Head-down tilt and manual hyperinflation enhance sputum clearance in patients who are intubated and ventilated

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The purpose of this prospective randomised cross-over study was to measure peak expiratory flow rates during manual hyperinflation and to determine if the addition of a head-down tilt to physiotherapy treatment increased sputum production in patients who are intubated and ventilated. Twenty patients who were intubated, ventilated and haemodynamically stable were randomised to a sequence of physiotherapy treatment in a flat side-lying or a head-down tilt position. Peak expiratory flow rates were measured for each breath during manual hyperinflation using a Vitalograph peak flow meter. Sputum wet weight was collected for each treatment position and static pulmonary compliance was measured before and immediately following physiotherapy treatment. There was a significant increase in peak expiratory flow (p < 0.001) and sputum production (p = 0.008) in the head-down tilt position. The mean difference and 95% confidence intervals for expiratory flow were 0.17 (0.15 to 0.19) l/sec and for the wet weight of sputum 1.97 (0.84 to 3.10) g. The peak expiratory flow rate was sufficient to produce annular flow in both flat side-lying (1.97 ± 0.09) l/sec and in the head-down tilt position (2.14 ± 0.08) l/sec. Static pulmonary compliance improved significantly following physiotherapy treatment (p = 0.003). The mean difference and 95% confidence intervals pre- and post-treatment for static pulmonary compliance were 5.18 (2.14 to 8.22) ml/cmH₂0. The results suggest that addition of a head-down tilt to physiotherapy treatment, including manual hyperinflation, in patients who are intubated and ventilated, increases sputum production and improves peak expiratory flow. [Berney S, Denehy L and Pretto J (2004): Head-down tilt and manual hyperinflation enhance sputum clearance in patients who are intubated and ventilated. Australian Journal of Physiotherapy 50: 9–14]

Key words: Head-Down Tilt; Intensive Care; Lung Hyperinflation; Peak Expiratory Flow Rate; Physiotherapy

Introduction

Physiotherapy treatment in intensive care has been associated with a reduction in the incidence of ventilator-associated pneumonia (Ntoumenopoulos et al 2002). It involves a combination of treatment techniques that have been shown to reduce the volume of retained secretions and improve both intrapulmonary shunt and lung and thorax compliance (Jones et al 1992, Hodgson et al 2000, Mackenzie et al 1980, Mackenzie and Shin 1985, Ntoumenopoulos and Greenwood 1996). The short term effects of manual hyperinflation with and without a head-down tilt on resolution of atelectasis, pulmonary compliance and sputum production have been well documented (Hodgson et al 2000, Jones et al 1992, Rothen et al 1993, Stiller et al 1990, 1996, 2000).

Patients who are intubated and ventilated may have increased sputum production (Jones 1997). In addition, it has also been shown that these patients have a significantly impaired bronchial mucociliary transport velocity. This can lead to an increased incidence of pulmonary complications such as secretion retention and pneumonia (Konrad et al 1994). Therefore secretion removal is a major aim of physiotherapy treatment in patients who are intubated and ventilated (Hodgson et al 2000).

Manual hyperinflation has been shown to be effective in secretion clearance (Hodgson et al 2000). It has been postulated that pulmonary secretions may be cleared during manual hyperinflation by the generation of annular two-phase gas-liquid flow (Maxwell and Ellis 1998). Annular flow occurs when velocities of at least 1000 cm/s are achieved during expiration (Leith 1968). Two-phase gas-liquid flow is expressed as a velocity, calculated by dividing peak expiratory flow by cross sectional area (Leith 1968). This means that for any given expiratory flow rate the velocity will change as the bronchial tree branches according to the cross sectional area of the airway through which it flows. Due to the viscosity of sputum, a critical expiratory flow must be generated for sputum movement to occur in the airways (Benjamin et al 1989, Clement and Hubsch 1968, Hodgson et al 2000, Kim et al 1985, Maxwell and Ellis 1998, 2003). It is also postulated that expiratory flow must be at least 10% faster than inspiratory flow for cephalad-directional movement of secretions in the airways to occur. This corresponds to an inspiratory:expiratory (I:E) flow ratio of less than 0.9 (Maxwell and Ellis 2003, Selshy and Jones 1990). A head-down tilt position also aims to mobilise pulmonary secretions through the use of gravity. The efficacy of gravity-assisted drainage has been well described in the spontaneously breathing, chronic sputum-producing population (Selshy and Jones 1990, Sutton et al 1992). Despite evidence of impaired mucociliary transport mechanisms in the intubated and ventilated patient (Konrad et al 1994), the efficacy of head-down tilt has not previously been studied.

The aim of this study was twofold: to document peak expiratory flow rates associated with manual hyperinflation in two treatment positions; and to investigate the effect on sputum production of adding a head-down tilt during physiotherapy treatment of patients who are intubated and ventilated.

Method

Design: This study was a prospective, randomised, cross-over design and patients acted as their own controls. All patients were intubated, ventilated, and were not haemodynamically compromised.
The study was approved by the Ethics and Human Research Committee at the Austin Hospital. Informed consent was obtained from the next of kin and from the treating intensive care physician.

**Subjects:** Sample size calculation was based on sputum wet weight using the mean difference and standard deviation from Hodgson et al (2000). For the given effect size, alpha = 0.05 (2 tailed) and power of 0.8, the sample size estimate was 20 subjects.

Twenty consecutive patients who met the inclusion criteria were recruited. Patients were included if they were intubated and ventilated, and would normally receive hyperinflation as a part of their physiotherapy treatment. Patients were excluded from the trial if they a) required a fraction of inspired oxygen (FiO₂) > 0.6, b) had a positive end expiratory pressure (PEEP) > 10 cmH₂O, c) had pulmonary pathology where lung hyperinflation was contra-indicated (e.g. acute respiratory distress syndrome, or exacerbation of chronic obstructive pulmonary disease), d) were prescribed head-up position for brain disease, e) had an unstable cardiovascular condition as defined by a mean arterial pressure (MAP) < 75 mmHg with a fluctuation of 15 mmHg with position change, or a heart rate > 130, or f) had an arterial oxygen saturation (SaO₂) < 90%. Patients were to be withdrawn from the study if they suffered cardiovascular compromise during the treatment as defined by the above variables.

**Treatment techniques:** Manual hyperinflation breaths were delivered using a Mapleson-C anaesthetic circuit using a 10 l/min oxygen gas flow. The spring-loaded Heidbrink expiratory valve was adjusted to the fully open position but was manually closed during inspiration. The hyperinflation breaths had a slow inspiration for three seconds duration to a peak airway pressure of 40 cmH₂O as measured by an inline manometer. A two-second end inspiratory pause was followed by an uninterrupted expiration during which the bag was held compressed. The manual hyperinflation treatment consisted of six sets of six hyperinflation breaths, each set followed by six breaths to a peak airway pressure of 20 cmH₂O. The manual hyperinflation treatment was performed by the principal investigator and was of 20 minutes duration.

Head-down tilt involved elevating the foot of the bed 35 to 45 degrees from the horizontal plane (measured using a protractor) whilst the patient was in a side-lying position on an air mattress.

Endotracheal suction was performed using size 12 Baxter catheters. The patients were suctioned three times throughout the procedure following every second set of hyperinflation breaths. The same catheter was used for each suction pass. Four millilitres of normal saline was used for lavaging down the endotracheal tube during treatment, and 1 ml used to wash through the suction catheter at the end of each treatment. An arterial line, ECG, and pulse oximeter were used to monitor the patient continuously.

**Procedure:** Each treatment included manual hyperinflation in both the flat and head-down tilt positions. Subjects were allocated to a treatment sequence randomly, using sealed envelopes. The first treatment sequence was performed in the morning and the alternate treatment sequence was performed in the afternoon (Figure 1). The two treatment sessions were separated by at least two hours. The appropriate side-lying position for treatment was decided upon based on the result of the morning chest radiograph. Both treatments were performed with the patients lying on the same side.

**Measurements Sputum wet weight:** When the patients had been turned into the appropriate flat side-lying position in preparation for treatment, they were suctioned once and the sputum was discarded as it was thought that this sputum was caused by positional change rather than the treatment.

In order to measure the wet weight of sputum suctioned, the secretions were collected in a disposable sputum trap. This was weighed before and after the treatment with a digital weighing scale. Before each measurement the scale was calibrated according to manufacturer’s guidelines. The treating physiotherapist was blinded to all sputum wet weight measurements.

**Peak expiratory flow rate:** Peak expiratory flow rates for each manual hyperinflation breath, were measured using a Vitalograph peak flow meter low flow range model (0 to 300 l/min). This was attached to a modified Mapleson-C circuit (Figure 2). The modification consisted of an outer circular plastic ring attached around the exhalation ports of the Heidbrink valve. The peak flow meter joined to the cylindrical modification of the exhalation port allowing all expiratory flow to exit through the peak flow meter.
Static pulmonary compliance: Following the preparatory turn and suction, patients were left undisturbed for a period of 10 minutes. Measurements of static pulmonary compliance were recorded pre- and immediately post-physiotherapy treatment. The principal investigator was blinded to all measures of static pulmonary compliance.

Static lung compliance was calculated using the formula of $V_t/(P_{IP} - P_{PEEP})$ as described by Nunn (1987). The exhaled tidal volumes, end inspiratory plateau pressure, and PEEP were read from the display on the ventilator by the assistant physiotherapist. Three readings of static pulmonary compliance were taken, and end-inspiratory plateau pressure was achieved using a 1.5 second pause at end inspiration which was programmed into the ventilator (Hodgson et al 2000, Mancebo et al 1988). Static pulmonary compliance was measured only on mechanical breaths. The ventilators used were either the Bear 1000 or the Bennetts Star ventilator.

In order to determine if annular flow occurred, the stereological technique of point counting was used to estimate the cross sectional area of the human trachea. A cross section of the standard male human trachea was projected by microfiche and a transparent grid of known interval was superimposed for use in calculation. Following calibration of the magnification factors, point counts were made every time the intersection of a grid fell on the tissue. Section area was then determined by multiplying the total point counts made by the calibrated units of each grid interval (Gunderson et al 1988). The cross sectional area of the trachea was calculated to be 1.95 cm$^2$.

Data management: Wet weight of sputum, static pulmonary compliance and all peak expiratory flow rates for the two treatments were compared using a two-way repeated measures analysis of variance (ANOVA). The two factors were position (two levels) and time (two levels). Probability values of $p < 0.05$ were deemed to be significant. Data are expressed as means and standard deviations (SD) and mean differences (95% confidence interval).

Results

Eighteen males and two females fulfilled the inclusion criteria for the study. All eligible patients approached gave their consent and no patients were withdrawn during the trial. The mean age of the patients was 51.3 years (range 23 to 82 years). All patients were intubated and mechanically ventilated with a mean FiO$_2$ of 0.41 (range 0.30 to 0.50). The demographic data for all patients are presented in Table 1.

Mean expiratory flow rates for each position are presented in Table 2. The mean and SD for peak expiratory flow achieved in the flat side-lying position was 1.97 ± 0.09 l/sec, and in the head-down tilt position 2.14 ± 0.08 l/sec. There was a significant increase in mean peak expiratory flow during manual hyperinflation in the head-down tilt position compared with flat side-lying ($F_{(1,17)} = 275.78$, $p < 0.001$). There was no interaction effect between time of treatment and position ($F_{(1,17)} = 1.36$, $p = 0.26$). The mean difference in flows was 0.17 (95% CI 0.15 to 0.19) l/sec which represented an 8% increase in peak expiratory flow.

The velocity of gas in the trachea was determined by dividing the peak expiratory flow by the cross sectional area of the trachea (1.95 cm$^2$). The mean velocities calculated for each position were 1010 cm/sec in flat side-lying and 1097 cm/sec in the head-down tilt position.

The head-down tilt position produced significantly more sputum than treatment in the flat side-lying position ($F_{(1,19)} = 8.79$, $p = 0.008$). There was no interaction effect between time of treatment and position ($F_{(1,19)} = 1.48$, $p = 0.24$). The mean difference in

| Table 1. Patient data. |
|---|---|---|---|
| Age | Sex | Diagnosis | Chest X-ray findings |
| 42 | F | C4 quadriplegia | No focal |
| 25 | M | Multi-trauma | R upper middle lobe collapse |
| 58 | M | C5 quadriplegia | L lower lobe collapse |
| 55 | M | Guillain-Barré syndrome | R lower lobe consolidation |
| 46 | M | Multi-trauma | Bi-basal consolidation |
| 43 | M | Septic shock | Bi-basal consolidation |
| 51 | M | Epidural abscess | L lower lobe collapse |
| 79 | F | Myasthenia gravis | L lower lobe collapse |
| 23 | M | C5 quadriplegia | L lower lobe collapse |
| 82 | M | Respiratory failure | L lower lobe consolidation |
| 66 | M | Septic shock | R lower lobe collapse |
| 33 | M | Overdose | R lower lobe collapse |
| 74 | M | Respiratory failure | R lower lobe consolidation |
| 77 | M | Guillain-Barré syndrome | R lower lobe collapse |
| 79 | M | Septic shock | L lower lobe consolidation |
| 25 | M | Respiratory failure | L upper lobe consolidation |
| 44 | M | Septic shock | R upper lobe consolidation |
| 40 | M | C5 quadriplegia | Lingula consolidation |
| 31 | M | C5 quadriplegia | Lingula collapse |
| 46 | M | Overdose | Bi-basal collapse |

F = female; M = male
sputum production between the two positions was 1.97 g (95% CI 0.84 to 3.10 g), which represent a 25% increase in sputum production in the head-down tilt position (Table 2).

Static pulmonary compliance improved significantly with physiotherapy treatment that included manual hyperinflation in both positions ($F(1,19) = 11.51, p = 0.003$). The mean difference in compliance was 5.18 (95% CI 2.14 to 8.22 ml/cmH$_2$O) which represented a 12% improvement in static pulmonary compliance immediately following treatment (Table 2.)

**Discussion**

Physiotherapists use manual hyperinflation as a treatment for the recruitment of collapsed lung and the mobilisation of excess pulmonary secretions (Hodgson et al 1999, King and Morrell 1992). The rationale for the use of the technique is the restoration of lung volume and the maximisation of peak expiratory flow (Maxwell and Ellis 1998). Whilst the addition of a head-down tilt has been demonstrated to improve resolution of atelectasis (Stiller et al 1996), the benefits on sputum production in the intubated patient have not previously been reported. The results of this study suggest that the expiratory flow rates observed during manual hyperinflation are sufficient to produce annular flow and thereby cause movement of sputum (Kim 1985, 1987; Maxwell and Ellis 1998). Furthermore, the addition of a head-down tilt position not only improved sputum production significantly but also increased the peak expiratory flow rates achieved.

Based on the theory of two-phase gas-liquid flow, secretions are able to be moved along the airways with annular and mist flow (Selsby and Jones 1990, Maxwell and Ellis 1998). The movement of secretions depends largely upon the relationship between inspiratory and expiratory flow, the flow rate of gas, and the viscoelastic properties of sputum. In order to achieve cephalad movement of pulmonary secretions it is thought that the expiratory flow rate should be at least 10% faster than the inspiratory flow rate. This results in an I:E flow ratio of less than 0.9 (Maxwell and Ellis 1998, 2003). Inspiratory and expiratory flow rates have been measured in a test lung model (Maxwell and Ellis 2002, 2003). These studies demonstrate that the desired I:E flow ratio and expiratory flow rate to promote cephalad movement of secretions can be achieved by physiotherapists using manual hyperinflation. Several authors have measured inspiratory flow (McCarren and Chow 1998) and expiratory flow (MacLean et al 1989, Jones et al 1992) in intubated patients during manual hyperinflation. However, to date no study has reported concurrent measurement in the same patient. This is no doubt due to the technical difficulties involved in measurement of flow in the clinical setting. Calculation of an I:E flow ratio in the current study is impossible as inspiratory flows were not measured; however, a previous study examining a similar group of intubated and ventilated patients reported an inspiratory flow rate of 0.71 l/sec (McCarren and Chow 1998). It is therefore possible to calculate a theoretical I:E flow ratio to determine if physiotherapists using manual hyperinflation in the clinical setting are likely to produce the vital ratio to achieve cephalad movement of pulmonary secretions. The inspiratory flows reported by McCarren and Chow were produced using an Air Viva resuscitation circuit, which has been shown to produce higher inspiratory flow rates than the Mapleson-C circuit (Maxwell and Ellis 2003). In the current study the mean peak expiratory flow rate during manual hyperinflation in the flat side-lying position using a Mapleson-C circuit was 1.97 l/sec and in the head-down tilt position was 2.14 l/sec. Using the inspiratory flows produced by McCarren and Chow (1998) in a similar patient case mix, the calculated theoretical I:E flow ratios for the study were 0.36 in flat side-lying and 0.33 in the head-down tilt position. These values fall well below the suggested I:E ratio necessary to produce cephalad movement of secretions.

The expiratory flow rates in the current study were higher than those reported previously (Maclean et al 1989, Jones et al 1992). The type of resuscitation circuit, operator technique, and inflation to a higher airway pressure may account for this difference.

The effectiveness of using gravity to assist with the drainage of pulmonary secretions has been described in patient populations with chronic and copious sputum production (Selsby and Jones 1990, Sutton et al 1992). No previous study has examined the effect of adding a head-down tilt on sputum production in the intubated and ventilated patient population. The results of this study indicate that the addition of a head-down tilt to a side-lying position increased both sputum production, by 25%, and expiratory flow rates, by 8%. The reduction in airway resistance from the removal of pulmonary secretions may have been an influential factor in the observed change in expiratoryflow (Webber et al 1986). However, to date no direct relationship or association between sputum clearance and airways resistance has been described in the intubated and ventilated population.

The improvement in secretion clearance by 25% is clinically important. It is unclear whether the 8% improvement in peak expiratory flow is clinically relevant. However, it is important that using a head-down tilt position does not have an adverse effect on expiratory flow rates during manual hyperinflation. Therefore the critical I:E ratio is likely to be maintained in this position.

Wet weight of sputum was used as an outcome measure although it may be influenced by the presence of saliva (Rossman et al

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**Table 2.** Mean and standard deviation for peak expiratory flow (l/sec) and sputum production (grams) for each treatment position and mean and standard deviation for static pulmonary compliance (pre- and post-treatment ml/cmH$_2$O).

<table>
<thead>
<tr>
<th></th>
<th>Morning</th>
<th>Afternoon</th>
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<tr>
<td></td>
<td>Flat</td>
<td>Head-down tilt</td>
</tr>
<tr>
<td>Mean peak expiratory flow (l/sec)</td>
<td>2.04 ± 0.06</td>
<td>2.19 ± 0.06</td>
</tr>
<tr>
<td>Mean sputum production (g)</td>
<td>3.68 ± 1.61</td>
<td>5.17 ± 2.83</td>
</tr>
<tr>
<td>Mean static pulmonary compliance (ml/cmH$_2$O)</td>
<td>41.91 ± 9.48</td>
<td>47.53 ± 13.87</td>
</tr>
</tbody>
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**References**

were no reliable and valid reports of protocols for this procedure in the literature. In addition, Cecins et al (1999) reported a strong linear relationship between the dry and wet weight of sputum in patients with cystic fibrosis. As the patients were intubated, it was felt the risk of corruption of sputum measurement by saliva was minimal.

A previous study (Hodgson et al 2000) reported that secretion clearance was enhanced by the use of manual hyperinflation compared with flat side-lying alone. The results of the current study would support the use of manual hyperinflation combined with a head-down tilt to improve secretion clearance in patients who are intubated and ventilated.

Consistent with previous findings, static pulmonary compliance improved after each physiotherapy treatment (Berney and Denehy 2002, Hodgson et al 2000, Jones et al 1992). This improvement may be explained by alveolar recruitment, volume restoration and secretion clearance (Hodgson et al 2000, Maxwell and Ellis 1998). The improvement in static pulmonary compliance immediately following physiotherapy treatment in the current study of 12% was consistent with a previous study where the immediate improvement was 11% (Berney and Denehy 2002).

There are several factors that may influence expiratory flow during manual hyperinflation; these include type of resuscitation circuit (Jones et al 1992, Maxwell and Ellis 2003), operator technique (McCarren and Chow 1998, Maxwell and Ellis 2002, Rusterholz and Ellis 1998) and lung volume (Maxwell and Ellis 1998). In an attempt to reduce the variability associated with expiratory flow measurement the same operator, Heidbrink valve, and flow meter were used for each patient. Peak expiratory flow rates were measured using a modified Magills resuscitation circuit. The resistance caused by this adaptation to the circuit was measured at 2 mmH2O/l/sec at a flow of 1 l/sec. This was not considered to increase airway resistance significantly as it was within the American Thoracic Society’s guidelines for standardisation of spirometry (American Thoracic Society 1994, updated 1995). Lung volume was not measured in the current study as manual hyperinflation was defined by reaching a peak airway pressure of 40 cmH2O rather than a pre-determined volume. Manual hyperinflation is performed for the purpose of re-inflation of atelectatic lung by increasing lung volume and removal of excess pulmonary secretions through fast expiratory flow (Maxwell and Ellis 1998). Although expiratory flow rate is proportional to end inspiratory lung volume (Maxwell and Ellis 1998), atelectasis has been demonstrated to resolve with hyperinflation to a peak airway pressure of 40 cmH2O regardless of the lung volume achieved (Rothen et al 1993). High inspiratory lung volumes that cause airway pressures in excess of 40 cmH2O may increase the risk of barotrauma (Haake et al 1987, Ware and Matthay 2000) and according to the results of the current study are most likely not required to produce annular flow.

Technical difficulties in the clinical situation associated with infection control and practicality meant that both inspiratory and expiratory flow rates could not be measured concurrently during manual hyperinflation. If these barriers could be overcome, future studies may be able to establish that the required I:E ratio for cephalad secretion movement is able to be achieved by physiotherapists performing manual hyperinflation in patients who are intubated and ventilated.

The use of ventilator hyperinflation instead of manual hyperinflation may allow concurrent measurement of inspiratory and expiratory flows in the clinical setting. Ventilator hyperinflation has been found to be equally as effective as manual hyperinflation in secretion clearance and in improving static pulmonary compliance (Berney and Denehy 2002) and is therefore a viable treatment alternative.

Methodology in this study would have been enhanced if the physiotherapist performing manual hyperinflation was blinded to measurement of peak expiratory flow. This was not practical, as it would have hindered the performance of the technique in the clinical setting. It is acknowledged that the stereological method of point counting provides only an estimate of the cross sectional area of the trachea as preparations may be affected by shrinking and hardening of tissues (Drury and Wallington 1967). In addition, the calculation of an I:E flow ratio was theoretical as the inspiratory flow rate used was from the study by McCarron and Chow (1998) on a different group of patients.

In conclusion, the addition of a head-down tilt to manual hyperinflation increases the sputum yield in patients who are intubated and ventilated. In addition, peak expiratory flow rates achieved during manual hyperinflation in the flat side-lying and in the head-down tilt position were sufficient to produce movement of pulmonary secretions. The results of this study would suggest that the head-down tilt position should be considered when the primary aim of treatment is sputum removal for patients who are intubated and ventilated.

Footnotes

(a)Ohmeda MA 105  (b)Bird pressure manometer. Tag Medical  (c)Baxter Health Care Corporation. Edward Critical Care Division. Irvine, Ca 92714-5686 USA  (d)Hewlett Packard monitoring systems M1046-9001b, HP GmBH, Boedhing, Germany  (e)40 cc specimen trap. Sherwood Medical, St Louis, MO 63103, USA; model no. 8884-724500  (f)PC400, Hewlett Packard, Boedhing, Germany  (g)Vitalographe medical instrumentation. Peak flow monitor. Vitalographe Ltd. Maids Moreton House Buckinghamshire MK 18, 1SW, England

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