J Rehabil Med 2006; 38: 381–386

OPTIMAL INTENSITY FOR RESPIRATORY MUSCLE ENDURANCE TRAINING IN PATIENTS WITH SPINAL CORD INJURY

Gabi Mueller, MS[1], Claudio Perret, PhD[2] and Christina M. Spengler, PhD MD[3]

From the [1]Swiss Paraplegic Research, Institute for Sports Medicine, [2]Swiss Paraplegic Research, Institute for Clinical Research, Nottwil and [3]Exercise Physiology, Institute for Human Movement Sciences, ETH Zurich, and Institute of Physiology and Center for Integrative Human Physiology (CIHP), University of Zurich, Zurich, Switzerland

Objective: **Respiratory muscle endurance of able-bodied persons, assessed by normocapnic hyperpnoea at 70% of their maximal voluntary ventilation, usually ranges from 10 to 20 minutes. The aim of this study was to determine the level of ventilation that patients with paraplegia and tetraplegia can sustain for 10–20 minutes to later be used as the guideline for respiratory muscle endurance training.**
Design: **Pilot study; cross-over setting.**
Subjects: **Two groups, 8 patients with paraplegia and 6 with tetraplegia.**
Methods: **Respiratory muscle endurance tests were performed at 3 different intensities of normocapnic hyperpnoea, i.e. 20%, 40% and 60% maximal voluntary ventilation. Subjects performed partial re-breathing from a bag to assure normocapnia. Respiratory endurance was separately analysed for patients with paraplegia and tetraplegia.**
Results: **Mean respiratory endurance times were 46.0, 18.9 and 4.2 minutes at 20%, 40% and 60% maximal voluntary ventilation in patients with tetraplegia and 51.8, 38.8 and 12.2 minutes in patients with paraplegia. The duration differed significantly at 60% maximal voluntary ventilation between the groups.**
Conclusion: **Minute ventilation to perform respiratory muscle endurance training can be set at around 40% of maximal voluntary ventilation for patients with tetraplegia and around 60% of maximal voluntary ventilation for patients with paraplegia, as these levels can be sustained for 10–20 minutes.**

Key words: Respiration, breathing exercises, maximal voluntary ventilation, spinal cord injuries.

J Rehabil Med 2006; 38: 381–386

Correspondence address: Gabi Mueller, Swiss Paraplegic Research, CH-6207 Nottwil, Switzerland. E-mail: gabi.mueller@paranet.ch

Submitted October 17, 2005; accepted April 26, 2006

INTRODUCTION

Complete spinal cord injury (SCI) results in diminished pulmonary function, due to paralysis of the respiratory muscles, depending on the lesion level (1). While persons with paraplegia lack abdominal muscle function and also lesion-dependent intercostal muscle function, persons with tetraplegia lack most of the expiratory and even some of the auxiliary inspiratory muscles (2). This may lead to more rapid fatigue of the respiratory pump in subjects with SCI during physical activity, as well as to a restricted pulmonary capacity (3). Furthermore, persons with SCI are generally at higher risk for progressive respiratory insufficiency compared with able-bodied people (4). Pulmonary complications are a major cause of death, in particular for persons with tetraplegia surviving the first 6 months after the trauma (5). The fact that patients with SCI activate their remaining respiratory muscles in daily life less than able-bodied persons, due to the lack of whole-body physical activity, may also explain the weakened respiratory system (6), particularly for persons with tetraplegia. Therefore, special attention should be given to the functioning and improvement of their respiratory pump.

Leith & Bradley (7) showed that respiratory muscle strength and endurance can be specifically increased by appropriate respiratory muscle training in able-bodied subjects. So far, studies showing an improvement of respiratory muscle function in patients with SCI focussed on respiratory resistance or resistance endurance training (8–11). However, for these patients, respiration causes major problems during physical activity (12) and for patients with tetraplegia also during the night (e.g. sleep apnoea) (13–16). Therefore, respiratory endurance seems to be more critical than respiratory muscle strength. Sedentary as well as trained able-bodied subjects (17) significantly increased the endurance of respiratory muscles as well as whole-body exercise endurance by means of normocapnic hyperpnoea training (NHT) at 60–70% of their individual maximal voluntary ventilation (MVV). In view of these effects in able-bodied subjects, NHT is expected to be even more beneficial for persons with weak respiratory muscles, such as people with SCI, but data is missing for this group.

Therefore, the first step to adapt NHT for persons with SCI is to test respiratory endurance in this group of subjects at different minute ventilations, i.e. different intensities. We hypothesize that, due to the partly lacking respiratory muscle mass, the minute ventilation that can be sustained for 10–20 minutes, an appropriate duration for NHT in this group of patients, will be higher for patients with paraplegia than for patients with tetraplegia. To test this hypothesis, patients with paraplegia as well as tetraplegia performed respiratory endurance tests (RETs) by means of exhaustive normocapnic hyperpnoea at three different intensities.

 ISSN 1650-1977
DOI: 10.1080/16501970600780369

METHODS

Thirty-three patients, 22 with paraplegia and 11 with tetraplegia, who were hospitalized in an SCI rehabilitation centre for first rehabilitation between September 2001 and July 2004, met the inclusion criteria (see below). Of these, 3 did not want to participate and 16 were excluded according to the exclusion criteria (see below). Finally, 8 patients with paraplegia and 6 patients with tetraplegia were enrolled in the study. Characteristics of these subjects are shown in Table I. Inclusion criteria were: age between 18 and 45 years with an acute traumatic, motor complete lesion (ASIA A or B). Exclusion criteria were: asthma, chronic obstructive pulmonary disease, pneumonia, tracheotomy, bronchial or urinary infections, irregular medication, peanut or latex allergy and epilepsy. In order to reach stable ventilatory function after injury, we enrolled patients with paraplegia 4–6 months after injury and patients with tetraplegia 6–8 months after injury (18, 19). Prior to the start of the study, all patients were informed in detail about the study and gave their written informed consent. The ethics committee of the canton Lucerne, Switzerland approved the study.

Equipment

Vital capacity, peak inspiratory and expiratory flows, forced in- and expiratory volumes in 1 s (FIV_1, FEV_1) and MVV were measured by a metabolic chart (Oxycon α, Jaeger, Hoechberg, Germany), using a turbine for volume measurements and fast-responding gas analysers. The system had been calibrated with a 3-litre syringe and certified mixed calibration gas before each test. Maximal inspiratory and expiratory pressures (Pi_{max}, Pe_{max}) were measured by a hand-held mouth pressure meter (Micro MPM, Micro Medical Ltd, Chatham Kent, UK) including a small air leak to prevent glottis closure.

RETs, i.e. normocapnic hyperpnoea to exhaustion, were performed using a special partial re-breathing device (SpiroTiger®, Fehraltorf, Switzerland) providing target respiratory frequency and tidal volume. During RETs, end-tidal CO_2 partial pressure and ventilatory variables were monitored and recorded breath by breath (Oxycon α) to verify normocapnia and target ventilation. Heart rate (HR) was measured by oximetry (OxyTip, Datex-Ohmeda 3900, Louisville, USA) on the right middle finger and blood pressure (BP) by plethysmography (Finapress BP Monitor, Ohmeda 2300, BOC Healthcare, Englewood, Colorado, USA) on the left middle finger, placing the left forearm on heart level (see Fig. 1 for experimental setup). Blood samples (20 µl) were drawn from an earlobe and analysed for blood lactate concentration enzymatically (Super GL Ambulance, Ruhrtal Labor Technik, Moehnesee, Germany). Perception of breathlessness and respiratory effort were indicated by the subjects at rest and at the end of each test on a visual analogue scale (VAS) ranging from 0 to 10.

Protocol

Every patient reported 6 times to the laboratory, with an interval between visits of at least 72 hours. During the first 3 sessions, lung function as well as Pi_{max} (from residual volume) and Pe_{max} (from total lung capacity), both measures of respiratory muscle strength, were assessed. Each measurement was repeated 3–6 times until values did not differ more than ±5%. The best effort within these limits was recorded. All respiratory measurements were conducted according to the spirometry testing standards in SCI (1) in an upright sitting position in the patient's own wheelchair. After lung function and respiratory muscle strength measurements, the NHT device was adjusted to 1 of the 3 intensities corresponding to 20%, 40% or 60% of each patient's individual MVV. Subjects were then familiarized with the technique to perform normocapnic hyperpnoea and they were also trained to use the VAS.

During the last 3 sessions, subjects performed 1 RET each day at either 20%, 40% or 60% of their MVV, in random order. During RET sessions, they were verbally encouraged to keep the target minute ventilation ($\dot{V}_E$) of the corresponding intensity. The test was stopped either by the patient due to exhaustion or by the experimenter, if $\dot{V}_E$ was more than 5 l/minute lower than the target value for more than 30 seconds or if the test duration reached 60 minutes. Patients had to abstain from caffeine for 24 hours before each test. Information about nutrition, sleep, physical activity and medication 24 hours prior to each test were given by a questionnaire.

HR and BP were registered at rest, every 2 minutes during and at the end of each test. Blood samples for blood lactate analyses were drawn at the same time-points. BP measurements were performed in patients with paraplegia only, as sympathetic activity regulating BP is absent in patients with tetraplegia and thus BP is influenced by other factors (e.g. micturition) causing random fluctuations (20).

Statistics

Between-group differences in respiratory muscle endurance, absolute $\dot{V}_E$ during RETs, breathlessness, respiratory effort, HR, BP and blood lactate concentration, were tested using Wilcoxon's rank sum tests. Systolic vs diastolic increases in BP between rest and test break off were also tested with Wilcoxon's rank sum tests. The Friedman two-way analysis of variance was used to assess within-group differences of RET variables between tests at the three different intensities. For HR, BP, breathlessness and respiratory effort, differences between rest and test

Table I. *Characteristics of patients with paraplegia and tetraplegia*

Sex	Age (years)	Height (cm)	Weight (kg)	TPI (months)	Lesion level	Smoker
Paraplegia						
m	30	180	75	6	Th4	No
m	22	178	62	4	Th5	No
f	26	168	53	4	Th5/6	No
m	23	198	83	4	Th6	Yes
m	39	170	80	5	Th10	No
m	26	182	72	4	Th11	No
m	32	185	70	4	Th11	No
m	45	178	73	4	L1	No
Mean (SD)	31 (8)	180 (9)	71 (10)	4 (1)		
Tetraplegia						
f	22	173	52	7	C4	No
f	39	153	41	6	C5	No
m	21	187	70	6	C6	No
m	21	183	59	7	C7	Yes
m	22	175	69	7	C7	No
m	22	172	58	6	C7	No
Mean (SD)	25 (7)	174 (12)	58 (11)	7 (1)		

TPI = time post injury; m = male; f = female; C = cervical lesion; Th = thoracic lesion; L = lumbar lesion; SD = standard deviation.

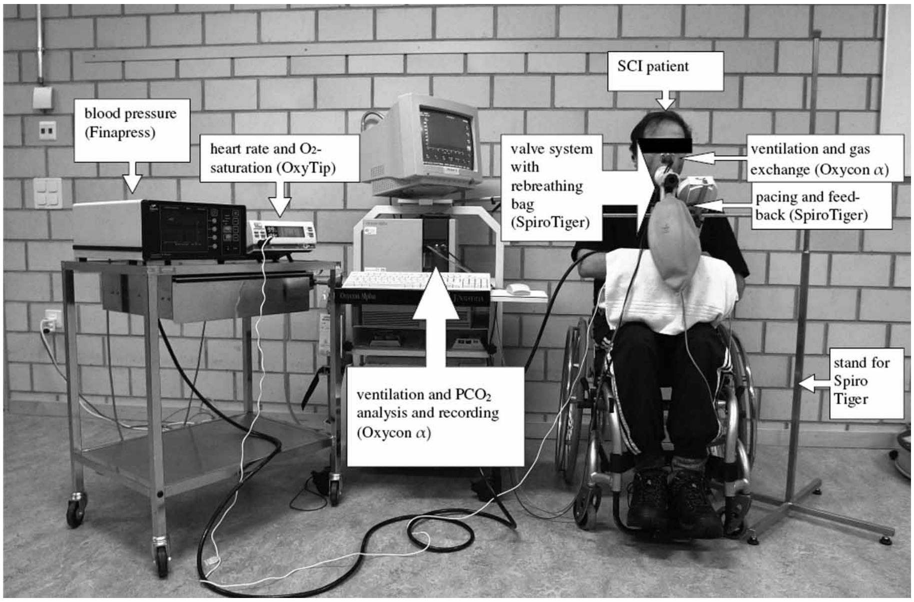

Fig. 1. Experimental setup.

break off were calculated for further analyses. Significance was accepted at $p < 0.05$. Statistical analyses were performed with a computer software package (Systat, Version 10.2; Systat Software Inc.; Point Richmond, CA, USA). Values are presented as mean (SD).

RESULTS

Spirometry and respiratory muscle strength

Lung function and respiratory muscle strength of patients with paraplegia and tetraplegia are presented in Table II. All variables were significantly higher in patients with paraplegia compared with tetraplegia.

RET: duration and respiratory assessments

RET duration at 60% MVV was significantly higher in patients with paraplegia compared with patients with tetraplegia being 12.2 (9.0) vs 4.2 (3.4) minutes (Fig. 2). Durations of RETs at 40% MVV (38.8 vs 18.9 minutes; $p = 0.053$) and 20% MVV (51.8 vs 46.0 minutes; $p = 0.391$) did not differ significantly between groups. Within groups, RET durations were significantly different between intensities ($p = 0.006$ for both groups). At 20% MVV, 6 patients with paraplegia and 2 with tetraplegia were stopped by the experimenter as they reached 60 minutes. Due to the higher absolute MVV of patients with paraplegia, their average $\dot{V}_E$ during RETs was significantly higher at 20%, 40% and 60% MVV compared with patients with tetraplegia (Fig. 3). Within both groups, $\dot{V}_E$ was significantly different between intensities ($p = 0.000$ for patients with paraplegia and $p = 0.007$ for patients with tetraplegia).

Perception of breathlessness did not differ between intensities for patients with paraplegia and tetraplegia ($p = 0.159$ and $p = 0.449$). In patients with paraplegia, perception of respiratory effort was significantly higher at the end of RETs at 60% ($p = 0.005$) and 40% ($p = 0.034$) MVV than at the end of the RET at 20% MVV while it did not differ between intensities in patients with tetraplegia ($p = 0.368$) (Table III).

RET: cardiovascular measurements

At rest, mean HR was 91 (12) bpm in patients with paraplegia and 74 (14) bpm in patients with tetraplegia. While BP was not assessed in patients with tetraplegia (for details please see methods), in patients with paraplegia resting systolic BP was

Table II. *Lung function and respiratory muscle strength (% predicted) for patients with paraplegia and tetraplegia presented as mean (SD)*

	Patients with paraplegia ($n = 8$)	Patients with tetraplegia ($n = 6$)	p-value
VC	100.5 (22.4)	59.3 (21.9)	0.007
FEV_1	100.9 (22.6)	58.2 (18.6)	0.007
FIV_1	104.8 (26.3)	60.8 (21.5)	0.012
PEF	106.5 (23.5)	57.0 (12.0)	0.002
MVV	127.4 (32.7)	68.0 (19.0)	0.003
Pi_{max}	81.4 (14.6)	59.0 (14.4)	0.010
Pe_{max}	42.3 (18.1)	20.7 (5.5)	0.004

VC = vital capacity; FEV_1 = forced expiratory volume in 1 s; FIV_1 = forced inspiratory volume in 1 s; PEF = peak expiratory flow; MVV = maximal voluntary ventilation; Pi_{max} = maximal inspiratory pressure; Pe_{max} = maximal expiratory pressure.

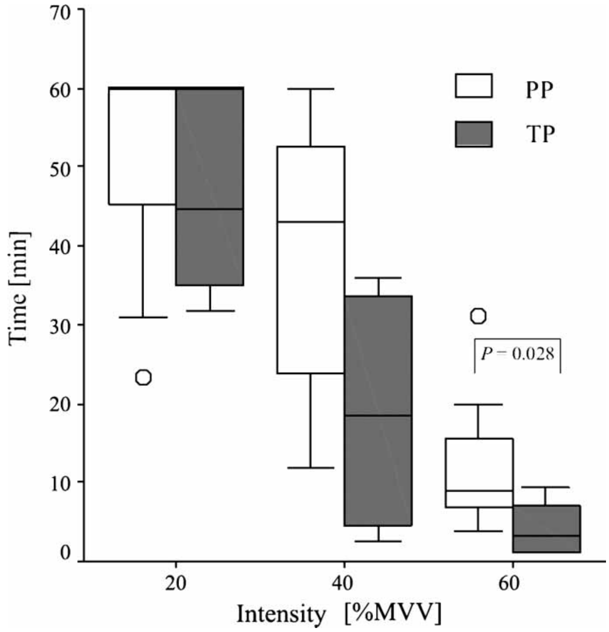

Fig. 2. Median (lines inside boxes) and lower and upper quartiles (lower and upper edge of boxes) and range (whiskers) for duration of respiratory endurance tests at different intensities for patients with paraplegia (PP) and for patients with tetraplegia (TP). MVV = maximal voluntary ventilation, o = outlier.

134 (28) mmHg and diastolic BP was 74 (11) mmHg. Increases in systolic BP between intensities were not significantly different ($p = 0.159$). Diastolic BP increased significantly more during RETs at 60% compared with 20% MVV ($p = 0.005$) and during 60% compared with 40% MVV ($p = 0.034$). Increases in diastolic BP between 20% and 40% MVV were not significantly different (Table III). Furthermore, at 60% MVV the increase in systolic BP, was significantly larger than the increase in diastolic BP ($p = 0.012$) while increases in systolic vs diastolic BP did not differ at 40% ($p = 0.483$) and 20% MVV ($p = 0.726$).

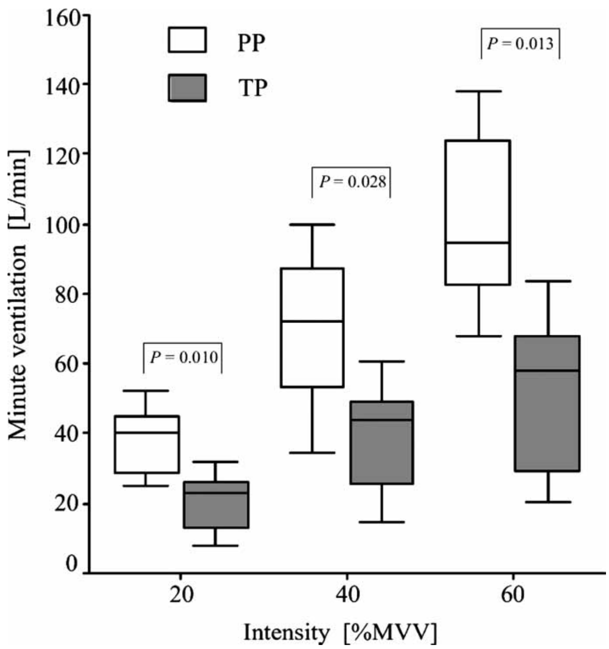

Fig. 3. Median (lines inside boxes) and lower and upper quartiles (lower and upper edge of boxes) and range (whiskers) of minute ventilation during respiratory endurance tests at different intensities for patients with paraplegia (PP) and for patients with tetraplegia (TP). MVV = maximal voluntary ventilation.

RET: blood lactate concentration

Blood lactate concentrations of the 3 tests are shown in Fig. 4A for patients with paraplegia and Fig. 4B for patients with tetraplegia. In patients with paraplegia, blood lactate concentrations during as well as at the end of RETs decreased significantly compared with resting levels at 20% MVV ($p = 0.005$) as well as at 40% MVV ($p = 0.034$). At 60% MVV, blood lactate concentration did not change throughout the test (Fig. 4A). In patients with tetraplegia, blood lactate concentrations decreased significantly compared with resting values during as well as at the end of the RET at 20% MVV only ($p = 0.014$). At 40% and 60% MVV, blood lactate concentration did not change throughout the test (Fig. 4B). Blood lactate concentrations did not differ between groups at identical intensities ($p = 0.180$–0.564).

DISCUSSION

Respiratory muscle endurance and optimal training intensity

This study confirms our hypothesis that respiratory muscle endurance is reduced in patients with SCI compared with able-bodied subjects, more so with higher lesion levels. While able-bodied subjects can breathe for 30 minutes at >60% of their individual MVV (21–23), patients with paraplegia only sustained this intensity for an average of 12.2 minutes while patients with tetraplegia only reached 4.2 minutes on average. Thus, when aiming for NHT durations of 10–20 minutes (as proven feasible for respiratory training in this group of patients) (9–11, 24–26), $\dot{V}_E$ can be set around 60% MVV for patients with paraplegia, but needs to be reduced to around 40% MVV for patients with tetraplegia. Although the perception of breathlessness was quite similar at the end of all tests in both groups, motivation to perform RETs may also have influenced performance in these patients with SCI, shown by rather large inter-individual differences of RET durations at given intensities. The above-mentioned guidelines should therefore be taken as starting levels in order to adjust the individual optimal training intensity.

It is noteworthy that respiratory endurance of patients with SCI is decreased compared with able-bodied subjects, although the $\dot{V}_E$ values were based on individual subjects' MVV (27). For patients with tetraplegia, MVV was significantly below that of able-bodied subjects. The decreased endurance may reflect a certain degree of muscle atrophy, occurring due to the immobilization of the patients during the first weeks after injury (28). Furthermore, in patients with SCI, breathing and thus respiratory muscles are stimulated only little during daily activities due to the smaller muscle mass available compared with able-bodied persons that are walking, running and lifting

Table III. *Differences (Δ) between rest and end of respiratory endurance tests at different intensities for patients with paraplegia and tetraplegia presented as mean (SD)*

	Patients with paraplegia (n = 8)			Patients with tetraplegia (n = 6)		
Intensity (% MVV)	20%	40%	60%	20%	40%	60%
Δ heart rate (bpm)	11 (11)	30 (14)	32 (22)	20 (17)	34 (19)	24 (16)
Δ systolic blood pressure (mmHg)	11.6 (24.5)	24.1 (24.3)	43.1 (18.1)‡	NA	NA	NA
Δ diastolic blood pressure (mmHg)	14.1 (10.5)	16.9 (9.7)	23.3 (12.9)*†	NA	NA	NA
Δ breathlessness (points)	5.01 (3.31)	4.39 (3.20)	5.58 (3.82)	2.59 (3.61)	3.03 (3.44)	3.36 (3.32)
Δ respiratory effort (points)	4.06 (2.47)	7.17 (3.06)	8.97 (1.83)*†	6.7 (2.97)	7.9 (2.86)	7.85 (1.72)

*Significant difference to 20% MVV; †Significant difference to 40% MVV; ‡Significant difference to Δ diastolic blood pressure at the same intensity. Note that there were no significant differences between groups of paraplegic and tetraplegic patients. MVV = maximal voluntary ventilation; NA = not applicable.

objects (6). In addition, the potential of shifting between the use of different respiratory muscles allowing some recovery at sub-maximal ventilations is reduced.

Lung function and respiratory muscle strength

While lung function of patients with paraplegia was similar to able-bodied subjects, respiratory muscle strength was lower than normal with Pi_{max} being around 20% and Pe_{max} around 60% lower than predicted from values assessed in able-bodied persons. In patients with tetraplegia, however, lung function and inspiratory muscle strength were reduced to about 60% of predicted while expiratory muscle strength was only around 20% predicted. As hyperpnoea consists of repeated forced inspirations and expirations, maximal strength of these muscles (and the loss of it in the course of the task) is likely a factor affecting endurance as well. This assumption is supported by the fact that respiratory muscle endurance was reduced in subjects with paraplegia in the presence of reduced muscle strength and despite normal lung function, including FIV_1, FEV_1 and MVV.

Cardiovascular responses to RETs

While BP was not assessed in patients with tetraplegia due to the sympathetic autonomic impairment at this lesion level (29), both systolic and diastolic BP increased significantly in patients with paraplegia during RETs with a tendency to larger changes with increasing $\dot{V}_E$. Also, systolic BP increased to a larger extent than diastolic BP at 60% MVV, suggesting that stroke volume increased during this task. This cardiovascular challenge, in particular during breathing at 60% MVV, strongly suggests that respiratory endurance training at this intensity will result in significant training effects.

Blood lactate metabolism

Interestingly, blood lactate concentrations decreased during RETs at 20% and 40% MVV for patients with paraplegia and at 20% MVV for patients with tetraplegia, probably meaning that working muscles increasingly consumed blood lactate as an energy source. This shift in the balance of lactate production vs consumption relative to resting conditions may result from the increased activity of respiratory muscles also using blood lactate as a fuel and/or the increased activity of the heart muscle, one of the major blood lactate consumers. The fact that blood lactate did not change during breathing at 60% MVV in patients with paraplegia and at 40% and 60% in patients with tetraplegia shows, in turn, that anaerobic metabolism was increasingly needed to achieve the work, also showing that patients with tetraplegia reached this limit "earlier", i.e. at a lower intensity than patients with paraplegia. This, in turn, supports our

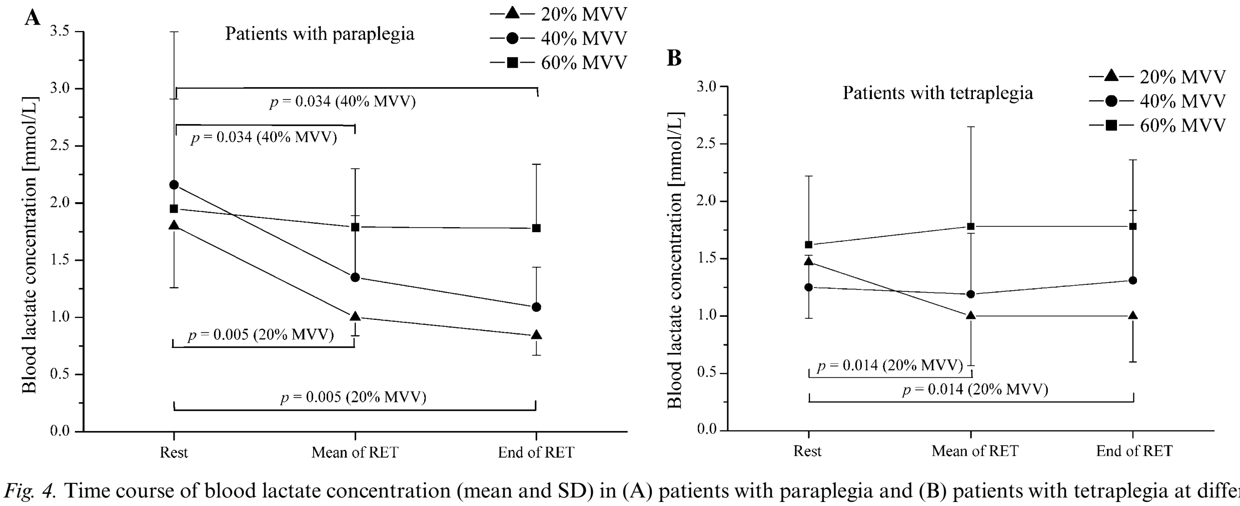

Fig. 4. Time course of blood lactate concentration (mean and SD) in (A) patients with paraplegia and (B) patients with tetraplegia at different intensities of the respiratory endurance tests (RET). MVV = maximal voluntary ventilation.

previous suggestion that the higher the lesion, the smaller the ability of the still innervated respiratory muscles to share the work and to recover in-between. The continuous work then likely results in a faster development of fatigue and the necessity to recruit fast twitch fibres running on anaerobic metabolism.

These metabolic changes during RETs, together with the cardiovascular changes observed, suggest that respiratory muscle endurance training – if performed in form of NHT at 60% MVV (patients with paraplegia) and 40% (patients with tetraplegia) – will result in significant training effects, e.g. increased respiratory muscle endurance probably accompanied by increased aerobic metabolism. Increased respiratory muscle endurance will, in turn, not only reduce the sensation of breathlessness during tasks involving heavy breathing, e.g. wheeling uphill, but also the shift towards increased aerobic metabolism (as observed in able-bodied people after this kind of training (22)) might help to reduce early arm muscle fatigue resulting from intramuscular acidosis. In addition, lung function of patients with tetraplegia is likely to improve, which would then result in improved airway clearance and reduction of pulmonary complications.

In conclusion, this study showed that respiratory muscle endurance of patients with tetraplegia is reduced compared with patients with paraplegia. The optimal intensity for patients with SCI to perform NHT for 10–20 minutes should be set at $\dot{V}_E$ around 60% MVV for patients with paraplegia and around 40% MVV for patients with tetraplegia. Due to inter-individual differences, however, this intensity should then be adapted individually using the above-mentioned values as guidelines.

ACKNOWLEDGEMENTS

Financial support was provided in part by the Swiss National Science Foundation (grant no. 31-61941.00). The SpiroTiger® devices were generously provided by idiag (Fehraltorf, Switzerland).

REFERENCES

1. Kelley A, Garshick E, Gross ER, Lieberman SL, Tun CG, Brown R. Spirometry testing standards in spinal cord injury. Chest 2003; 123: 725–730.
2. De Troyer A, Estenne M. Functional anatomy of the respiratory muscles. Clin Chest Med 1988; 9: 175–193.
3. Silva AC, Neder JA, Chiurciu MV, Pasqualin DC, da Silva RC, Fernadez AC, et al. Effect of aerobic training on ventilatory muscle endurance of spinal cord injured men. Spinal Cord 1998; 36: 240–245.
4. Lanig I, Peterson W. The respiratory system in spinal cord injury. In: Kraft G, ed. Physical medicine and rehabilitation clinics of North America; topics in spinal cord injury medicine. Philadelphia: WB Saunders Co; 2000, p. 29–43.
5. DeVivo MJ, Black KJ, Stover SL. Causes of death during the first 12 years after spinal cord injury. Arch Phys Med Rehabil 1993; 74: 248–254.
6. Monroe MB, Tataranni PA, Pratley R, Manore MM, Skinner JS, Ravussin E. Lower daily energy expenditure as measured by a respiratory chamber in subjects with spinal cord injury compared with control subjects. Am J Clin Nutr 1998; 68: 1223–1227.
7. Leith DE, Bradley M. Ventilatory muscle strength and endurance training. J Appl Physiol 1976; 41: 508–516.
8. Gross D, Ladd HW, Riley EJ, Macklem PT, Grassino A. The effect of training on strength and endurance of the diaphragm in quadriplegia. Am J Med 1980; 68: 27–35.
9. Huldtgren AC, Fugl-Meyer AR, Jonasson E, Bake B. Ventilatory dysfunction and respiratory rehabilitation in post-traumatic quadriplegia. Eur J Respir Dis 1980; 61: 347–356.
10. Rutchik A, Weissman AR, Almenoff PL, Spungen AM, Bauman WA, Grimm DR. Resistive inspiratory muscle training in subjects with chronic cervical spinal cord injury. Arch Phys Med Rehabil 1998; 79: 293–297.
11. Wang TG, Wang YH, Tang FT, Lin KH, Lien IN. Resistive inspiratory muscle training in sleep-disordered breathing of traumatic tetraplegia. Arch Phys Med Rehabil 2002; 83: 491–496.
12. Wien MF, Garshick E, Tun CG, Lieberman SL, Kelley A, Brown R. Breathlessness and exercise in spinal cord injury. J Spinal Cord Med 1999; 22: 297–302.
13. Burns SP, Kapur V, Yin KS, Buhrer R. Factors associated with sleep apnea in men with spinal cord injury: a population-based case-control study. Spinal Cord 2001; 39: 15–22.
14. Burns SP, Little JW, Hussey JD, Lyman P, Lakshminarayanan S. Sleep apnea syndrome in chronic spinal cord injury: associated factors and treatment. Arch Phys Med Rehabil 2000; 81: 1334–1339.
15. McEvoy RD, Mykytyn I, Sajkov D, Flavell H, Marshall R, Antic R, et al. Sleep apnoea in patients with quadriplegia. Thorax 1995; 50: 613–619.
16. Sajkov D, Marshall R, Walker P, Mykytyn I, McEvoy RD, Wale J, et al. Sleep apnoea related Hypoxia is associated with cognitive disturbances in patients with tetraplegia. Spinal Cord 1998; 36: 231–239.
17. Spengler CM, Boutellier U. Breathless legs? Consider training your respiration. News of Physiological Sciences 2000; 15: 101–105.
18. Anke A, Aksnes AK, Stanghelle JK, Hjeltnes N. Lung volumes in tetraplegic patients according to cervical spinal cord injury level. Scand J Rehabil Med 1993; 25: 73–77.
19. Liaw MY, Lin MC, Cheng PT, Wong MK, Tang FT. Resistive inspiratory muscle training: its effectiveness in patients with acute complete cervical cord injury. Arch Phys Med Rehabil 2000; 81: 752–756.
20. Teasell RW, Arnold JM, Krassioukov A, Delaney GA. Cardiovascular consequences of loss of supraspinal control of the sympathetic nervous system after spinal cord injury. Arch Phys Med Rehabil 2000; 81: 506–516.
21. Boutellier U, Buchel R, Kundert A, Spengler C. The respiratory system as an exercise limiting factor in normal trained subjects. Eur J Appl Physiol Occup Physiol 1992; 65: 347–353.
22. Spengler CM, Roos M, Laube SM, Boutellier U. Decreased exercice blood lactate concentrations after respiratory endurance training in humans. Eur J Appl Physiol Occup Physiol 1999; 79: 299–305.
23. Boutellier U, Piwko P. The respiratory system as an exercise limiting factor in normal sedentary subjects. Eur J Appl Physiol Occup Physiol 1992; 64: 145–152.
24. Uijl SG, Houtman S, Folgering HT, Hopman MT. Training of respiratory muscles in individuals with tetraplegia. Spinal Cord 1999; 37: 575–579.
25. Loveridge B, Badour M, Dubo H. Ventilatory muscle endurance training in quadriplegia: Effects on breathing pattern. Paraplegia 1989; 27: 329–339.
26. Derrickson J, Cielsa N, Simpson N, Imle PC. A comparison of two breathing exercise programs for patients with quadriplegia. Phys Ther 1992; 72: 763–769.
27. McMahon ME, Boutellier U, Smith RM, Spengler CM. Hyperpnea training attenuates peripheral chemosensitivity and improves cycling endurance. J Exp Biol 2002; 205: 3937–3943.
28. Burnham R, Martin T, Stein R, Bell G, MacLean I, Steadward R. Skeletal muscle fibre type transformation following spinal cord injury. Spinal Cord 1997; 35: 86–91.
29. Figoni SF. Exercise responses and quadriplegia. Med Sci Sports Exerc 1993; 25: 433–441.