Ventilatory and cardiovascular responses to unsupported low-intensity upper limb exercise in normal subjects

The ventilatory and cardiovascular responses, and the rating of perceived exertion (RPE) to three types of unsupported low-intensity upper limb exercise (static, dynamic - unilateral and bilateral) were investigated in 22 normal subjects. A significant increase in tidal volume, respiratory rate, minute ventilation, oxygen consumption, carbon dioxide production and pulse rate occurred during all three exercises ($p < 0.05$). With the exception of tidal volume, these increases were significantly greater with dynamic exercise ($p < 0.05$). Local RPE was significantly higher than general RPE following both static and dynamic exercise ($p < 0.05$) with no significant differences between the three exercises. These findings provide some basis for the development of exercise protocols for testing in post-operative patients.

Following major abdominal or cardiothoracic surgery, functional residual capacity is reduced by an average of 20-40 per cent and patients typically breathe with a low tidal volume ($V_t$) and absence of periodic deep breaths (Bourn and Jenkins 1992, Fairshier and Williams 1987). These changes lead to airway closure and the resultant intrapulmonary shunting and ventilation/perfusion ($V/Q$) mismatching is responsible for the hypoxaemia observed in the early post-operative period (Bourn and Jenkins 1992, Fairshier and Williams 1987). The aim of physiotherapy in the immediate post-operative period is to increase alveolar ventilation and prevent respiratory complications using techniques such as positioning, deep breathing exercises, and supported huffing and coughing.

Ambulation and low-intensity exercise of the upper and lower limbs are also used for this purpose (Dean and Ross 1992, Tucker et al 1996). These simple, non-invasive techniques directly and profoundly affect multiple steps of the oxygen transport pathway (Dean and Ross 1992) and, in post-operative patients, often elicit spontaneous coughing (Dean 1993).

The physiological responses to static arm elevation have been examined in normal subjects and in patients with chronic airflow limitation (CAL) (Baarends et al 1995, Epstein et al 1995). Although the physiological responses to unsupported low-intensity dynamic upper limb exercise (ULE) have been reported, the types of exercises studied involved only flexion or extension of the forearm (Lewis et al 1983) or required subjects to maintain the arms at or above 90 degrees shoulder flexion while performing small amplitude vertical movements (10cm) of the upper arm (Celli et al 1988, Criner and Celli 1988). Unsupported arm elevation has been
shown to increase the contribution to ventilation made by the diaphragm in both normal subjects and some patients with CAL (Celli et al 1988, Criner and Celli 1988). However, to date there appears to be no published studies which have examined the physiological responses to the specific types of unsupported low-intensity ULE incorporating full range of glenohumeral joint movement generally used by physiotherapists in the management of post-operative patients. The purpose of this study was to investigate the ventilatory and cardiovascular responses, and rating of perceived exertion (RPE) to these exercises in normal subjects with the aim of determining suitable exercise protocols for testing in post-operative patients.

Methods
A within-subject, repeated measures design was used.

Subjects
Ethics approval was granted by the Human Research Ethics Committee of Curtin University of Technology and the Committee for Human Rights of the University of Western Australia, and written, informed consent was obtained from subjects prior to testing. Advertisements inviting participation in the study were placed on noticeboards in one of the major adult hospitals in Perth and in the School of Physiotherapy. In addition, an announcement about the study was made on local radio. Thirty-three subjects volunteered to participate in the study. Of these, nine were excluded due to the following conditions: hypertension (systolic blood pressure [SBP] > 140 mmHg or diastolic blood pressure [DBP] > 90 mmHg, n = 6); musculoskeletal abnormality of the cervical or thoracic spine resulting in pain or limited movement (n = 2) and participation in resistive or aerobic training programs involving the upper limbs (n = 1). In addition, two subjects withdrew their consent due to personal circumstances prior to completion of the second testing session.

Subjects attended two testing sessions, one week apart. During the initial session they were familiarised with the testing procedure and instrumentation. The physiological responses and degree of subjective effort to three types of unsupported low-intensity ULE were investigated during the second session.

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<tr>
<th>Variable</th>
<th>Mean</th>
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<td>Height (cm)</td>
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<td>Weight (kg)</td>
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<td>% predicted</td>
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<td>FEV₁/FVC (%)</td>
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Abbreviations: SD - standard deviation; y – years; cm – centimetres; kg – kilograms; BMI – body mass index (weight/height²); m – metres; SBP – systolic blood pressure; DBP – diastolic blood pressure; MAP – mean arterial blood pressure (mmHg) – millimetres of Mercury; FVC – forced vital capacity (l) – litres; % predicted – percentage of predicted normal value; FEV₁ – forced expiratory volume in one second; FER – forced expiratory ratio; % – per cent

Subjects were told to fast for two hours prior to the study. Testing was performed in an environment controlled for temperature and humidity. All instruments were calibrated prior to the testing of each subject. The gas analysers were calibrated according to the

Table 1. Demographic, resting blood pressure and lung function data for the 22 subjects (means and SDs)

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Subjects attended two testing sessions, one week apart. During the initial session they were familiarised with the testing procedure and instrumentation. The physiological responses and degree of subjective effort to three types of unsupported low-intensity ULE were investigated during the second session.

Measurements
At the initial session, the subject's age, height, weight, neck and shoulder range of movement were measured and past medical history and physical activity level recorded. With the subject seated, resting SBP and DBP were measured using an automated oscillometric monitor (Dinamap, 1846SX vital signs monitor, Critikon, Tampa, Florida, USA), and from these values mean arterial pressure (MAP) was derived. Forced vital capacity (FVC) and forced expiratory volume in one second (FEV₁) were measured in sitting, via a standard technique (American Thoracic Society 1987) using a wedge bellows spirometer (Vitalograph, Model S, Buckingham, UK). The highest values taken from three satisfactory attempts were recorded and used to calculate the forced expiratory ratio (FER = FEV₁/FVC).

A breath–by–breath gas analysis system (Benchmark Exercise System, PK Morgan, Gillingham, Kent, UK) was used to measure and record respiratory gas exchange at rest, during exercise and on recovery. Inspiratory and expiratory flow rates were measured by a low resistance pneumotach with negligible deadspace. Tidal volume was derived by integration of the expired flow signal from the pneumotach. Expired gas was sampled on a breath–by–breath basis by a rapidly responding Zirconia oxygen fuel cell and an infra red carbon dioxide cell to determine respective gas concentrations. Oxygen consumption (VO₂) and carbon dioxide production (VCO₂) were subsequently derived. Arterial oxygen saturation (SpO₂) and pulse rate (PR) were measured continuously using a pulse oximeter with ear sensor attachment (Ohmeda Biox 3700e, Ohmeda, Boulder, Colorado, USA). Systolic and diastolic blood pressures were recorded once at rest, immediately following the completion of each exercise and at the commencement of the fourth minute of recovery. The Borg scale (Borg 1970) was used to measure local (ie arm exertion) (RPEr) and general (RPEg) RPE immediately upon the completion of each exercise.

Subjects were told to fast for two hours prior to the study. Testing was performed in an environment controlled for temperature and humidity. All instruments were calibrated prior to the testing of each subject. The gas analysers were calibrated according to the
Raw data for $V_T$, $f$, $V_{E}$, $V_{O_2}$, $V_{CO_2}$, PR, MAP and SpO$_2$% are expressed as means with SDs in parentheses. RPE scores are given as medians with ranges in parentheses. The table also shows the percentage change between the exercise and resting values for $V_T$, $f$, $V_{E}$, $V_{O_2}$, $V_{CO_2}$, PR and MAP for each of the three types of exercise. *p < 0.05 vs rest; †p < 0.01 SSF vs USF and BSF.

**Abbreviations**: SSA - static shoulder abduction; USF - dynamic unilateral shoulder flexion; BSF - dynamic bilateral shoulder flexion; $V_T$ - tidal volume; ml - millilitres; %change - percentage change from resting value; $f$ - respiratory frequency; $V_{E}$ - minute ventilation; l - litres; min - minute; $V_{O_2}$ - oxygen consumption; kg - kilogram; $V_{CO_2}$ - carbon dioxide production; PR - pulse rate; MAP - mean arterial blood pressure; mmHg - millimetres of mercury; SpO$_2$% - arterial oxygen saturation; RPE$_L$ - local rating of perceived exertion; RPE$_G$ - general rating of perceived exertion.

The first exercise was preceded by a 10min period of baseline (resting) data collection during which subjects sat quietly with arms resting on their thighs. The three exercises were:

- Static shoulder abduction (SSA): 90 degrees glenohumeral abduction with elbows extended and forearms in mid pronation.
- Dynamic unilateral shoulder flexion (USF): glenohumeral flexion commencing with arms by sides with full elbow flexion and ending at the limit of glenohumeral flexion with full range elbow extension performed alternately with the right and left upper limbs.
• Dynamic bilateral shoulder flexion (BSF); glenohumeral flexion (see description for USF) performed simultaneously with both upper limbs.

Both dynamic exercises (USF and BSF) were performed at a constant cadence of 69 beats per minute, controlled by a metronome. During USF, each beat of the metronome required the subject to perform one repetition of USF while the contralateral arm remained in the start position. The sequence was then performed alternately with each arm in time with the metronome for the duration of the exercise. During BSF, one beat of the metronome required the subject to move both arms simultaneously from the start position to the end of glenohumeral flexion. The next beat of the metronome required the subject to return their arms to the start position. This sequence was repeated in pace with the metronome for the 2min exercise period.

Data smoothing and statistical analyses

Resting (baseline) values of $V_T$, $VO_2$, $VCO_2$, $Spo_2$ per cent and PR were calculated using data collected during the 5th to 9th minute of the 10min baseline period. The mean, standard deviation (SD) and coefficient of variation (CV) for these variables were calculated. Outliers were identified by observation, tested statistically (outside of 2 SD) and excluded from further data analysis. The mean, SD and CV were then recalculated, with these values taken to represent baseline measures. Resting respiratory rate was determined by visual inspection. The number of data points for the 22 subjects that qualified as outliers during the baseline period was 2 (SD, 1; range 1-5). Table 2 also displays the mean percentage increase in $V_T$, respiratory rate, $V_{E'}$, $VO_2$, $VCO_2$, PR, MAP and $Spo_2$ per cent are presented in Table 1. The average number of data points for the 22 subjects that qualified as outliers during the baseline period was 2 (SD, 1; range 1-5). Table 2 also displays the mean percentage increase in $V_T$, respiratory rate, $V_{E'}$, $VO_2$, $VCO_2$, PR and MAP in response to the three exercises.

The increase in respiratory rate, $V_{E'}$, $VO_2$, and $VCO_2$ were significantly greater with both types of dynamic exercise than static exercise (Table 2). Although $V_T$ increased by a greater amount with dynamic than static exercise, this difference was not significant (mean increase with USF 63 ml, $p = 0.253$ and BSF 84 ml, $p = 0.319$). During SSA, the increase in $V_T$ was due to a proportionately larger increase in $V_T$ than respiratory rate. With USF, the increase in $V_T$ was due to comparable increases in both $V_T$ and respiratory rate, while in contrast the increase in respiratory rate contributed proportionately more than $V_T$ to the increase in $V_T$ during BSF (Table 2). Despite the observed differences in the genesis of the ventilatory response with the two forms of dynamic exercise, no significant difference was found for any of the ventilatory or metabolic data between USF and BSF ($V_T$, $p = 0.818$; respiratory rate, $p = 0.058$; $V_{E'}$, $p = 0.353$; $VO_2$, $p = 0.545$; $VCO_2$, $p = 0.422$). Following all three types of exercise, $PR$, $V_T$, respiratory rate, $VO_2$, and $VCO_2$ had returned to resting values by the fourth minute of recovery (PR, $V_T$, respiratory rate, $VO_2$, and $VCO_2$ were within 2 bpm, 120 ml, 2 breaths per minute, 0.5 ml/kg/min and 0.5 ml/kg/min respectively).

Immediately after exercise a significant increase in SBP (mean [SD]) was observed for SSA (121 [17.8] mmHg, $p = 0.007$), USF (128 [15.6] mmHg, $p < 0.001$) and BSF (124 [18.1] mmHg, $p = 0.002$) when compared to the resting value (116 [14] mmHg). By the fourth minute of recovery, SBP was not significantly different from resting value for all three types of exercise. There were no significant changes in DBP with any of the exercises. Mean arterial pressure increased immediately following USF only but had returned to resting value by the end of the recovery period (Table 2).

Rating of perceived exertion

Local and general RPE scores are given in Table 2. Following static and dynamic exercise, RPE was significantly greater than RPE_d ($p < 0.05$). There were no significant differences in RPE, or RPE_d between SSA, USF and BSF.

Discussion

The findings of this study have shown that, in normal subjects, unsupported low-intensity static and dynamic ULE of short duration, typical of the exercises used by physiotherapists in the management of post-operative patients, results in significant increases in $V_{E'}$, respiratory rate, $V_{E'}$, $VO_2$, $VCO_2$, and PR. These responses occurred in the absence of clinically significant increases in MAP.
Static exercise
The increases in $VO_2$, $VCO_2$, and PR occurring during SSA were of a similar magnitude to the changes observed by Couser et al (1992) who studied the effects of two minutes of static shoulder flexion at 90 degrees in normal subjects. In both studies increases in $V_e$ were largely accounted for by increases in $V_T$. The variation in glenohumeral position from flexion to abduction does not appear to be an important determinant influencing the metabolic response to unsupported low-intensity static ULE. This is plausible given that there is little difference in glenohumeral and scapular torque between glenohumeral flexion and abduction (Hagberg 1981), and both glenohumeral positions involve the recruitment of a similar exercising muscle mass and a similar degree of isometric contraction (Cummins and Gladden 1983). The increases in $V_T$, respiratory rate, $V_e$, $VO_2$, $VCO_2$, and PR in the present study were greater than reported by Baarends et al (1995) who studied the effects of two minutes of static shoulder abduction at 90 degrees in 13 normal subjects. The differences may be explained by the time period over which data were averaged. Baarends et al (1995) averaged data over the entire two minutes of exercise and not the last minute as was the case in our study.

In attempting to establish a safe exercise protocol for use in patients following cardiac surgery, BP response to SSA was also measured. Although there was a transient increase in SBP immediately following exercise, there were no changes in MAP or DBP. One limitation of our study is that BP was not measured during exercise as movement of the arm may affect the accuracy of BP measures determined using an automated system. Asmussen (1981) reported a substantial rise in SBP and DBP occurring at the onset of low-intensity static exercise (10-25 per cent maximum voluntary contraction) which fell rapidly at the cessation of exercise. This is greater than the BP response occurring during low-intensity dynamic exercise at a similar workload and at an equivalent $VO_2$ (Asmussen 1981). In the present study it is reasonable to assume that BP was higher during both static and dynamic exercise than the reported values. Continuous monitoring of BP via an indwelling arterial line (where present) may be advisable when patients with acute cardiorespiratory dysfunction perform ULE.

Dynamic exercise
The observed increases in $V_T$, $VO_2$, $VCO_2$, and PR with dynamic exercise are consistent with low-intensity exercise in normal subjects (Pardy et al 1984). There was no difference between USF and BSF for $V_T$, $V_e$, $VO_2$, $VCO_2$, and PR. However, the ventilatory response during USF was more consistent than during BSF. The group variance in $V_T$ (SD, 503 ml) and respiratory rate (SD, 7.99 breaths per minute) during BSF was greater than during USF ($V_T$, SD, 399 ml; respiratory rate, SD, 3.82 breaths per minute) which may indicate that subjects differed in the breathing pattern adopted during the two forms of exercise. Possible explanations for this may include the rhythmical nature of USF and a greater resistance to expansion of the chest wall with BSF. Subjects may co-ordinate their respiratory rate with the rate of exercise. Similar synchronisation is evident in other forms of rhythmical exercise (Lewis et al 1983). It is possible that the ventilatory requirements of BSF were too demanding for this synchronised "slow" pattern of breathing and hence some subjects adopted a much faster respiratory rate with BSF than USF. Limitation in thoracic spine extension or tightness within the trunk musculature (e.g latissimus dorsi) will limit the excursion of the upper limbs above the head. Such limitations will be exaggerated in BSF because during bilateral movements subjects are unable to compensate with side flexion of the trunk. This may increase the resistance of the chest wall to expansion during BSF and thus increase the work of breathing. An alternative explanation may be the greater trunk stabilisation required to lift the weight of both arms. These two factors may be responsible for the trend towards higher RPE$^c$ scores obtained during BSF compared with USF.

The type of unsupported dynamic ULE investigated in our study differs from that studied by others. Most studies have required subjects to maintain their arms at or above 90 degrees shoulder flexion while performing small amplitude vertical movements (10cm) of the arms (Breslin and Garoutte 1995, Celli et al 1988). The intensity, rate and duration of exercise varies between studies; on occasions, exercise was performed to exhaustion (Celli et al 1988), while another study controlled respiratory rate and $V_T$ and required subjects to exercise for only two minutes (Breslin and Garoutte 1995). This type of dynamic exercise requires a significant degree of static muscle contraction to maintain the arms at or above 90 degrees shoulder flexion, and hence differs significantly from the exercises examined in the present study.

Rating of perceived exertion
The intensity of the exercises studied was intentionally low and this was reflected in the relatively low scores for RPE$^c$. Previous studies have shown that subjects can differentiate between general and local RPE (Gamarale 1972). Our findings are consistent with this as subjects reported higher RPE$^c$ than RPE$^l$ scores for each of the three exercises. Of particular interest however is the comparison of RPE scores during static and dynamic exercise. Despite there being no differences in RPE$^c$ and RPE$^l$ with the three types of exercise, $VO_2$ was significantly lower during SSA. This is in keeping with the findings of Asmussen (1981) who showed that at an equivalent value of $VO_2$ subjects perceive static exercise to be more difficult than dynamic exercise.

Implications for upper limb exercise in post-operative patients
Guidelines for the prescription of exercise in patients with acute...
cardiopulmonary dysfunction are scarce and those appropriate for healthy individuals and patients with chronic conditions are rarely appropriate for the patient with acute dysfunction. Dean and Ross (1992) recommend the use of clinical signs (eg heart rate and rhythm, respiratory rate and pattern, BP and SpO2 per cent) and symptoms when prescribing exercise for such patients. The increases in heart rate observed in the present study, if replicated in post-operative patients, are within the guidelines for exercise intensity recommended for patients following cardiac surgery (American College of Sports Medicine 1995). Oxygen saturation measured with a pulse oximeter remained unchanged with all types of exercise. While recognising the limitations of pulse oximetry to detect small changes in oxygen saturation when resting values are in the region of 97 per cent (Webb et al 1991), a small increase or no change in oxygen saturation is the normal response to submaximal exercise in healthy subjects (Moss and Make 1993). Many patients with acute cardiopulmonary dysfunction will have a low oxygen saturation at rest and continuous monitoring of SpO2% during exercise is recommended.

The optimal form of exercise in the acute post-operative period is low-intensity exercise with frequent rests to ensure that excessive physiological demands are minimised on an already stressed cardiopulmonary system and to account for increased fatigue and deconditioning (Dean and Ross 1992). If the RPE scores recorded in this study are replicated in post-operative patients, then unsupported ULE as performed in this study is within these guidelines.

The increases in V̇O2 and respiratory rate in response to exercise are potentially of benefit for the post-operative patient as they may improve alveolar ventilation and increase flow rates. Mucociliary clearance is enhanced in normal subjects during exercise (Wolff et al 1977). The rise in heart rate and pulmonary blood flow during exercise should result in an increase in lung perfusion, with the potential for improving V/Q matching and increasing oxygen transport through the body via the systemic circulation (Dean 1993).

Upper limb exercise has been shown to produce a disproportionate increase in the contribution of the diaphragm to ventilation which is associated with a reduction in the contribution made by the accessory muscles (Celli et al 1988, Criner and Celli 1988). This arises because the accessory muscles of respiration have dual roles: primarily as agonists, antagonists and stabilisers to glenohumeral and scapular motion; and secondly to assist the diaphragm when ventilatory demand is increased, such as during exercise (Celli 1993). However, the ability to recruit the accessory muscles to assist the diaphragm with inspiration is limited during exercise when these muscles are acting in their primary role (Celli 1993). Therefore ULE may not only improve alveolar ventilation in patients following upper abdominal or cardiac surgery but also facilitate improved diaphragm contraction.

Given the absence of studies examining the effects of ULE in the immediate post-operative period, we recommend that studies be performed to establish guidelines for prescribing ULE for such patients. There is a need for these studies to investigate the physiological responses to ULE as well as the effects of ULE on diaphragm function. The findings of this study provide some basis for the development of exercise protocols for testing in patients in the early post-operative period.

Acknowledgements

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References


