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High Frequency Chest Wall Oscillation: AIRFLOW BIAS AND SECRETION CLEARANCE

ABSTRACT

High frequency chest wall oscillation (HFCWO) mobilizes pulmonary secretions principally via air-liquid interaction. During HFCWO, chest compression-induced oscillations create rapid air movement in and out of the lungs. Vibrations to the chest wall cause transient increases in airflow in the lungs that enhance gas-liquid interactions and mucus mobility. Flow bias (inspiratory vs. expiratory) determines whether secretions move upstream or downstream. Maximum clearance occurs when high expiratory bias airflow velocities are generated. Laboratory and clinical studies confirm that the synchronized effects of flow bias and oscillations frequency (cycles/second) correlate strongly with significant mucus clearance. Effects were seen in both peripheral and central lung regions. Their magnitude may be measured at the mouth as mean oscillated volume. Currently, there are several commercially available HFCWO devices. Theoretically, all such devices operate upon the same principles and are assumed to provide comparable therapy. However, comparative studies to confirm this assumption are lacking. Given the critical importance of the HFCWO-induced airflow effects on the effectiveness of mucus transport, intra-device studies comparing mean oscillated volumes at the mouth are needed to better understand differences that may exist.

PULMONARY DEFENSE

Lung health depends upon effective mechanisms to clear pulmonary secretions and inhaled debris from the airways. Larger particles are cleared from the upper airways by coughing, swallowing or other expectoration. Smaller particles are entrapped in mucus lining the lower airways and are removed by a combination of the unidirectional “escalator” effect of the mucociliary clearance (MCC) system and airflow. Effective MCC depends upon synchronistic ciliary motion and, critically, airflow moving away from peripheral lung regions and directed towards the head (cephalad).

AIRFLOW BIAS AND SECRETION CLEARANCE

Cephalad airflow bias regulates the movement of airway mucus during normal breathing [1, 2]. In healthy individuals, airway diameters increase on inspiration and decrease on expiration. During normal (tidal) breathing, airway narrowing during exhalation results in increased airflow velocity and shearing forces that induce a cephalad airflow bias. This airflow bias is greatly amplified during coughing or sneezing because increased transmural pressure causes the airways to constrict [3]. Cough generates a burst of airflow creating shear stress at the air-mucus interface and resulting in accelerated mucus flow [4, 5].

IMPAIRED AIRFLOW AND DIMINISHED SECRETION CLEARANCE

MCC function may be impaired by several factors that arrest or delay mobilization of mucus from distal lung regions to central airways. These include 1) increased mucus production; 2) abnormal mucus rheology; 3) abnormal ciliary activity and; 4) loss of ciliated cells [6]. Most patients with acute or chronic respiratory conditions present with some degree of one or more of these anomalies. Measurements of tracheal mucus velocity (TMV) in diverse patient populations demonstrate rates markedly below that of healthy control subjects [7-9]. In acute airway diseases leading to ciliary dysfunction and/or mucus hypersecretion, including respiratory infections or severe asthma attacks, cough is the main mechanism for clearing secretions from central airways while the role of cephalad airflow bias in mobilizing secretions from peripheral airways is increased [3]. In chronic airway diseases characterized by mucus hypersecretion, including cystic fibrosis (CF), bronchiectasis and chronic bronchitis, both cough and cephalad airflow bias are critical to airway patency [3].

IMPAIRED MCC AND THERAPEUTIC INTERVENTIONS

Airway Clearance Therapy (ACT): When MCC is impaired, a variety of therapeutic interventions, including nebulized medications, antibiotics and ACT interventions are used to enhance secretion clearance. The goal of ACT is to prevent mucus retention which helps maintain airway patency and maximize gas exchange. Among the large array of ACT modalities in current use, theoretical foundations and mechanisms of action vary greatly [3, 10].

HIGH FREQUENCY CHEST WALL OSCILLATION (HFCWO)/CHEST PHYSIOTHERAPY (CPT)

HFCWO technology was first developed in the 1980's as an alternative to traditional chest physiotherapy (CPT). CPT relies upon manual percussion of successive lung segments to loosen secretions from the airways alternating with postural positioning. The viscosity of mucus is such that, in the absence of effective MCC mechanisms, it resists cephalad flow [3]. High Frequency Chest Wall Oscillation devices are designed to provide expiratory bias in airflow required for effective mucus propulsion [11, 12].

HFCWO OPERATION AND ACTION

HFCWO therapy is administered via a vest-like garment that generates airflow oscillations sufficient to produce coughlike shear forces which may decrease secretion viscosity [13, 14, 21]. These effects assist patients in mobilizing secretions from smaller to larger airways where they can be more easily removed by expectoration or coughing. On inflation, pressure is exerted on the thorax, forcing the chest wall to compress and generate a short burst of expiratory flow. Pressure pulses are superimposed on a small positive pressure baseline. On deflation, the chest wall recoils to its resting position, causing inspiratory flow. HFCWO can generate volume changes and produce 300 to 1500 staccato coughs per minute [3, 20]. Repetitive cough induces significantly more mucus clearance than a single cough, and even more clearance with an increased frequency of repetitive cough or airflow oscillations [14]. HFCWO induces rapid air movement that mimics cough which enhances mucus mobility [14] .

HIGH FREQUENCY CHEST WALL OSCILLATION (HFCWO)

Studies of the effects of airflow on mucus mobility and velocity have elucidated several likely mechanisms of action. Among key findings, HFCWO has been shown to: 1) generate an airflow bias that accelerates TMV and propels mucus flow from peripheral towards central airways [12, 13, 15-18]; 2) produce mucus-airflow interactions that may favorably reduce mucus physical characteristics including viscosity [19, 21]; and 3) create shear forces at the air-mucus interface that promote mucus clearance [12, 22]. HFCWO mechanisms enhance secretion clearance by mimicking the mucolytic and mucokinetic effects of normal mucocilliary clearance (MCC).

AIRFLOW EFFECTS

Studies in in vitro and animal models: The relationship between nonsymmetrical airflow and mucus mobilization has been evaluated over several decades by numerous research teams. They found, among other effects, that during HFCWO therapy, chest compression - induced oscillations create rapid air movement in and out of the lungs and that the magnitude of these effects may be measured at the mouth as mean oscillated volume. Increased mean oscillated volume increases mucus clearance from the peripheral and central airways in a cephalad direction [14, 22, 23]. HFCWO generates peak expiratory airflows sufficiently greater than peak inspiratory flows ($V_E/V_1 > 1$) resulting in mucus transport toward the airway opening. The increase in expiratory airflow bias is similar to that which occurs during a cough [23].

AIRFLOW BIAS AND TRACHEAL MUCUS CLEARANCE RATES

Among techniques used to measure MCC, most are based on two basic principles: 1) direct measurement of the transport rate of deposited particles in an anatomically defined airway [7, 8, 22, 24] or; 2) measurement of the rate of elimination on inhaled aerosols from the tracheobronchial tree [25, 26]. HFCWO studies have utilized both methods. Under experimental conditions, HFCWO has been shown to dramatically accelerate tracheal mucus clearance rates (TMCR) [12, 13, 15-18]. In three studies by King, et al, HFCWO was shown, under varying conditions, to increase TMCR up to 340%, 240% and again 240% of spontaneously breathing controls [12, 15, 16].

Rubin et al demonstrated comparable effects [17]. The magnitude of TMCR was found to be frequency-dependent. Key studies and conclusions are cited below:

- King, et al. (1990) Found that TMCR during HFCWO 240% greater than control ($p = < 0.001$) and in line with previous results [16].
- Chang, et al. (1988) Via an experimental model using mucus gel simulants, suggests that non-symmetrical airflow at the air-mucus interface significantly enhances mucus clearance during HFCWO [13].
- Warwick. (1991) Using a Fleish pneumotach to measure inspiratory and expiratory airflows during HFCWO, showed that the passive staccato coughs produced result in the expulsion of generally greater volumes of air from the lungs than with forced expiration, thus supporting the hypothesis that HFCWO effectiveness relies, in part, on the 300-1500 staccato coughs produced per minute [18].
- King, et al. (1983) Studied tracheal mucus clearance (TMC) by direct observation of the rate of displacement of a charcoal particle spot by means of a fiberoptic bronchoscope and found that mucus clearance was most pronounced in the range of 11 to 15 Hz, reaching a peak value of 340% of control at 13 Hz [15].

AIRFLOW BIAS AND PERIPHERAL LUNG MUCUS CLEARANCE

Some patients have excessively thick, sticky mucus that tends to plug the airways. In such patients, the effect of HFCWO may be stronger in the lung periphery than in the central airways, and more effective than conventional CPT at mucus clearance [12, 14, 17, 22]. An important early four-year retrospective-prospective clinical study comparing CPT with HFCWO showed unprecedented, sustained improvement in several pulmonary function parameters using HFCWO [27]. Carbon particles and radioactive tracers permit visualization of HFCWO effects in the peripheral airways [12, 17, 22]. Studies of HFCWO-enhanced sputum induction demonstrate significantly higher yields of cells likely derived from peripheral lung regions (alveolar macrophages) with High Frequency Chest Wall Oscillation than without [28, 29].

- Gross, et al. (1985) investigated the effect of high frequency chest compression (HFCWO) on clearance of secretions from peripheral lung regions. Technetium -99 labelled sulfur colloid aerosol generated by nebulizer was used to assess regional clearance. Overall, HFCWO enhanced both central and peripheral mucus clearance in normal dogs [22].
- Hansen, et al. (1990) Administered HFCWO for one year to a 48 year-old CF patient with Pseudomonas aeruginosa and a two-year history of declining pulmonary function test (PFT) scores. After 12 months, PFTs returned to levels measured five years before initiation of the therapy. A baseline technetium aerosol scan showed absence of ventilation in the upper lobes, but after 8 months of HFCC, a repeat test showed that ventilation was restored in these regions [23].
- Agostinis, et al. (1995) Assessed the sputum-induction efficacy of a thirty-minute treatment with high-frequency chest compression (HFCWO) combined with hypertonic saline (HS) solution and found a significantly higher percentage of cells probably derived from peripheral lung regions as suggested by a greater percentage of macrophages [28].
- McKinnon, et al. (1996) Found that inhaled nebulized water + high frequency chest compression (NW+ HFCWO) yielded superior sputum specimens in 52 heavy smokers compared to nebulized water alone. Specimen adequacy, determined by presence of alveolar macrophages, showed significantly greater proportions of these diagnostically important cells [29].

AIRFLOW BIAS AND MUCOLYTIC EFFECTS

Mucus transport can be altered by changes in the physical properties of mucus. Among those properties, viscosity, elasticity, and spinability (capacity to form threads under traction) may be affected. Reductions in mucus spinability and viscoelasticity correlate with accelerated transport. Severalstudies demonstrate oscillation airflow – induced mucolytic effects. These changes occur as airflow reduces cross-linkages, viscoelasticity and spinability resulting in improving mucus transport [4, 14, 15, 19, 21].

- Tomkiewicz, et al. (1994) Measured oscillatory air flow – induced rheological variables, including spinability and viscoelasticity, in mucus gel simulants. Data showed that both mucus spinability and viscoelasticity decreased significantly, suggesting that oscillating air flow may act as a physical “mucolytic,” which may enhance cough clearability [21].
- App, et al. (1998) Results of this study evaluating the effects of high-frequency oscillations on the breakdown of mucus viscoelasticity in cystic fibrosis (CF) sputum samples suggest that such oscillations can break down DNA [19].

SUMMARY

Abundant studies demonstrate the effects of chestcompression-induced increased mucus clearance in part due to cephalad airflow bias. Currently, there are several commercially available devices marketed to deliverer HFCWO therapy. Devices vary significantly in terms of pressure and frequency settings, as well as in delivery systems and garment construction. Given the apparent importance of airflow effects on the magnitude of mucus transport, intra-device assessments comparing cephalad airflow bias are needed to understand differences that may exist.

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