower airways will increase air flow velocity in airways that are still open.

## SUBJECTIVE BENEFITS FROM HFCC

During adolescence, desired independence often conflicts with the assistance required to perform conventional chest physiotherapy (44). It was this desired independence that popularized HFCC use (1,21), which is also less time-consuming and less labour-intensive (49). For the same reasons, Braverman (50) proposed that HFCC be implemented as part of a donor lung procurement protocol to increase rates of successful lung recovery.

Patients with cystic fibrosis have reported greater satisfaction and compliance with HFCC than with conventional chest physiotherapy or positive expiratory pressure (27,51,52), and have reported a strong belief in the efficacy of HFCC (27). HFCC allows all areas of the chest to receive treatment simultaneously without requiring the patient to change positions (10). By permitting the self-administration of therapy, HFCC can also reduce health care costs (22) and impact positively on caregiver workload. Children as young as three years of age have been successfully treated with HFCC at home under parental supervision (19). This therapeutic modality is helpful for anyone who is unable to tolerate other techniques for mucus expectoration (53).

The HFCC vest has not been associated with significant side effects when moderate pressures are applied (4,27). Kluft et al (10) reported that while some patients initially complain of a sense of chest constriction while using the vest, they quickly adapt to this sensation and are able to tolerate the therapy because of the greater ease of breathing following therapy.

## CONCLUSIONS

The weight of current opinion suggests that HFCC increases mucolysis, mucus transport and pulmonary function in patients with cystic fibrosis, while improving their quality of life. It appears to be an adequate alternative to other mucus clearance modalities. HFCC is now also being used to enhance mucus clearance in children with developmental disorders involving neuromuscular dysfunction.

HFCC decreases end-expiratory lung volume. This can exacerbate airway obstruction in people with cystic fibrosis and chronic obstructive pulmonary disease. However, it is possible that a reduction in airway size may result in increased linear airway velocities for improved mucus mobilization from airways that are still open in patients with obstructive airways disease or neuromuscular disorders.

Increasing end-expiratory pressure can increase end-expiratory lung volume. Positive end-expiratory pressure may be critical as an adjunct to HFCC therapy for people with obstructive airway disease, and may be extended to the realm of neuromuscular disorders. Increasing end-expiratory lung volume results in an increased oscillated volume during HFCC at the airway opening. Oscillated volume appears to be an important component of the effectiveness of HFCC.

It is conceivable that the HFCC-induced decrease in end-expiratory lung volume might result in more mucus clearance in airways that are still open than what could result from a positive end-expiratory pressure-induced increase in lung volume.

**DISCLOSURE:** The authors have no financial interest with the company that produces the high-frequency chest compression vest. RLJ has received the occasional grant to do research projects with the company.

## REFERENCES

1. Warwick WJ, Hansen LG. The long-term effect of high-frequency chest compression therapy on pulmonary compli-cations of cystic fibrosis. Pediatr Pulmonol 1991;11:265-71.
2. Regnis JA, Robinson M, Bailey DL, et al. Mucociliary clearance in patients with cystic fibrosis and in normal subjects. Am J Respir Crit Care Med 1994;150:66-71.
3. Regnis JA, Zeman KL, Noone PG, Bennett WD. Impaired small airway clearance in patients with cystic fibrosis, as compared to normal subjects and COPD. Am J Resp Crit Care Med 1996;153:A71. (Abst)
4. Gross D, Zidulka A, O'Brien C, et al. Peripheral mucociliary clearance with high frequency chest wall compression. J Appl Physiol 1985;58:1157-63.

5. Tomkiewicz RP, Biviji AA, King M. Effects of oscillating air flow on the rheological properties and clearability of mucus gel simulants. Biorheology 1994;31:511-20.
6. Dasgupta B, King M. Molecular basis for mucolytic therapy. Can Respir J 1995;2:223-30.
7. King M, Phillips DM, Gross D, Vartian V, Chang HK, Zidulka A. Enhanced tracheal mucus clearance with high frequency chest wall compression. Am Rev Respir Dis 1983;128:511-5.
8. King M, Zidulka A, Phillips DM, Wight D, Gross D, Chang HK. Tracheal mucus clearance in high-frequency oscillation: Effect of peak flow rate bias. Eur Respir J 1990;3:6-13.
9. King M, Phillips DM, Zidulka A, Chang HK. Tracheal mucus clearance in high-frequency oscillation. II: Chest wall versus mouth oscillation. Am Rev Respir Dis 1984;130:703-6.
10. Kluft J, Beker L, Castagnino M, Gaiser J, Chaney H, Fink RJ. A comparison of bronchial drainage treatments in cystic fibrosis. Pediatr Pulmonol 1996;22:271-4.
11. Hansen LG, Warwick WJ. High-frequency chest compression system to aid in clearance of mucus from the lung. Biomed Instrum Technol 1990;24:289-94.
12. Fink JB, Mahlmeister MJ. High-frequency oscillation of the airway and chest wall. Respir Care 2002;47:797-807.
13. Arens R, Gozal D, Omlin KJ, et al. Comparison of high frequency chest compression and conventional chest physiotherapy in hospitalized patients with cystic fibrosis. Am J Respir Crit Care Med 1994;150:1154-7.
14. Zahm JM, King M, Duvivier C, Pierrot D, Girod S, Puchelle E. Role of simulated repetitive coughing in mucus clearance. Eur Respir J 1991;4:311-5.
15. King M, Agarwal M, Shukla JB. A planar model for mucociliary transport: Effect of mucus viscoelasticity. Biorheology 1993;30:49-61.
16. Chang HK, Weber ME, King M. Mucus transport by high-frequency nonsymmetrical oscillatory airflow. J Appl Physiol 1988;65:1203-9.
17. Jones RL, Lester RT, Brown NE. Effects of high-frequency chest compression on respiratory system mechanics in normal subjects and cystic fibrosis patients. Can Respir J 1995;2:40-6.
18. Gross D, King M. High frequency chest wall compression: A new non-invasive method of chest physiotherapy for mucociliary clearance. Physiother Canada 1984;36:137-9.
19. Warwick WJ. Airway clearance by high frequency chest compression. Pediatr Pulmonol 1992;S8:138-9.
20. Beck GJ. Chronic bronchial asthma and emphysema. Rehabilitation and use of thoracic vibrocompression. Geriatrics 1966;21:139-58.
21. Langenderfer B. Alternatives to percussion and postural drainage. A review of mucus clearance therapies: Percussion and postural drainage, autogenic drainage, positive expiratory pressure, fluttervalve, intrapulmonary percussive ventilation, and high-frequency chest compression with the ThAIRapy Vest. J Cardiopulm Rehabil 1998;18:283-9.
22. Scherer TA, Barandun J, Martinez E, Wanner A, Rubin EM. Effects of high-frequency oral airway and chest wall oscillation and conventional chest physical therapy on expectoration in patients with stable cystic fibrosis. Chest 1998;113:1019-27.
23. Phillips GE, Pike SE, Jaffe A, Bush A. Comparison of active cycle of breathing and high-frequency oscillation jacket in children with cystic fibrosis. Pediatr Pulmonol 2004;37:71-5.
24. Majaesic CM, Montgomery M, Jones RL, King M. Reduction in sputum viscosity using high frequency chest compressions (HFCC) compared to conventional chest physiotherapy. Pediatr Pulmonol 1996;S13:308. (Abst)
25. Dasgupta B, Tomkiewicz RP, Boyd WA, Brown NE, King M. Effects of combined treatment with rhDNase and airflow oscillations on spinnability of cystic fibrosis sputum in vitro. Pediatr Pulmonol 1995;20:78-82.
26. Wielinski CL, Warwick J. Change in pulmonary function over a 30-month period for high-frequency vest users versus non-users in a cystic fibrosis population. Am J Respir Crit Care Med 1996;153:A71. (Abst)
27. Oermann CM, Sockrider MM, Giles D, Sontag MK, Accurso FJ, Castile RG. Comparison of high-frequency chest wall oscillation and oscillating positive expiratory pressure in the home management of cystic fibrosis: A pilot study. Pediatr Pulmonol 2001;32:372-7.
28. Braggion C, Cappelletti LM, Cornacchia M, Zanolla L, Mastella G. Short-term effects of three chest physiotherapy regimens in patients hospitalized for pulmonary exacerbations of cystic fibrosis: A cross-over randomized study. Pediatr Pulmonol 1995;19:16-22.
29. Tecklin JS, Clayton RG, Scanlin TF. High frequency chest wall oscillation vs. traditional chest physical therapy in CF – a large, one-year, controlled study. Pediatr Pulmonol 2000;S20:304 (Abst)
30. Donahue M. "Spare the cough, spoil the airway": Back to the basics in airway clearance. Pediatr Nurs 2002;28:107-11.
31. Toder DS. Respiratory problems in the adolescent with developmental delay. Adolesc Med 2000;11:617-31.
32. Ndukwu IM, Shapiro S, Nam AJ, Schumm PL. Comparison of high-frequency chest wall oscillation (HFCWO) and manual chest physiotherapy (MCPT) in long-term acute care hospital (LTAC) ventilator-dependent patients. Chest 1999;116(Suppl 2):311S. (Abst)
33. Hess DR. The evidence for secretion clearance techniques. Respir Care 2001;46:1276-93.
34. Zidulka A, Gross D, Minami H, Vartian V, Chang HK. Ventilation by high-frequency chest wall compression in dogs with normal lungs. Am Rev Respir Dis 1983;127:709-13.
35. Perry RJ, Man GC, Jones RL. Effects of positive end-expired pressure on oscillated tidal volume during high frequency chest compression. Chest 1996;110:655.
36. Leblanc P, Ruff F, Milic-Emili J. Effects of age and body position on "airway closure" in man. J Appl Physiol 1970;28:448-51.
37. Hofmeyr JL, Webber BA, Hodson ME. Evaluation of positive expiratory pressure as an adjunct to chest physio-therapy in the treatment of cystic fibrosis. Thorax 1986;41:951-4.
38. Khirani S, Biot L, Eberhard A, Baconnier P. Positive end expiratory pressure and expiratory flow limitation: A model study. Acta Biotheor 2001;49:277-90.
39. van der Schans CP, van der Mark TW, de Vries G, et al. Effect of positive expiratory pressure breathing in patients with cystic fibrosis. Thorax 1991;46:252-6.
40. Falk M, Kelstrup M, Andersen JB, et al. Improving the ketchup bottle method with positive expiratory pressure, PEP, in cystic fibrosis. Eur J Respir Dis 1984;65:423-32.
41. Falk M, Mortensen J, Kelstrup M, Lanng S, Larsen L, Ulrik CS. Short-term effects of positive expiratory pressure and the forced expiration technique on mucus clearance and lung function in CF. Pediatr Pulmonol 1993;S9:268. (Abst)
42. Granton JT, Tulis DE, Allard J, Sullivan C, Kesten S. A trial of domiciliary nasal positive pressure ventilation in patients with advanced cystic fibrosis. Am J Respir Crit Care Med 1996;153:A71. (Abst)
43. Perry RJ, Man GC, Jones RL. Effects of positive end-expiratory pressure on oscillated flow rate during high-frequency chest compression. Chest 1998;113:1028-33.
44. de Boeck C, Zinman R. Cough versus chest physiotherapy. Am Rev Respir Dis 1984;129:182-4.
45. Guérin C, Fournier G, Milic-Emili J. Effects of PEEP on inspiratory resistance in mechanically ventilated COPD patients. Eur Respir J 2001;18:491-8.
46. McIlwaine PM, Wong LT, Peacock D, Davidson GF. Long-term comparative trial of conventional postural drainage and percussion versus positive expiratory pressure physiotherapy in the treatment of cystic fibrosis. J Pediatr 1997;131:570-4.
47. Dosman CF, Zuberbuhler PC, Tabak JI, Jones RL. Effects of positive end-expiratory pressure on oscillated volume during high frequency chest compression in children with cystic fibrosis. Can Respir J 2003;10:94-8.
48. Wrigge H, Putensen C. What is the "best PEEP" in chronic obstructive pulmonary disease? Intensive Care Med 2000;26:1167-9.
49. Woo MS. High frequency chest compression and PEP. Pediatr Pulmonol 2004;S26:152-3.
50. Braverman JM. Increasing the quantity of lungs for transplantation using high-frequency chest wall oscillation: A proposal. Prog Transplant 2002;12:266-74.
51. Oermann CM, Swank PR, Sockrider MM. Validation of an instrument measuring patient satisfaction with chest physiotherapy techniques in cystic fibrosis. Chest 2000;118:92-7.
52. Anbar RD. Compliance with use of ThAIRapy Vest by patients with cystic fibrosis. Pediatr Pulmonol 1998;S17:346. (Abst)
53. Rueling S, Adams C. Close to the vest: A novel way to keep airways clear. Nursing 2003;33:56-7.