The effect of angle and oscillation on mucous simulant speed in flexible tubes

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ABSTRACT

Background and Purpose. The aim of this study was to investigate, in a tube model, how the speed of a mucous simulant was influenced by angle and different types of oscillations. Method. Using a repeated-measures study design, the primary outcome measure was the mucous simulant speed calculated from the time taken for the mucous simulant to travel a distance of 10 cm. Ultrasonic gel diluted to a viscosity (113 Poise), approximating human sputum, was introduced into a flexible tube similar in diameter to the human adult trachea. The tube was subjected to discrete angles of 0° and 30°, 60° and 90° downward. Symmetrical oscillation was applied in both the transverse and longitudinal directions with frequencies of 5, 15 and 25 Hz at amplitudes of 1 mm and 2 mm peak-to-peak using a commercially available oscillator. Asymmetrical oscillation was applied using repeated cycles of slow acceleration and fast deceleration in the longitudinal direction at 0° and 30° downward and up a 5° incline using a custom-built apparatus. Results. Each 30° angle increment of the tube from 0° to 90° significantly increased mucous simulant speed (p<0.001). Symmetrical oscillation did not provide an advantage over angle in terms of mucous simulant speed; however, asymmetrical oscillation increased mucous simulant speed beyond that caused by angle for all angles tested (p<0.001) and was able to drive mucous simulant up a small incline (5°) in this tube model. It was found that certain types of longitudinal oscillation elongated the mucous simulant. Conclusions. The present study supports the use of gravity to assist in secretion clearance. Asymmetrical oscillation is a novel technique which warrants further investigation. Copyright © 2005 John Wiley & Sons, Ltd.

Key words: angle, oscillation, mucous simulant

INTRODUCTION

Secretion clearance of the airways is a common goal of respiratory physiotherapy. Retained secretions can predispose a patient to reduced ventilation, infection and a decline in pulmonary function (Smith and Ellis, 2000). The use of gravity, via the physiotherapy technique of postural drainage is often combined with oscillatory physiotherapy techniques such as percus-
sion, vibration and shaking. However, little is known about how best to apply these oscillations nor their relative merits. Oscillation at 4 Hz in humans (Gallon 1991), 13 Hz in dogs (King et al., 1983; Gross et al., 1985) and 25–35 Hz in rabbit tracheas (Radford et al., 1982) has been shown to increase mucous clearance. Further, the oscillations used in these experiments were applied in different ways. Manually applied percussion was used by Gallon (1991), circumferential oscillation around the thorax was used by King et al. (1983) and Gross et al. (1985), and transverse oscillation was used by Radford et al. (1982). In addition, percussion on the human thorax has been observed to cause an oscillation amplitude of 1–2 mm in the human trachea (Radford et al., 1982). Therefore, symmetrical oscillation in the present study used a range of frequencies, applied at various orientations, at amplitudes of 1 mm and 2 mm peak-to-peak. It is known that asymmetrical airflow can enhance secretion clearance provided that expiratory flow exceeds inspiratory flow by more than 10% (Kim et al., 1987). It is not known if asymmetrically applied oscillation could also enhance secretion clearance. The aim of the present study was to examine the effect of angle on mucous simulant speed, the effect of symmetrical oscillation in terms of frequency, amplitude and direction on mucous simulant speed, and whether asymmetrical oscillation provides an advantage over angle alone in terms of mucous simulant speed.

**METHOD**

The present study used a repeated-measures design, in a tube and mucous simulant model. The tube was subjected to various angles and to symmetrical and asymmetrical oscillation. The time taken for the leading edge of mucous simulant to travel a distance of 10 cm within the tube was recorded. From this the primary outcome measure, the average mucous simulant speed, was calculated.

The tubing used for all trials was clear, flexible polyvinyl chloride (PVC) food-grade tubing of internal diameter 16 mm and wall thickness 2 mm (Dayco Pacific Pty). This tubing was chosen as it approximated the internal diameter of the human adult trachea (Pedley et al., 1977). Each 16 cm long tube had the middle 10 cm portion marked with circumferential etchings on the outer surface. A subset of six tubes was etched with an additional circumferential marking in the middle of the tube to allow timing over the first and last 5 cm of the 10 cm run. This subset of tubes was used for the asymmetrical oscillation trials at 0° and 5° elevation only as elongation of the mucous simulant slowed it over the last 5 cm of the 10 cm run. The tubes were cleaned and dried before each trial.

Mucous simulant was prepared by combining Aquasonic 100 Ultrasound (US) Transmission Gel (Parker Laboratories Inc., USA) by volume with tap water in a specific ratio of two volumes of gel to three volumes of water. The mucous simulant was tested for viscosity (Stresstech Rheometer: ReoLogica Instruments AB, Sweden, 1985) at a frequency of 0.01 Hz at 20°C, which corresponded to the laboratory temperature under which all the experiments were performed. The mucous simulant had a viscosity of 113P which was in the range of human sputum (Dulfano et al., 1971).

Symmetrical oscillations were delivered to the mucous simulant in the tube using a Gearing and Watson Stimulator (Type V4, England). It was adapted to provide oscillations in both the transverse and longitudinal
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directions by fitting two different aluminium mounts: a transverse and a longitudinal mount. The tube was secured to either mount by two 25.5 cm adjustable and reusable cable ties. The symmetrical oscillation trials were performed as follows.

- For each angle, three timed mucous simulant runs were performed without oscillation. This was the 0 Hz condition.
- For each angle three timed mucous simulant runs were performed at an oscillation amplitude of 1 mm peak-to-peak, each at frequencies of 5 Hz, 15 Hz and 25 Hz.
- For each angle three timed mucous simulant runs were also performed at an amplitude of 2 mm peak-to-peak, at frequencies of 5 Hz, 15 Hz and 25 Hz.

The asymmetric oscillation apparatus (Figure 1) consisted of a tube mounted securely on a trolley, which was attached by a string to a free weight of 133.0 g, measured by digital scales accurate to 0.01 g (AND, EK-600H, Japan). The entire apparatus, except for the free weight, was mounted on a wooden base, which was adjustable for angle. The trolley moved up and down the base with a frequency of 1.05 Hz. A single cycle was broken down into three phases: a return phase, an acceleration phase and a fast deceleration phase. The return phase occurred as the return machine pulled the trolley and free weight back a distance corresponding to the peak-to-peak amplitude of 16 mm. The acceleration phase occurred as the trolley was released, then accelerated by the free weight over the peak-to-peak amplitude. The fast deceleration phase occurred as the trolley was rapidly decelerated by the stopper. The asymmetrical oscillation trials were performed in the longitudinal direction only. A minimum of three trials were performed at each of the following angles: 0°, 30° depression and 5° elevation.

For all trials, 1 mL of mucous simulant was introduced well inside the end of the tube with a 2 mL syringe. This 1 mL sample was approximately 18–20 mm long. As there was 30 mm at the end of the tube before the etch mark, there was about 5 mm

FIGURE 1: Asymmetrical oscillation apparatus consisting of: (A) a hard, smooth wooden base upon which (B) a trolley, (C) a pulley and (D) a return machine were mounted. (E) A free weight, connected to the trolley via a string, provided a slow constant acceleration to the trolley. The quick deceleration phase was caused by (F) the stopper contacting the return machine. The return machine also replaced the trolley into its original position after the quick deceleration phase. The peak-to-peak amplitude of the oscillation (G) was given by the distance between the stopper (F) and the return machine (D) at the beginning of the acceleration phase of the trolley.
between the tube etching and the edge of the simulant and another 5 mm between the end of the tube and the other edge of the simulant. The tube was then placed in the oscillation apparatus at the appropriate angle and the oscillations commenced. The timer was started as the leading edge of the mucous simulant passed the start of the etching on the tube, after having travelled about 5 mm. The timer was stopped as the leading edge of mucous simulant reached the stop mark. The time for each trial was recorded to the nearest second. The mucous simulant speed was calculated by dividing the run distance (in millimetres) by time (in seconds) to yield a mucous simulant speed in mm/s. For each angle and symmetrical oscillation condition, three repetitions were performed.

An additional series of experiments was also performed in order to quantify the degree of elongation of mucous simulant for each symmetrical oscillation condition in the horizontal. The protocol for mucous simulant introduction was the same as that for the trials. Each symmetrical oscillation condition was applied for three minutes in the horizontal. Mucous simulant elongation was defined to be the distance between the leading and trailing edge of the mucous simulant and was measured with a millimetre ruler. In addition, mucous simulant elongation for asymmetrical oscillation was measured for each asymmetrical trial. The statistical analysis was performed using both independent $t$ tests and multiple analyses of variance (MANOVA). Independent $t$ tests (Microsoft Excel 2000, alpha value of 0.05) were performed when assessing the impact of a single variable, be it a change of angle or oscillation condition, on the pooled mucous simulant speed. The following example illustrates how mucous simulant speeds were compared for symmetrical oscillation between angle A and angle B. Mucous simulant speeds for all symmetrical oscillation trials conducted at angle A were pooled and a $t$ test was performed with pooled mucous simulant speeds performed for all symmetrical oscillation trials at angle B. This process was repeated when comparing between other variables, such as amplitude. MANOVA was also performed (using Bonferroni coefficients) to ascertain which variables were responsible for the change in mucous simulant speed.

**RESULTS**

When the effect of angle alone was tested, a significant increase ($p<0.001$) in mucous simulant speed was found with increasing the tube angle from 0° to 90° (Figure 2). Further, the difference in mucous simulant speed between each of the inclination angles was less as the angle increased. More specifically, mucous simulant speed increased by 0.54 mm/s between 0° and 30°, by 0.40 mm/s between 30° and 60°, and by 0.26 mm/s between 60° and 90°.

Frequency, amplitude and direction of symmetrical oscillation had no significant effect on mucous simulant speed for any of the angles tested. In contrast, the application of asymmetrical oscillation at both angles tested (0° and 30°) significantly ($p<0.001$) increased mucous simulant speed and was sufficient to drive it up a small incline of 5° (Figure 3).

An interesting finding of the present study was that the application of symmetrical oscillation caused the mucous simulant to elongate (Figure 4). Symmetrical oscillation in the longitudinal direction at higher frequencies and amplitudes caused an increase in mucous simulant elongation of about 0.8 cm (Figure 4). Further, the effect for asymmetrical oscillation was greater, inducing a mean mucous simulant elonga-
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FIGURE 2: Mucous simulant speed versus angle of inclination. At each angle, the mucous simulant speeds were pooled. Vertical bars represent one standard deviation (SD) of the pooled mucous simulant speeds at each angle. * Represents a significant difference ($p<0.001$) between the pooled mucous simulant speeds.

FIGURE 3: Mucous simulant speed for asymmetrical oscillation and no oscillation at the angles of $-5^\circ$ (uphill), $0^\circ$ (horizontal) and $30^\circ$ (downhill). At each angle, the mucous simulant speeds were pooled. Vertical bars represent one standard deviation (SD) of the pooled mucous simulant speeds at each angle. * Represents a significant difference ($p<0.001$) between the pooled mucous simulant speeds for the no-oscillation condition and the asymmetrical oscillation condition at $0^\circ$. # Represents a significant difference ($p<0.001$) between the pooled mucous simulant speeds for the no-oscillation condition and the asymmetrical oscillation condition at $30^\circ$. The asymmetrical oscillation was able to move the mucous simulant up a $5^\circ$ incline. Note, for the no-oscillation condition at $0^\circ$ and $-5^\circ$ the mucous simulant speed was less than 0.02 mm/s, which was the limit of reading of the experiment.
tion for all asymmetrical trials of 10.1 cm. It was also noted that the mucous simulant ran slower as it elongated. This was confirmed during asymmetrical oscillation where mucous simulant speed was faster over the first 5 cm (small elongation) than the last 5 cm (large elongation).

DISCUSSION

This is the first study to examine the effect of gravity and different types of oscillations on mucous simulant speed in a tube model. The present study demonstrated that the application of symmetrical oscillations to a mucous simulant with a viscosity similar to that of human sputum, in a tube model, did not increase the speed of the mucous simulant beyond that attributed to gravity. However, the application of asymmetrical oscillation, in a longitudinal direction, to mucous simulant in a tube, did increase mucous simulant speed beyond that due to gravity. The present study is also the first to show that a mucous simulant bolus elongated when oscillation was applied in the longitudinal direction.

Mucous simulant speed increased significantly with increasing angle, though it did not increase linearly with the angle of inclination of the tube. At an angle of only 30°, mucous simulant speed was already 45% of its maximum value at 90°. An explanation for this phenomenon may be partly found from an analysis of the force on a mass on an inclined plane. For an object on an inclined plane, the force acting on it in a direction parallel to and down the plane is given by $F = mg \sin \alpha$ (Bueche, 1986), where $m$ is the mass of the object in kg, $g$ is the acceleration due to gravity (about 9.8 m/s²) and $\alpha$ is the angle of inclination of the plane. The mucous simulant speed was approximately proportional to the force on the mucous simulant down the plane. This force varies as the sine of the angle of inclination.

![Graph](https://via.placeholder.com/150)

**FIGURE 4:** Mucous simulant spread after being subjected to three minutes of all types of symmetrical oscillations in the horizontal. Note: there are only three histograms above 0 Hz (no-oscillation condition) as there was no measurable simulant spread for one of these no-oscillation conditions and so this results lies on the x-axis.
and so the speed of mucous simulant down the plane is approximately proportional to the sine of the angle of inclination. As the sine of 90° is 1.0 and the sine of 30° is 0.5, 50% of the gravity-induced mucous simulant speed at 90° is available at only 30°. This is a significant finding as small angles have a disproportionately large effect on gravity-induced mucous simulant speed; however, frictional forces and the viscoelasticity of the mucous simulant will affect its overall speed.

The present study found no significant difference in mucous simulant speed between the conditions of no oscillation and symmetrical oscillation. This result is different to that found when thoracic oscillation was applied in vivo to animals. In experiments with dogs, an optimal frequency of 13 Hz resulted in a tripling of sputum clearance compared to the no-oscillation condition (King et al., 1983; Gross et al., 1985). In an experiment using excised rabbit tracheas, a doubling of sputum transport speed was observed in the frequency range of 25–35 Hz (Radford et al., 1982). The fact that the present study did not find a frequency effect may be attributed to in vivo factors, which were not examined in this study, or the application of discrete oscillation frequencies. The fact that experiments on dog and rabbit tracheas found different optimal oscillation frequencies could mean that ciliary resonance effects are species and size specific. For cilia, it would be expected that smaller cilia in smaller animals would have a higher resonant frequency as the resonant frequency of oscillation of an object is inversely proportional to length (Bueche, 1986). It is also possible that the trachea as a whole may have a resonant frequency.

The direction of symmetrical oscillation, be it in the longitudinal or transverse directions, had no significant effect on mucous simulant speed. No studies, in which externally applied oscillations to the thorax, were found which were able to identify the direction of the oscillation on specific airways. In such studies it would be difficult to correlate the area of applied oscillation on the thorax to individual airway orientations and oscillation directions. It is also possible that the applied oscillations may also circumferentially compress and decompress the airways. In the application of externally applied thoracic oscillations in dogs, a pneumatic cuff was wrapped around the thorax (King et al., 1983; Gross et al., 1985). In such a situation, it is conceivable that the majority of the oscillation experienced at the airway level was one of circumferential compression and decompression.

Though symmetrical oscillation made no difference to mucous simulant speed, it did elongate the bolus. The application of longitudinal symmetrical oscillation (15 Hz and 25 Hz at an amplitude of 2 mm peak-to-peak and 25 Hz at an amplitude of 1 mm peak-to-peak) over three minutes, in the horizontal position, showed a consistent increase in mucous simulant elongation. The increase in elongation was observed without any net movement of the sputum; that is, the elongation was symmetrical in the two tails. For large plugs of mucus, it is possible that such oscillations may assist in elongating them so they no longer obstruct the airway. The increased elongation may also be beneficial as it would thin the mucus out and bring more in contact with surface cilia which could enhance removal.

In the present study it was demonstrated that the application of an asymmetrical oscillation resulted in a net movement of mucous simulant, whereas the application of symmetrical oscillation did not. An explanation for this phenomenon may be found in
the magnitudes of the accelerations applied. Over a cycle of asymmetrical oscillation, the accelerations applied were opposite and unequal in magnitude, whereas over a cycle of symmetrical oscillation the accelerations applied were opposite but equal in magnitude. Thus, a net movement of mucous simulant would be expected for asymmetrical oscillation but not for symmetrical oscillation. Indeed, asymmetrical oscillations were able to push the mucous simulant up a small incline of 5° against gravity.

It is possible that the mechanism of asymmetrical oscillations may play a role in existing physiotherapy techniques. In percussion, as the hand hits the chest, an energy impulse compresses the thorax. As the hand is removed, the thorax passively recoils. It could be assumed that the accelerations experienced by the airways would be much greater on hand strike than hand release. Therefore, it would be expected that percussion has a greater asymmetrical component than manually applied vibration, where the oscillations are more symmetrical (B McCarren, personal communication, 2005) in nature. However, it is not yet known what threshold accelerations are beneficial, nor how the degree of benefit may increase with increasing accelerations. It also remains to quantify the forces and accelerations used clinically.

The present study used a tube and mucous simulant model to approximate the human trachea and sputum. Although the tube used was of a comparable diameter to the human trachea, it was dry and lacked cilia. However, in some disease states such as cystic fibrosis, asthma and chronic bronchitis, the cilia are compromised and the tube model becomes a better approximation. A further limitation of the present study is that tidal airflows were excluded and it is known that these airflows can have a significant impact on mucous simulant movement in tubes (Kim et al., 1987; Jones, 2002). Diluted US gel was used to model human sputum. Though its viscosity was found to be in the range of normal human sputum (Dulfano et al., 1971), there are many other properties of the mucous simulant, such as elasticity, which may differ from human sputum. In addition, we were unable to compare mucous simulant speeds between symmetrical and asymmetrical oscillations because the frequency and amplitudes of these oscillations were so different.

The present study found that gravity had a significant effect on mucous simulant speed in a tube model. Further, it was found that nearly 50% of the mucous simulant speed caused by gravity at an angle of 90° was available at only 30°. This investigation found that symmetrical oscillation did not significantly increase mucous simulant speed. However, this type of oscillation did lead to an elongation of the mucous simulant bolus which may assist mucociliary clearance in vivo by bringing more of it in contact with cilia. Asymmetrical oscillation is a novel concept that the present study was the first to examine. Asymmetrical oscillation was found to significantly increase mucous simulant speed in this tube model; however, further research is required to determine if physiotherapy techniques can produce such an oscillation in the clinical context and if so, whether it would result in increased mucociliary clearance.

**IMPLICATIONS**

This tube model suggests that postural drainage increases secretion clearance. Gravity appears to have a maximal effect at an airway tilt of 90°. However, approximately 50% of this effect can be achieved at an angle of 30°. Further, this model suggests
that asymmetrical oscillation increases secretion clearance, but that symmetrical oscillation does not. Further research is needed to determine whether asymmetrical applied oscillation is effective in vivo.

REFERENCES


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