Vibration and its effect on the respiratory system

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Vibration is a manual technique used widely to assist with the removal of pulmonary secretions. Little is known about how vibration is applied or its effect on the respiratory system. The purpose of this study was to describe mechanical consequences of vibration on the chest wall of a normal subject and the effects of vibration on expiratory flow rates and volumes. The effects of vibration were compared to other interventions of chest wall compression, chest wall oscillation, cough, huff from high lung volume, inspiration to total lung capacity with relaxed expiration, tidal breathing, and sham. Sixteen physiotherapists applied vibration and other interventions in a randomised order to the chest wall of a healthy adult female subject. The magnitude and direction of the force and the frequency of vibration were measured by an instrumented bed with seven load cells. Inductive plethsysmography measured the change in chest wall circumference with vibration. A heated pneumotachometer measured inspiratory and expiratory flow rates, which were integrated to provide volumes. Vibration was applied with a mean resultant force of 74.4 N (SD 47.1). The mean (SD) change in chest wall circumference and frequency of vibration were 0.8 cm (SD 0.4) and 5.5 Hz (SD 0.8) respectively. The mean peak expiratory flow rate was 0.97 l/s (SD 0.27). Peak expiratory flow rates with vibration were less than 20% of those achieved with cough or huff from high lung volume but greater than with chest wall compression, chest wall oscillation, relaxed expiration from total lung capacity, sham treatment or tidal breathing. **[McCarren B, Alison JA and Herbert RD (2006): Vibration and its effect on the respiratory system. *Australian Journal of Physiotherapy* 52: 39-43]**

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Introduction

Vibration is defined as the manual application of a fine oscillatory movement combined with compression to the patient's chest wall (McCarren et al 2003). Vibration is widely used by physiotherapists to assist with the removal of secretions (McCarren et al 2003).

Vibration may increase secretion clearance by increasing expiratory flow rates (Wanner et al 1996). Both chest wall compression (Gross et al 1985) and chest wall oscillation (3–17 Hz) (King et al 1983) have been shown to increase expiratory flow rates in dogs. It is difficult to assess the contribution of this mechanism in humans during the application of vibration because very little is known about the amount of compression or the frequency and change in chest wall circumference during the oscillations applied by physiotherapists. Furthermore, the physiological effects of vibration on expiratory flow rates and volume are unknown. Therefore the aim of this study was to quantify compression and oscillation characteristics of vibration and the effects of vibration on flow rates and volumes. An additional aim was to compare expiratory flow rates and volumes produced by vibration with those produced by other interventions that increase expiratory flow rates.

Method

Physiotherapists currently treating patients with respiratory disorders or considered to have extensive experience in cardiopulmonary physiotherapy were recruited. The physiotherapists applied vibration to one healthy subject whose weight, height and lung function were within normal ranges. The peak expiratory flow rate (PEFR) of the subject was measured[a] prior to each testing session to ensure stable lung function (less than 5% variability from initial value) (American Thoracic Society 1987). All lung function measures were taken using procedures that conformed to American Thoracic Society guidelines (1987) and compared to the normative data of Crapo et al (1981). The study protocol was approved by the Human Research Ethics Committee of the University of Sydney.

The subject was randomly positioned in right or left side-lying on an instrumented bed. The physiotherapists were asked to apply vibration, the compression component of vibration without the oscillation (chest wall compression), the oscillation component of vibration without the compression (chest wall oscillation), or sham treatment to the subject. The purpose of the chest wall compression and chest wall oscillation was to assess the effects of these components of vibration. The subject was asked not to actively expire during the application of vibration, chest wall compression, and chest wall oscillation. A sham intervention was also applied to assess non-specific effects of intervention. The sham intervention was the application of mock ultrasound to the subject's triceps. The ultrasound machine display appeared to indicate an output. The physiotherapists and the subject did not know the ultrasound was a sham.

In addition, the physiotherapist asked the subject to perform the following interventions of coughing, huffing from high lung volume (huff$_{TLC}$), normal breathing (tidal breathing) and inspiration to total lung capacity with relaxed expiration (TLC$_{relax}$). The order of the eight interventions was randomised. The physiotherapist asked the subject to take a 'big breath' prior to all of the interventions with the exception of tidal breathing and sham. This was an attempt to standardise inspiratory lung volume so that the effect of lung recoil on expiratory flow rates was similar for each intervention, with the exception of tidal breathing and sham.

Table 1. Direction and magnitude (N) of mean forces applied to the chest wall during vibration, chest wall compression and chest wall oscillation. Data are means and SDs.

Intervention	Direction of force	Magnitude of force
Vibration	Vertical	64.4 (25.5)
	Cephalo-caudal	13.3 (11.6)
	Horizontal (right-left)	19.8 (14.1)
Chest wall oscillation	Vertical	26.4 (19.8)
	Cephalo-caudal	9.1 (12.6)
	Horizontal (right-left)	12.0 (16.9)
Chest wall compression	Vertical	69.3 (33.9)
	Cephalo-caudal	11.8 (12.1)
	Horizontal (right-left)	18.6 (14.7)

The magnitude and direction of the forces applied during vibration, chest wall compression and chest wall oscillation were measured with an instrumented bed with seven load cells[b] (Chiradendjnant et al 2001). Force data were used to determine the frequency of oscillation of vibration. Inductive plethysmography[c] was used to measure change in chest wall circumference. One band of the plethysmograph was secured to the lower border of the rib cage of the subject's chest wall. The plethysmograph was calibrated with Vernier calipers. Force and displacement signals were sampled at 50 Hz.

The accuracy of inductive plethysmography was assessed prior to the conduct of the study by subjecting the plethysmograph to known longitudinal displacements. The root mean square difference between 50 measures with inductive plethysmography and a reference standard measurement with Vernier callipers[d] was 0.60 mm. The frequency response of the inductive plethysmography was assessed by connecting the plethysmograph band in series with a force transducer[e] and applying oscillations with frequencies from 0.5 to 8 Hz. The mean (SD) coherence was 0.8 (SD 0.1), phase lag was close to zero at –13.1 degrees (SD 24.1), with a mean gain in displacement of 0.03 cm/N (SD 0.01).

Flow rates during all interventions were measured via a mouthpiece with a heated pneumotachograph[f] with a frequency response of > 12Hz. Flow signals were integrated to provide volume measurements (Maxwell et al 2001). Measures of peak inspiratory flow rate of the inspiration immediately prior to the intervention (PIFR), PEFR, mean expiratory flow rate from 50–100% expired volume ($FR_{E(50–100\%VE)}$) and volumes of the inspiratory and expiratory phases of each intervention were obtained. The $FR_{E(50–100\%VE)}$ was calculated to determine the effect of vibration on expiratory flow rates of the small airways (Macklem and Wilson 1965). Flow data were collected at 20 Hz. Each intervention was performed three times by each physiotherapist.

Data and statistical analysis The resultant force of vibration was calculated from the vertical, cephalo-caudal, and horizontal forces. For each physiotherapist we calculated the mean, the mean of the peak forces, and the mean amplitude of the force oscillations from the resultant forces applied during vibration. In addition, the mean amplitude of change in chest wall circumference during oscillations of vibration was calculated. After satisfying the tests of normality, a one-way ANOVA for repeated measures with *post hoc* Dunnett's test was used to compare respiratory parameters and the vertical forces observed during vibration with those of the other interventions. Results are expressed as means and standard deviations (SD). For the repeated measures SDs of means are reported.

Results

The subject was a 38 year old female with a BMI of 22.9 kg/m^2 and a FEV_1 and FVC 100% of predicted. Her PEFR varied by less than 3% throughout the testing period. She was naive to the cardiopulmonary physiotherapy interventions and their proposed effects on the respiratory system. Sixteen physiotherapists (13 females) volunteered for the study. They had a mean 10.5 years (SD 8.1) of clinical experience, of which 8.6 years (SD 7.5) were in the cardiopulmonary area.

Description of application of interventions A typical trace from a single application of vibration (Figure 1) shows that oscillatory forces are applied after an initial compression of the chest wall.

The magnitude and direction of the forces applied during the interventions are presented in Table 1. During vibration, physiotherapists applied a mean resultant force of 74.4 N (SD 47.1) and a mean peak force of 137.1 N (SD 66.7). The vertical forces applied during vibration (64.6 N (SD 25.5)) and chest wall compression (69.3 N (SD 33.9)) were similar ($p = 0.7$) and were more than 2.4 times greater than the forces applied during chest wall oscillation (26.4 N (SD 19.8)) ($p = 0.002$).

During vibration, the oscillation of the chest wall was applied at a mean frequency of 5.5 Hz (SD 0.8) (range 3.4 to 7.9 Hz) with a mean oscillatory force of 50.1 N (SD 67.5). Chest wall circumference data were not available from four physiotherapists, however their mean resultant force applied during vibration (74.4 N (SD 30)) was the same as the entire group. The remaining physiotherapists (n = 12) applied a mean amplitude of change in chest wall circumference of

Table 2. Effects of interventions on peak flow rates and respiratory volumes during inspiration and expiration. Data are means and SDs of 15 subjects.

	PEFR (l/s)	PIFR (l/s)	PEFR/PIFR	V_I (l)	V_E (l)
Vibration	0.97 (0.27)	1.30 (0.20)	0.75	1.56 (0.23)	2.35 (0.31)
CWO	0.83 (0.21)	1.30 (0.19)	0.64	1.60 (0.27)	2. 31 (0.39)
CWC	0.82 (0.22)	1.29 (0.22)	0.64	1.60 (0.40)	2.14 (0.34)
TLC_{relax}	0.66 (0.20)	1.22 (0.32)	0.52	1.64 (0.20)	2.06 (0.20)*
Cough	8.14 (0.92)*	1.63 (0.22)*	5.07	1.73 (0.23)‡	1.84 (0.26)‡
$Huff_{TLC}$	7.76 (0.72)*	1.73 (0.20)*	4.60	1.95 (0.38)*	2.19 (0.37)
V_T	0.38 (0.06)*	0.52 (0.06)*	0.72	0.56 (0.14)*	0.64 (0.14)*
Sham	0.41 (0.07)*	0.52 (0.07)*	0.79	0.52 (0.06)*	0.58 (0.07)*

*significantly different from vibration ($p < 0.001$). ‡significantly different from vibration ($p < 0.05$). PIFR = peak inspiratory flow rate. V_I = inspired volume. V_E = expired volume. CWC = chest wall compression. CWO = chest wall oscillation. TLC = total lung capacity. V_T = tidal volume.

0.8 cm (SD 0.4) during the oscillations of vibration.

Effect of interventions on respiratory flow rates and volumes The PEFR generated by vibration was 0.97 (0.27) l/s. This was at least 15% faster than the PEFR that occurred during all other interventions with the exception of cough and huff$_{TLC}$. Vibration produced a much slower PEFR than (less than 20% of) voluntary cough ($p < 0.001$) and huff$_{TLC}$ ($p < 0.001$). Table 2 shows the mean peak inspiratory and peak expiratory flow rates and volumes that occurred during the interventions. There were no significant differences between mean PIFR prior to vibration and chest wall compression ($p = 1.00$), chest wall oscillation ($p = 0.88$) or TLC$_{relax}$ ($p = 1.00$). However the mean PIFRs prior to cough ($p < 0.001$) and huff$_{TLC}$ ($p < 0.001$) were at least 20% faster than the mean PIFRs prior to vibration. Only cough and huff $_{TLC}$ had PEFR/PIFR greater than 1.1. The volume of the inspirations prior to the interventions, with the exception of huff $_{TLC}$ and cough, varied by less than 250 ml.

The FR$_{E(50–100\%VE)}$ of vibration (0.52 l/s (SD 0.12)) was faster than the FR$_{E(50–100\%VE)}$ of both TLC$_{relax}$ (0.29 l/s (SD 0.08)) ($p < 0.001$) and chest wall oscillation (0.43 (0.12) l/s) ($p = 0.02$), but was not significantly different to that of chest wall compression (0.47 l/s (SD 0.15)) ($p = 0.66$).

Discussion

This is the first study to describe the magnitude and direction of forces and the frequency and amplitude of change in chest wall circumference that occurs when physiotherapists apply vibration to a healthy human subject.

Description of vibration During vibration, physiotherapists applied a compressive force and superimposed an oscillatory force (Figure 1), producing a mean resultant force (averaged across subjects) of 74.4 N and a peak force of 137.1 N. Only one other study (Rivington-Law et al 1984) has measured the forces applied during vibration. In that study pressure between the physiotherapist's hands and the patient's chest wall was measured using a blood pressure cuff. The authors reported that vibration was applied at a peak pressure of 20 cmH$_2$O. It is difficult to compare the different measures.

During vibration physiotherapists applied a mean amplitude of oscillation forces of 50.1 N, which resulted in a mean change in chest wall circumference of 0.8 cm at a mean frequency of 5.5 Hz. The frequency of vibration we observed is much lower than the previously cited range of 10 to 16 Hz (Bateman et al 1981, Wong et al 2003). Bateman and associates (1981) reported that a physiotherapist applied vibration to a black anaesthetic bag at a frequency of 12 to 16 Hz, whereas Wong and associates (2003) noted that physiotherapists applied vibration to the chest wall of an intubated and ventilated sheep at a mean rate of 10.5 Hz (SD 2.3). As the fastest recorded alternating voluntary movements of the upper limb (finger tapping) has been reported to be 8.5 Hz, increasing to 9.3 Hz after intensive practice (Freund 1983), it would be surprising if vibration could be applied at such high rates. It is not apparent why Bateman et al (1981) and Wong et al (2003) found such high frequencies.

Effects of vibration on expiratory flow rates Vibration as applied by this group of physiotherapists increased PEFR by 50% compared to flow rates of TLC$_{relax}$. Three factors appear to contribute to these flow rates: lung recoil, compression and oscillation. The mean data from our study were consistent with a simple model in which PEFR of vibration (PEFR$_{vibration}$) was the sum of the flow rates due to elastic recoil (PEFR$_{TLCrelax}$), the flow rate due to chest wall compression (PEFR$_{CWC}$ – PEFR$_{TLCrelax}$) and the flow rate due to chest wall oscillation (PEFR$_{CWO}$ – PEFR$_{TLCrelax}$). That is:

$$PEFR_{vibration} = PEFR_{TLCrelax} + (PEFR_{CWO} - PEFR_{TLCrelax}) + (PEFR_{CWC} - PEFR_{TLCrelax})$$

The mean value observed for the right side of this equation (0.99 l/s), calculated from values in Table 2, is close to the observed mean value for PEFR of vibration of 0.97 l/s, supporting the idea that the effects on PEFR of elastic recoil, compression and oscillation are additive. This model is supported by the individual data (Figure 2). As lung recoil (PEFR $_{TLCrelax}$) contributes 67% of the total PEFR$_{vibration}$, patients should be encouraged to inspire maximally prior to vibration to maximise the elastic recoil contribution to PEFR$_{vibration}$. The additional effects of the compression and oscillation contribute an additional 15% and 14% respectively to PEFR$_{vibration}$ in this subject. The relative contributions of lung recoil, chest wall compression and chest wall oscillation to PEFR may differ according to variations in chest wall compliance and airway resistance. This requires further investigation. These findings in humans confirm the results of previous studies in animals. Studies in dogs have

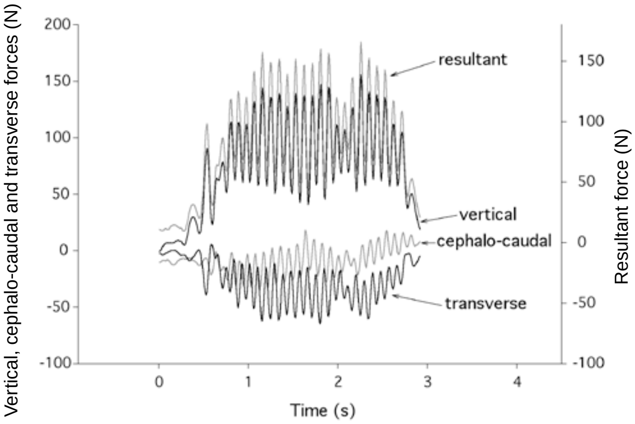

Figure 1. Forces produced during a single application of vibration.

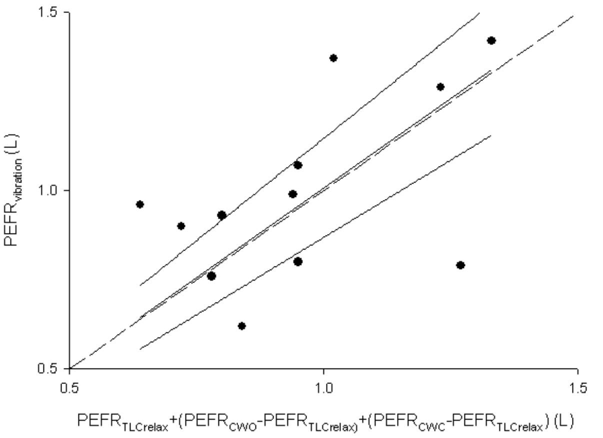

Figure 2. The relationship of the individual subjects' real and calculated PEFR of vibration (n = 13). Real PEFR = 1.01 (95% CI 0.86 to 1.15) × calculated PEFR; Pearson's r = 0.57, $p < 0.001$. The solid lines are the regression line and 95% confidence interval. The dashed line is the line of identity. $\text{PEFR}_{\text{vibration}}$ is the peak expiratory flow rate of vibration, $\text{PEFR}_{\text{TLCrelax}}$ is the peak expiratory flow rate of relaxed expiration after inspiration to total lung capacity, PEFR_{CWO} is the peak expiratory flow rate of chest wall oscillation and PEFR_{CWC} is the peak expiratory flow rate of chest wall compression.

shown that both increasing chest wall compression (Gross et al 1985) and increasing the frequency (3–17 Hz) of chest wall oscillation (King et al 1983) increases expiratory flow rates. As vibration is the only manual cardiopulmonary physiotherapy intervention that has both compressive and oscillatory characteristics it may be the most effective manual technique to increase expiratory flow rates in patients who are unable to effectively cough or huff, for example unconscious or unco-operative patients.

An additional physiological mechanism by which vibration could increase expiratory flow rates is enhanced active expiration by recruiting expiratory muscles (Gross et al 1985). Some support for this proposal comes from the observation that there is an increase in expiratory flow rate during vibration in spontaneously breathing, unparalysed subjects (our study and that of MacLean et al 1989) but not during vibration in paralysed, ventilated sheep (Wong et al 2003). This activation of the respiratory muscles requires further investigation.

Flow rates generated during vibration (0.97 l/s) were much lower than those achieved during huff or cough. In so far as high expiratory flow rates facilitate clearance of secretions, this suggests cough and huff are likely to be more effective than vibration at clearing secretions. However if a patient is unable to effectively huff or cough, vibration may provide a mechanism for increasing expiratory flow rates.

Theoretical effects of vibration on secretion clearance The expiratory flow rates generated during vibration would not be adequate to augment secretion clearance by annular flow. In vitro studies suggest that annular flow can assist removal of secretions when there is an expiratory bias to airflow (i.e. PEFR/PIFR > 1.1) (Kim et al 1987). This results in a mass movement of secretions by annular flow towards the mouth if a critical volume and thickness of secretions are present (Kim et al 1987). The PEFR/PIFR of 0.75 that occurred during vibration indicates an inspiratory bias rather than an expiratory bias; hence secretion clearance would not be expected to occur with this flow profile. This inspiratory bias could be due to the fact that prior to the application of vibration the physiotherapist asked the patient to take a 'deep' breath, which resulted in a 'gasp-like' inspiration and may have increased peak inspiratory flow rates. A possible clinical implication is that physiotherapists should encourage a much slower inspiratory flow rate prior to vibration so that expiratory flow rates generated by vibration would be greater than inspiratory flow rates.

The frequency of vibration in our study was 5.5 Hz. Vibration at this frequency may alter mucus rheology and assist with removal of secretions. King and associates (1983) showed that five minutes of in vitro vibration (5–8 Hz) on sputum obtained from a patient with pneumonia resulted in a decrease in sputum viscosity. It is not known whether clinically important decreases in sputum viscosity occur with brief applications of chest wall vibration in vivo. Decreased viscosity may increase the ability of the cilia to move mucus (Wanner 1996).

The main limitation of this study was that vibration was applied to a normal subject's chest wall. The study provided a description of the application of vibration and resultant respiratory responses but did not address the effects of vibration in a clinical population. In clinical practice, vibration is applied to patients who have excessive secretions or difficulty clearing secretions. These patients tend to have altered chest wall compliance and airway obstruction, both of which could alter the application of vibration and its effects on the respiratory parameters. The findings of this study need to be replicated in patients with problems of secretion clearance.

Footnotes [a]Wright Standard Peak Flow Meter, Clement Clarke, London, UK [b]XTRAN Pty Ltd, Australia [c]Respitrace™, Ambulatory Monitoring Inc, Ardsly, NY [d]Mitutoyo, Japan [e]Grass Instrument Division of Astro-Med Inc, West Warwick, Rhode Island [f]Hans Rudolph Model 3813, Hans Rudolph Inc, Kansas City, Missouri

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