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TA 14-18
NEDU TR 16-01
January 2016

Influence of Very High Breathing Resistance on Exercise Tolerance, Part 1 – Dry Exercise

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REPORT DOCUMENTATION PAGE					*Form Approved OMB No. 0704-0188*
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1. REPORT DATE *January 2016*	**2. REPORT TYPE** Technical Report				**3. DATES COVERED**
4. TITLE AND SUBTITLE Influence of Very High Breathing Resistance on Exercise Tolerance, Part 1 – Dry Exercise					**5a. CONTRACT NUMBER**
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Warkander D., Ph.D. Shykoff, B., Ph.D.					**5d. PROJECT NUMBER**
					5e. TASK NUMBER TA 14-18
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Navy Experimental Diving Unit 321 Bullfinch Rd Panama City, FL 32407					**8. PERFORMING ORGANIZATION REPORT NUMBER** NEDU TR 16-01
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Sea Systems Command 1333 Isaac Hull Avenue, SE Washington Navy Yard D.C. 2037					**10. SPONSOR/MONITOR'S ACRONYM(S)** NAVSEA
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) NEDU TR 16-01
12. DISTRIBUTION / AVAILABILITY STATEMENT A: Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT A breathing apparatus with a partial failure may have higher breathing resistance (R) than expected or a breathing apparatus may be needed for harder work than it was designed for. The effects of very high R on physical endurance and on breathing was not known. Fifteen subjects took part in this IRB approved study to determine such effects during moderate exercise (60% of peak O_2 consumption) on a cycle ergometer on dry land at sea level. R was such that the work of breathing per volume (volume-averaged pressure) ranged from nominal 3 to 9 kPa (J/L), i.e. up to 3 times higher than NEDU's limits for diving. Individuals' exercise endurance varied greatly. With the least high R, it ranged from 4.5 min to the protocol's maximum 60 min, with the highest R two subjects continued for 60 min, while one other exercised for less than 2 min. The endurance time for the 90th percentile was 12 min at the lowest R and 3 min for the highest. In general, the minute ventilation decreased (reduced breathing frequency, unchanged tidal volume and duty cycle) with increasing R and the end-tidal CO_2 values increased, some subjects reaching levels close to 8% of the dry gas (57 mm Hg). No subject reached the abort limit of 65 mm Hg. Some subjects who maintained high CO_2 levels reported no or low dyspnea. Rating of perceived exertion did not correlate with R. Reactions to very high R are not predictable. Low scores for dyspnea or perceived exertion do not indicate acceptable R. NEDU's limits for R in a diver's breathing apparatus cannot be used at sea level. Values for R found in simulated or real failures of breathing apparatus can be used with the endurance times found here to judge likely endurance times.					
15. SUBJECT TERMS control of breathing, ventilation, CO_2, carbon dioxide, hypercapnia, CO_2 retention, dyspnea, exercise, performance, endurance.					
16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT** SAR	**18. NUMBER OF PAGES** 36	19a. NAME OF RESPONSIBLE PERSON Nancy Hicks
a. REPORT A	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified			**19b. TELEPHONE NUMBER** *(include area code) 850-230-3170*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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INTRODUCTION

Breathing resistance in a breathing apparatus is unavoidable. Acceptable levels of breathing resistance to allow for long term use of the breathing apparatus have been found empirically [1] [2] [3] [4] and have been implemented [5] [6] in standards for testing of breathing apparatus. However, the effect on a wearer's exercise endurance would be unclear if the breathing resistance were to become far higher than expected, due to a partial failure or usage at work rates higher than those for which the apparatus had been approved.

Advance knowledge of how long a wearer will be able to tolerate breathing through a particular breathing apparatus can be essential when judging if a certain task is likely to be possible in either a long term or short term (emergency) situation. Thus, the main purpose of this study was to determine the effects of different levels of very high breathing resistance on endurance exercise at a moderate work rate (approximately 60% $VO_{2\ max}$). Primarily, endurance times were determined and the nature of the changes in various ventilatory parameters were described.

METHODS

The Institutional Review Board at NEDU approved protocol number 14-50/40069, "Influence of very high breathing resistance on exercise tolerance, part 1 – dry exercise". A total of fifteen military personnel from NEDU gave written informed consent before beginning the study. Each subject participated in six tests; one to determine peak oxygen uptake and five to measure exercise endurance while the subject breathed against different elevated breathing resistances.

During testing, a subject wore an oronasal mask with one-way valves (model 2700, Hans Rudolph, Shawnee, KS). The pressure drop was less than 0.8 cm H_2O at a flow of 100 L/min. The valve dead space for dry measurements was 77 mL, and mask dead space was approximately 50 mL for a medium mask and 65 mL for a large mask. Breathing gas was room air. Experiments were conducted at sea level.

Breathing resistance was varied in five steps. The least high level was selected to impose a total work of breathing per volume (WOB_{tot}/V_T) of 3 kPa, matching NEDU's limit at 1 atm. [6]. WOB_{tot}/V_T for the highest level was three times higher. The resistance levels were increased by a factor $3^{1/4}$, i.e. WOB_{tot}/V_T of 100%, 132%, 173%, 228% and 300% of NEDU's limit.

Ventilatory measurements were made using commercial exercise testing equipment (Cosmed k4b2, Cosmed USA; Chicago, IL) placed at the common port of the one-way valves. The Cosmed also recorded the heart rate measured by a Polar heart rate monitor (Polar Electro Inc, Lake Success, NY). A mass spectrometer (MGA 1100) analyzed the CO_2 from a sample of gas (60 mL/min) drawn at the mouth. Inspiratory flow was measured by a screen pneumotachometer (Microtach II, nSpire Medical, Longmount CO) placed at the inlet of the inspiratory valve with a transducer (683-5INCHD4V, AllSensors, Morgan Hill, CA) to measure the change in pressure across the screen. To measure the mask pressures, a differential pressure transducer (683-20INCHD4V, AllSensors, Morgan Hill, CA) was connected to the space in front of the subject's mouth. The non-Cosmed signals were recorded at 100 Hz (BioPac Systems, Goleta CA).

Subjects were asked every 3 minutes to give Relative Perceived Exertion (RPE) scores (Table 1) and dyspnea scores, where dyspnea scores ranged from 0 to 2 [1], where 0 indicated no difficulty in breathing, 1 meant that the effort of breathing was noticeable but could be sustained for at least 5 minutes, 2 indicated that the subject did not think that he could continue for more than five minutes, 3 was assigned if the subject quit because of difficulty in breathing.

Determinations of peak oxygen update

The first exercise test for each subject was the determination of peak rate of oxygen uptake ($\dot{V}O_{2\ peak}$) on a cycle ergometer (Monark, Vansbro, Sweden). Ergometer load was increased every three minutes in steps of 50 W initially, then 25 W when the subject appeared to be near his exercise capacity, until the subject could no longer continue. Subjects were asked to give scores of Relative Perceived Exertion (RPE), before each increase in workload. Sub-maximal values were used to estimate $\dot{V}O_{2\ max}$ using the Åstrand nomogram [7].

Table 1. Scale for Rating of Perceived Exertion [8].

Exertion	RPE
no exertion at all	6
extremely light	7
	8
very light	9
	10
light	11
	12
somewhat hard	13
	14
hard (heavy)	15
	16
very hard	17
	18
extremely hard	19
maximal exertion	20

Endurance tests

All other exercise tests in this study measured endurance on the cycle ergometer set at 60% of $\dot{V}O_{2\ max}$ while the subject breathed against a breathing resistance. The order of the breathing resistance exposures was randomly assigned. After a three-minute warmup at 50 W, subjects cycled at the workloads selected to produce 60% of their individual $\dot{V}O_{2\,max}$ until they chose to stop. They also would have been told to stop if there had been excessive accumulation of CO_2.

Design of resistance elements

A number of resistance elements (Figure 1) were fabricated in-house to fit into the inspiratory and expiratory ports of the Hans Rudolph valve assembly. To determine the resulting WOB_{tot}/V_T, the mask and valve assembly were placed on a headform and a breathing simulator was used to breathe at minute ventilations ranging from 15 to 135 L/min. Holes for air were tested with diameters (labeled A in Figure 1) varied in 15 even steps from 3.0 to 10.2 mm (0.12 to 0.40 inches). The results are illustrated in Figure 2 and tabulated in Table A1 in the Appendix. The pressure drop was a function of the flow and the square of the flow.

Selection of resistance elements

An estimate of each subject's expected minute ventilation at the endurance workload was obtained by interpolating the recordings made during the $\dot{V}O_{2\,peak}$ measurements. From this estimate of minute ventilation the data in Figure 2 was used to select the resistance element that would most closely match each desired total WOB/V_T. Thus, different subjects had differently sized resistance elements for the same desired resistance level.

For simplicity, the letter R will refer to the resistance level (hole size). The lowest R (largest hole) will be referred to as R1 and the highest (smallest hole), R5. The same size resistance element was applied to the inspiratory side as to the expiratory side, thus making the imposed R as symmetrical as practically possible.

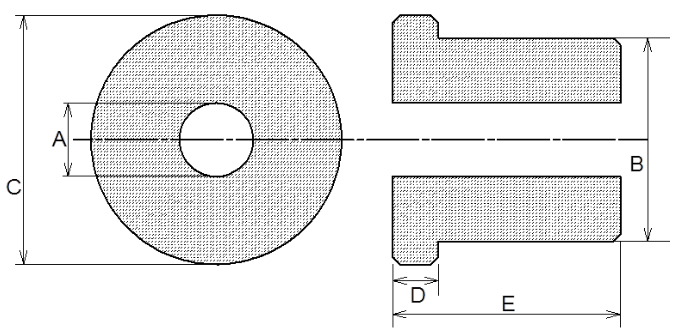


Figure 1. Sketch of resistance elements (NEDU Design Note number 15-03), both viewed from one end and as a cross-section. Dimension A varied, B was 28 mm (1.1 in), C was 34.9 mm (1.375 in), D was 6.2 mm (0.25 in) and E was 31.8 mm (1.25 in).

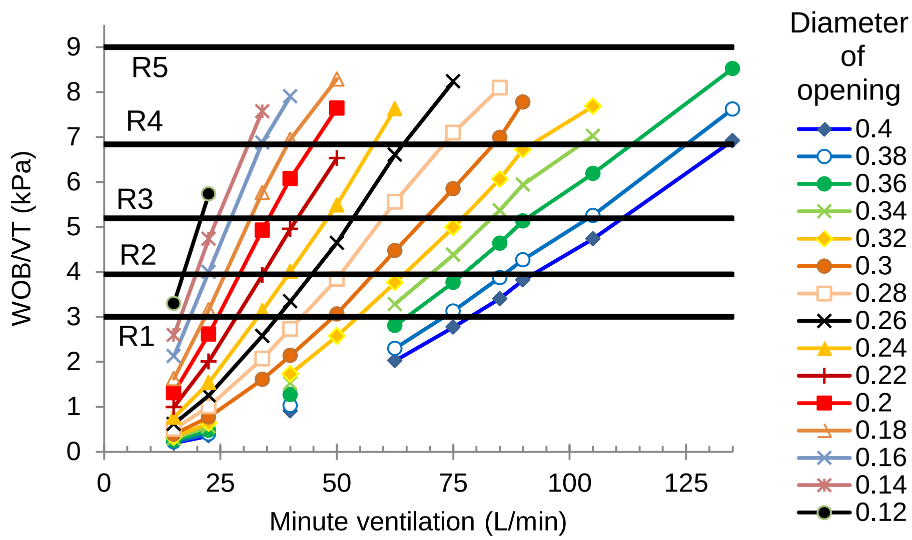


Figure 2. Total work of breathing per tidal volume (WOB/V_T) values measured at different minute ventilations for each size of resistance element. The diameter is measured in inches.

Calibrations

The mass spectrometer was calibrated initially according to the standard procedure to correct for gas interactions, then adjusted daily with air and a span gas (5% CO_2 and 16% O_2 in nitrogen). The pressure transducer outputs were compared to a water manometer.

Data analysis

Breath by breath measurements of minute ventilation ($\dot{V}_E$), tidal volume (V_T), breathing frequency (f_R), heart rate and respiratory duty cycle (T_i/T_{tot}), were determined by the Cosmed device. End-tidal CO_2 ($etCO_2$), peak inspiratory and expiratory pressures, and inspired flow ($\dot{V}_{in}$) were determined from the 100 Hz data. Inspiratory work of breathing per volume (WOB_{in}/V_T) was calculated from $\dot{V}_{in}$, inspiratory mask pressure and the integrated $\dot{V}_{in}$ for each breath.

Values were averaged over the one minute that ended 30 seconds before the termination of exercise (to avoid transients at failure or timing errors).

Abort criteria

Each subject was free to stop an experiment at any time. An experiment would have been stopped if the $etCO_2$ exceeded a partial pressure of 65 mm Hg.

Statistical analysis

The influence of resistance level on each measured parameter was calculated by linear regression of the pooled subject data against resistance. The statistical significance of the slope was determined, with $\alpha = 0.05$ used as the limit of significance.

RESULTS

The subjects varied widely in height, weight, and apparent aerobic fitness (Table 2). The group consisted of both divers and non-divers.

Table 2. Subject characteristics. Median values, with minimum to maximum in parentheses.

	15 men, 1 woman
Age (years)	33 (24 – 53)
Height (cm)	175 (163 – 193)
Body mass (kg)	91 (76 – 107)
VO_2 peak ($L \cdot min^{-1}$) +	3.1 (1.9 – 5.8)
VO_2 max ($L \cdot min^{-1}$) ‡	3.3 (2.4 – 5.8)
($mL \cdot min^{-1} \cdot kg^{-1}$) ‡	36 (25 – 57)
HR at peak (beats/min)	189 (167 – 196)
Shaft power at 60% (W)	110 (85 – 150)

+measured values, ‡determined from a nomogram [7].

During the R exposure, some subjects could not exercise for at least three minutes at the exercise load before they stopped work. Presenting their results would be correct for illustrating what happened, but also potentially misleading since a cardio-respiratory steady state was probably not reached. Therefore, both sets of data are graphed and are summarized in Tables A2 and A3 in Appendix A. In addition, the subjects who were stopped after 60 minutes had not reached exhaustion and may have had different responses to R if they had. Summary data excluding those subjects are shown in Table A4 and will be discussed separately. The coefficients of variation (CVar, ratio of SD and mean) of the tabulated variables showed no particular influence from the level of R (calculated from the data in Tables A2 - A4).

The graphs that follow here have resistance levels labelled from 1 to 3 (relative to NEDU's limit). The corresponding nominal WOB/V_T varied from 3 to 9 kPa. Slopes of parameters *vs.* R are expressed using the nominal WOB/V_T, not the relative R or the measured WOB/V_T. As will be discussed, if minute ventilation was reduced from the unloaded condition used to choose resistance elements, actual WOB/V_T was less than the nominal value.

The comments given by the subjects are compiled in Table A5.

Endurance times

Table 3a summarizes the endurance time results for all subjects. Figure 3 shows the endurance times for each of the subjects at each of the resistance levels. The endurance times ranged from 4.5 to 60 minutes with R1. Five subjects lasted the full hour allowed in the protocol. Even with R5 there were two subjects who lasted an hour, but one subject stopped after 1.7 minutes (i.e. still during the warm up period). The

CVar increased monotonically from 63% with R1 to 131% with R5. The average endurance with R5 was 41% of the endurance with R1.

Table 3b summarizes the endurance times for the subjects who were not stopped by the 60-minute limit. The CVar ranged from a low of 50% (R1) to a high of 83% (R3) without any particular pattern. The average endurance with R5 was 35% of the endurance with R1.

Table 3a. Summary of endurance times (in minutes) for all subjects for each resistance level.

	R1	R2	R3	R4	R5
Maximum	60	60	60	60	60
Mean	33.6	28.4	26.0	19.3	14.7
SD	21.0	21.1	22.2	21.9	19.3
Normalized to R1	100%	91%	82%	55%	41%
Median	30.9	21.7	20.5	9.4	8.2
CVar	0.63	0.74	0.85	1.13	1.31
25th percentile	16.3	15.4	7.1	5.0	4.1
10th percentile	12.3	7.0	5.6	4.3	2.6
Minimum	4.5	5.4	5.0	2.6	1.7

Table 3b. Summary of endurance times (in minutes) for subjects who exercised for less than 60 min for each resistance level.

	R1	R2	R3	R4	R5
Maximum	34.6	35.2	56.0	27.5	26.7
Mean	20.4	16.9	17.5	9.2	7.7
SD	10.1	8.7	15.3	6.8	6.5
Normalized to R1	100%	91%	79%	45%	35%
Median	17.9	16.1	10.9	7.3	5.8
CVar	0.50	0.52	0.87	0.74	0.84
25th percentile	14.2	11.3	5.8	4.6	3.9
10th percentile	10.5	6.9	5.5	4.2	2.3
Minimum	4.5	5.4	5.0	2.6	1.7

For easier viewing, Figure 4A shows just the median (shown also in Figure 3), the upper and lower quartiles, and the time that at least 90% of the subjects endured. Figure 4B is a “survival” graph that shows the number of subjects remaining at a given time.

The average slope for the endurance times of all subjects was -3.1 (SE= 0.74) min per kPa of WOB/V_T ($p<0.001$). For the subjects who exercised for at least 3 minutes at load (n=8) the average slope was -2.6 (SE=0.86) min per kPa of WOB/V_T ($p<0.05$). For the subjects who exercised for at least 3 minutes at load but less than 60 minutes (n=5) the average slope was -3.1 (SE=1.0) min per kPa of WOB/V_T ($p<0.05$).

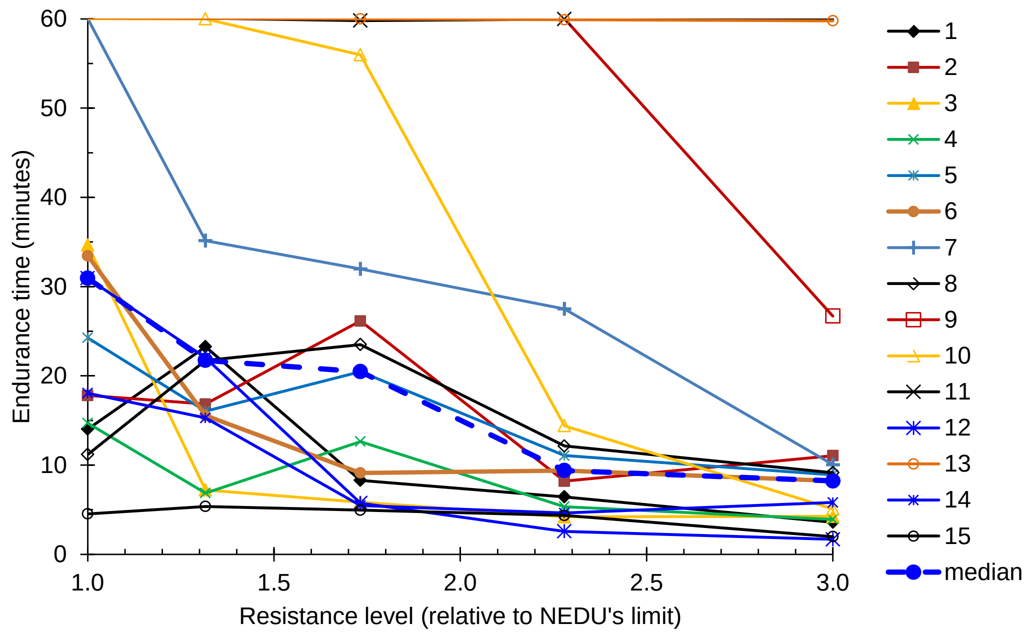


Figure 3. Endurance times for all subjects at each of the resistance loads. Some lines overlap at the cut-off time of 60 minutes for all resistance levels. Each solid line-symbol pair indicates a subject, while the blue dashed line and filled circle show the median times.

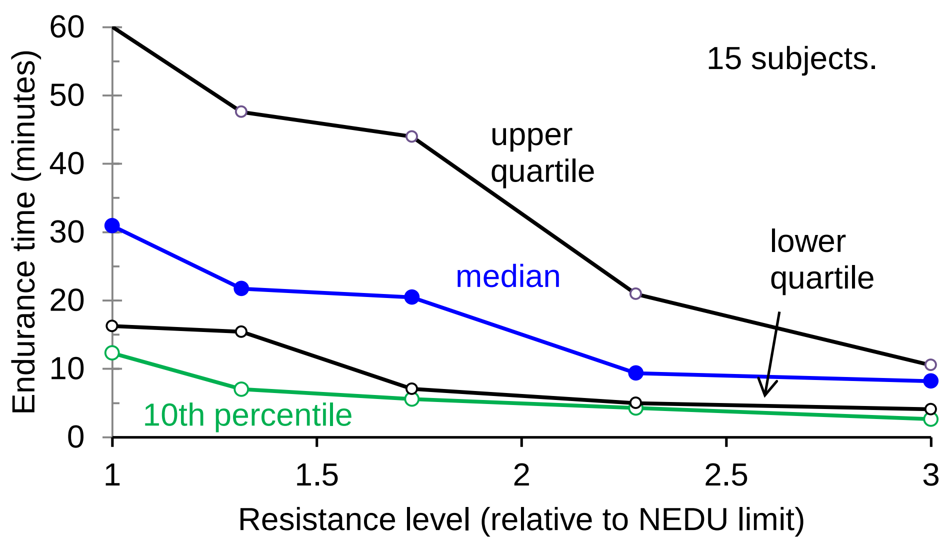


Figure 4A. Endurance times at each of the resistance loads, shown as median, upper and lower quartiles, and the time that at least 90% of the subjects endured (10^{th} percentile).

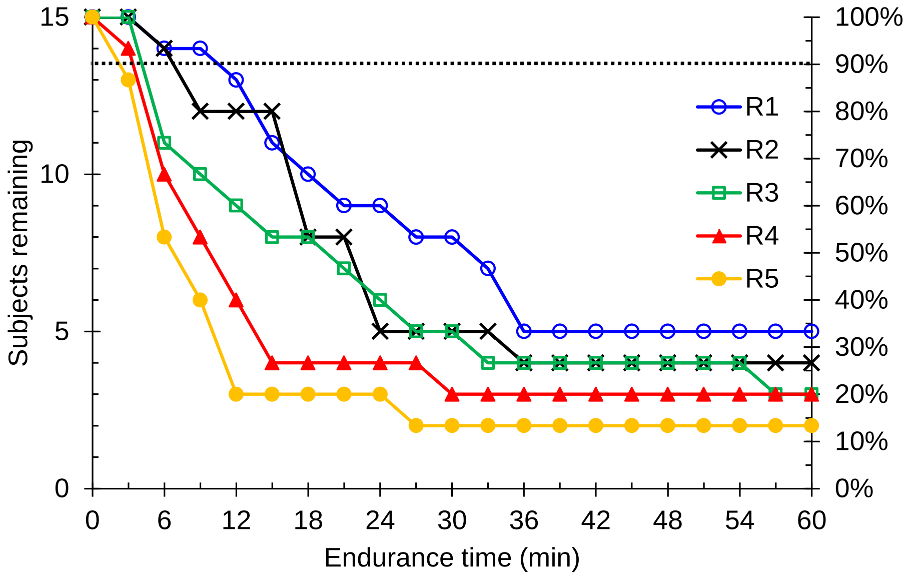
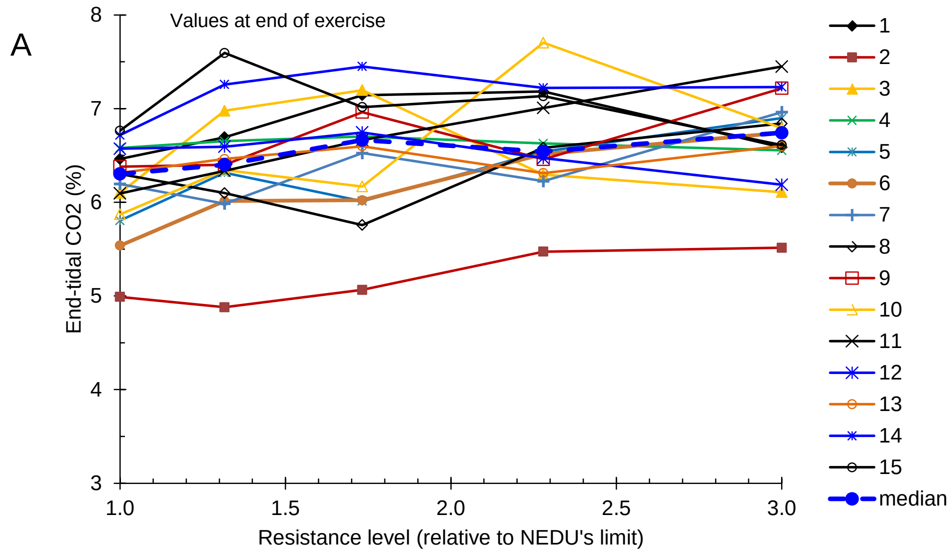


Figure 4B. Survival plot of the number of subjects remaining after each 3-minute period.

End-tidal CO_2 values

Figure 5A shows the $etCO_2$ values for all subjects at the end of exercise. The average slope (mean ±SE) for all subjects was 0.09 ±0.03 kPa CO_2 per kPa of nominal WOB/V_T ($p<0.05$). Figure 5B shows the $etCO_2$ values for the subjects who exercised for at least 3 minutes at load. For those subjects the slope was 0.23 ±0.07 kPa CO_2 per kPa of nominal WOB/V_T ($p<0.01$). For the subjects who exercised for at least 3 minutes at load but less than 60 minutes overall (n=11), the slope was 0.31 ±0.09 kPa CO_2 per kPa of nominal WOB/V_T ($p<0.05$). No subject was stopped for $etCO_2$ exceeding the abort criterion. See Discussion for interpretation of some of the slope values.



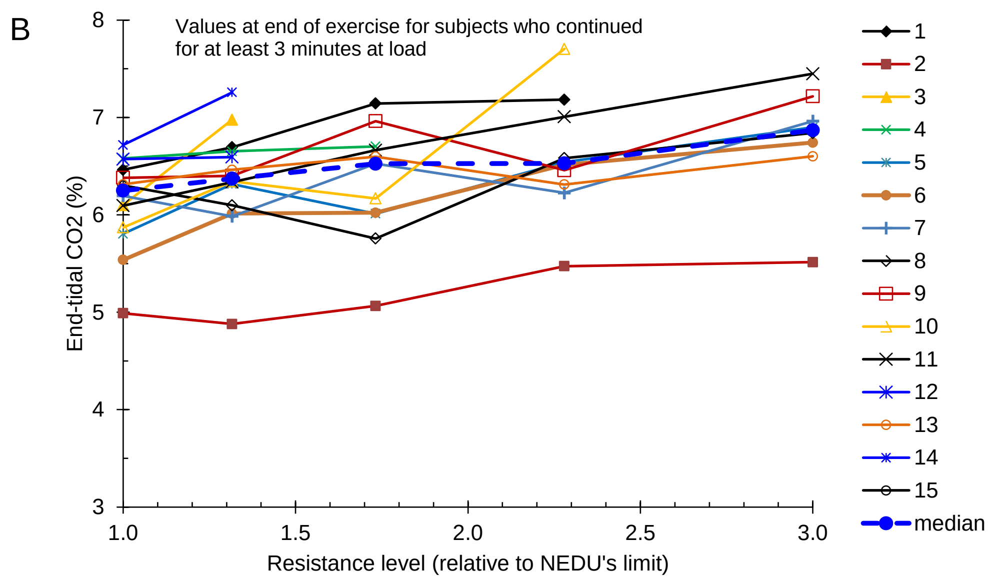


Figure 5. One-minute average end-tidal CO_2 values at the end of exercise. Panel A shows values for all subjects. Panel B shows values for subjects who continued for at least 3 minutes at load.

Minute ventilation

Figure 6A shows one-minute average $\dot{V}_E$ at end of exercise for all subjects, The average slope (mean ±SE) for all subjects was -3.4 ±0.4 L/min per kPa of nominal WOB/V_T ($p<0.0001$). Figure 6B shows $\dot{V}_E$ only for the subjects who completed at least 3 minutes of exercise at load. For them, the slope was -4.7 ±1.0 L/min per kPa of nominal WOB/V_T ($p<0.001$). For the subjects who exercised for at least 3 minutes at load but for less than 60 minutes overall, the slope was -4.3 ±1.4 kPa CO_2 per kPa of nominal WOB/V_T ($p<0.05$).

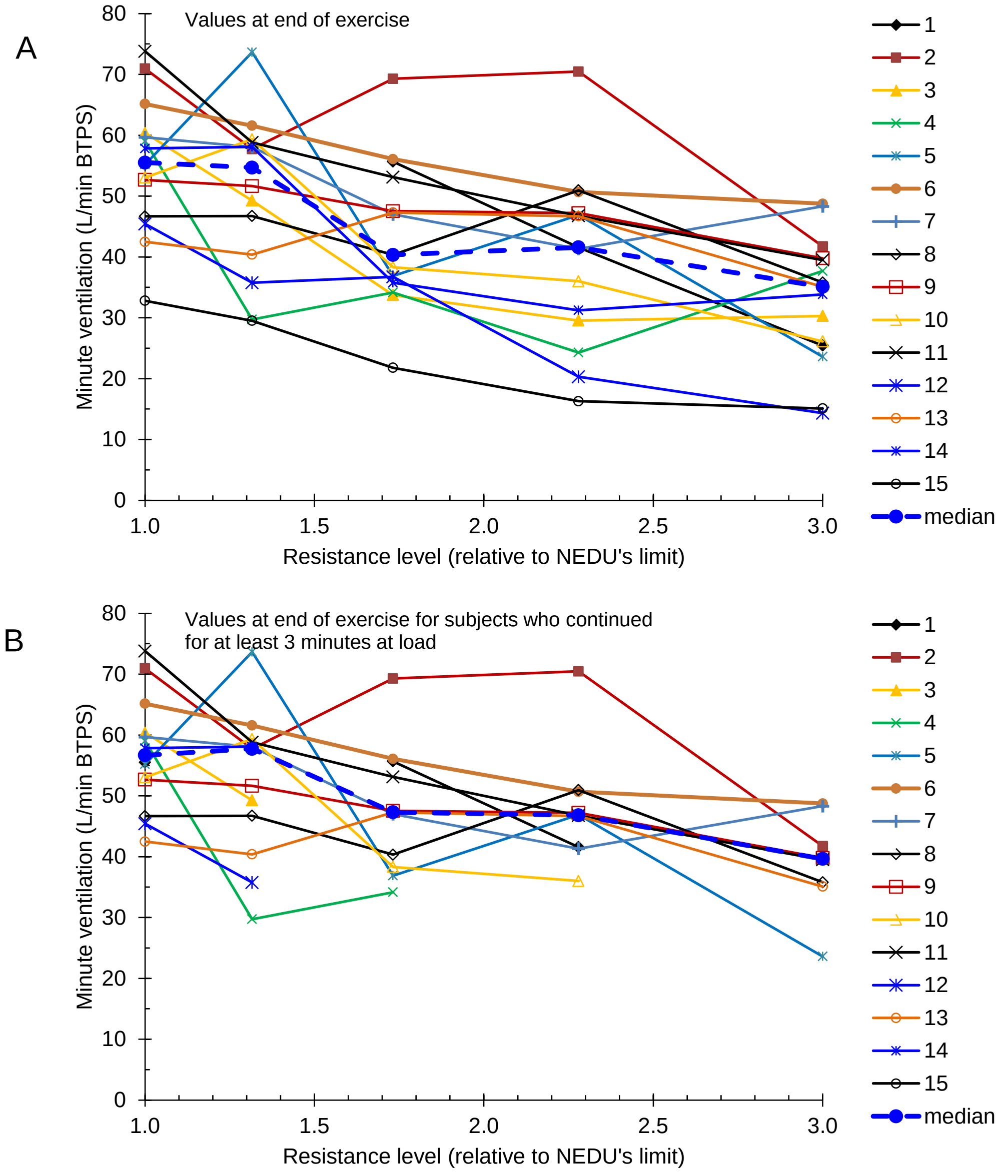


Figure 6. One minute average $\dot{V}_E$ at the end of exercise. Panel A shows values for all subjects. Panel B shows values for subjects who continued for at least 3 minutes at load.

Tidal volume

Figure 7A shows the one-minute average V_T at the end of exercise. Figure 7B shows the V_T for the subjects who exercised for at least 3 minutes at load. The slopes were not significantly different from zero.

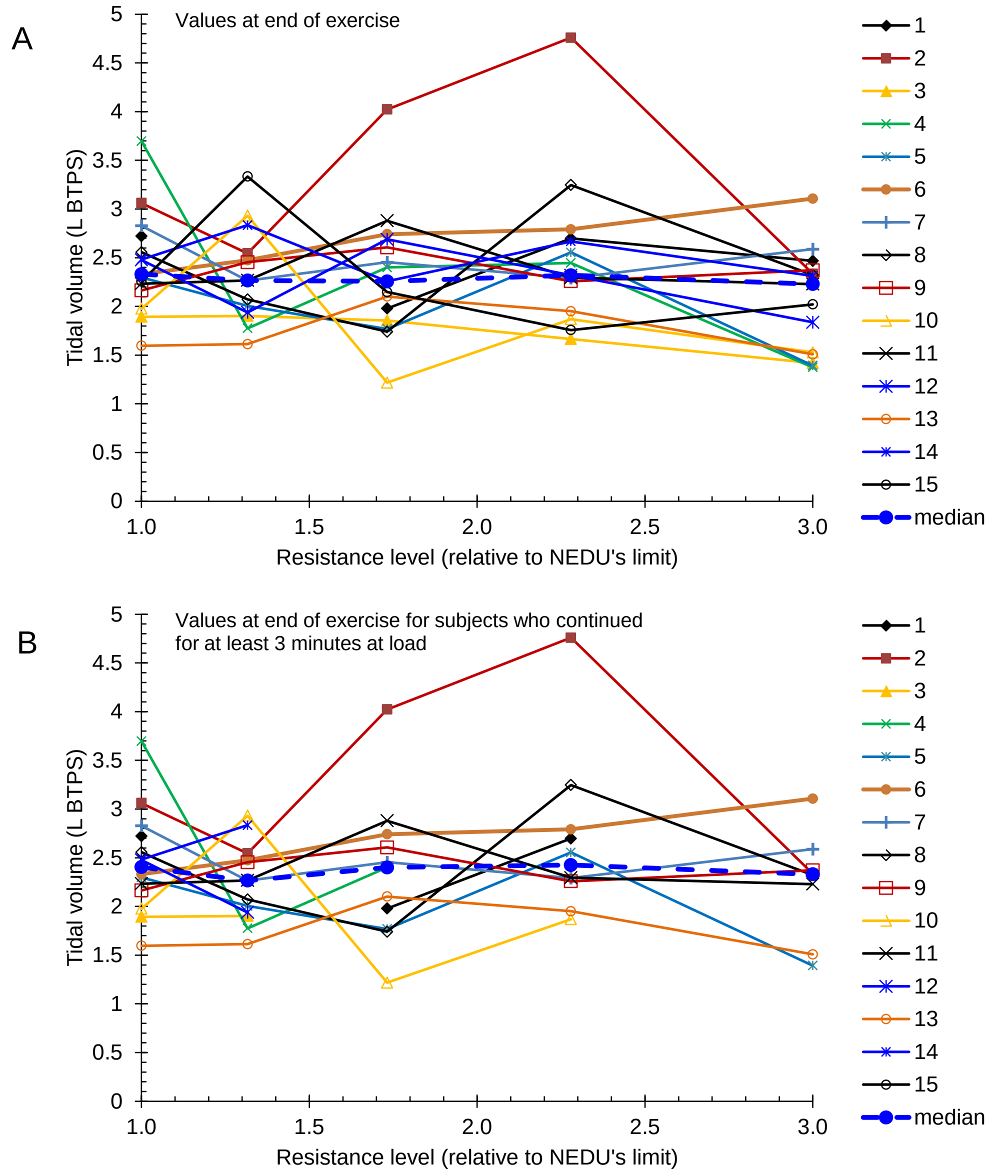


Figure 7. One minute average V_T at the end of exercise. Panel A shows values for all subjects. Panel B shows values for subjects who continued for at least 3 minutes at load.

Breathing frequency

Figure 8A shows the one-minute average breathing frequency (f_R) at end of exercise. The average slope of f_R *vs.* R-load (mean ±SE) for all subjects was -1.4 ±0.4 breaths/min per kPa of nominal WOB/V_T ($p<0.0001$). Figure 8B shows f_R for the subjects who exercised for at least 3 minutes at load. For them, the change in f_R with R was -1.8 ±0.6 breaths/min per kPa of nominal WOB/V_T ($p<0.001$). For the subjects who exercised for more than three minutes at load but for less than 60 minutes overall, the slope of f_R with R was -2.6 ±0.9 kPa CO_2 per kPa of nominal WOB/V_T ($p<0.05$).

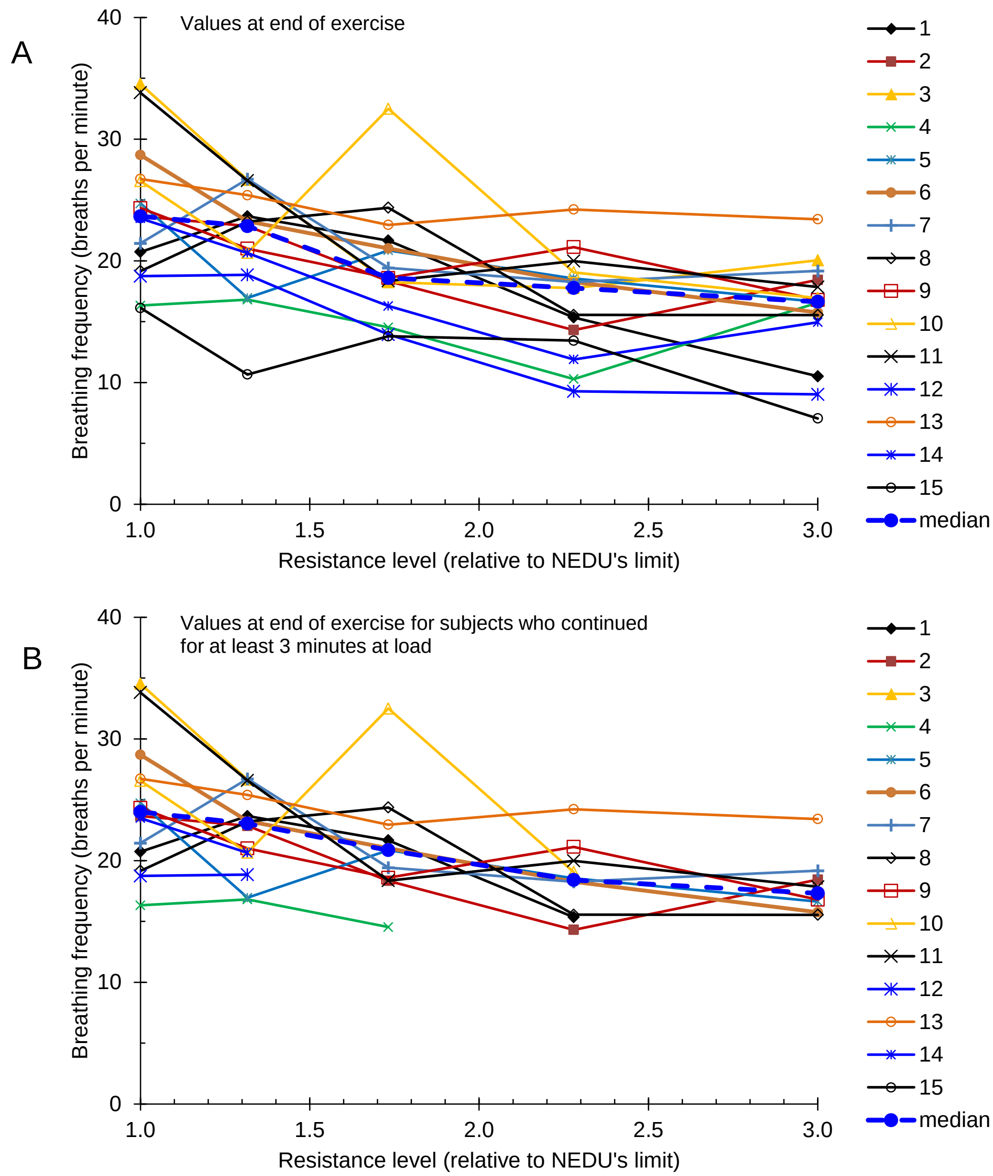


Figure 8. One minute average breathing frequency at the end of exercise. Panel A shows values for all subjects. Panel B shows values for subjects who continued for at least 3 minutes at load.

Duty cycle

Figure 9A shows the one-minute average respiratory duty cycle (T_i/T_{tot}) at end of exercise. Figure 9B shows the duty cycle for the subjects who exercised for at least six minutes overall. The slope of T_i/T_{tot} as a function of R was not different from zero. Some subjects varied their duty cycle very much, but others kept theirs essentially constant.

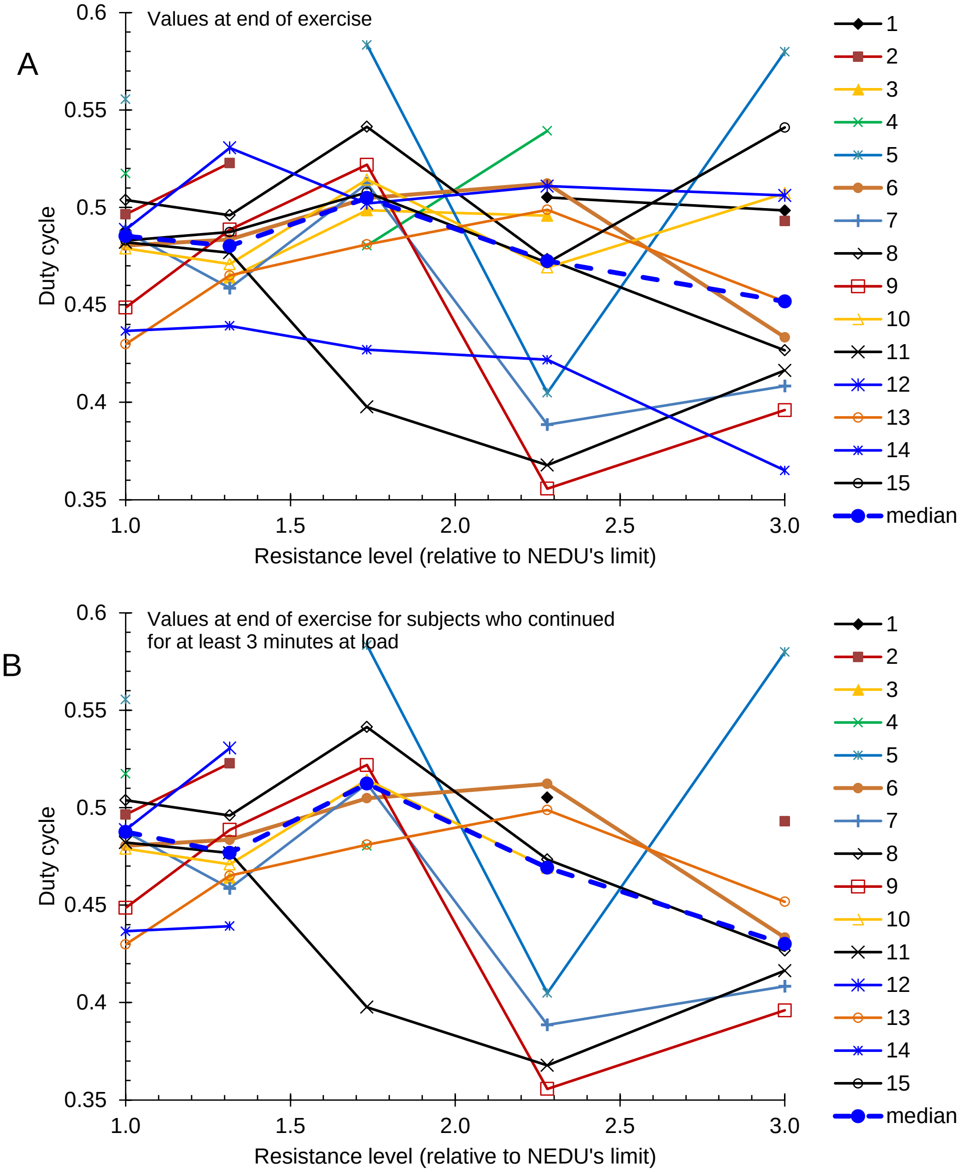


Figure 9. One minute average duty cycle at the end of exercise. Panel A shows values for all subjects. Panel B shows values for subjects who continued for at least 3 minutes at load.

Peak mask pressures

Figures 10A and 10B show the one minute average peak inspiratory and expiratory mask pressures at end of exercise. The magnitude of the pressures increased with R.

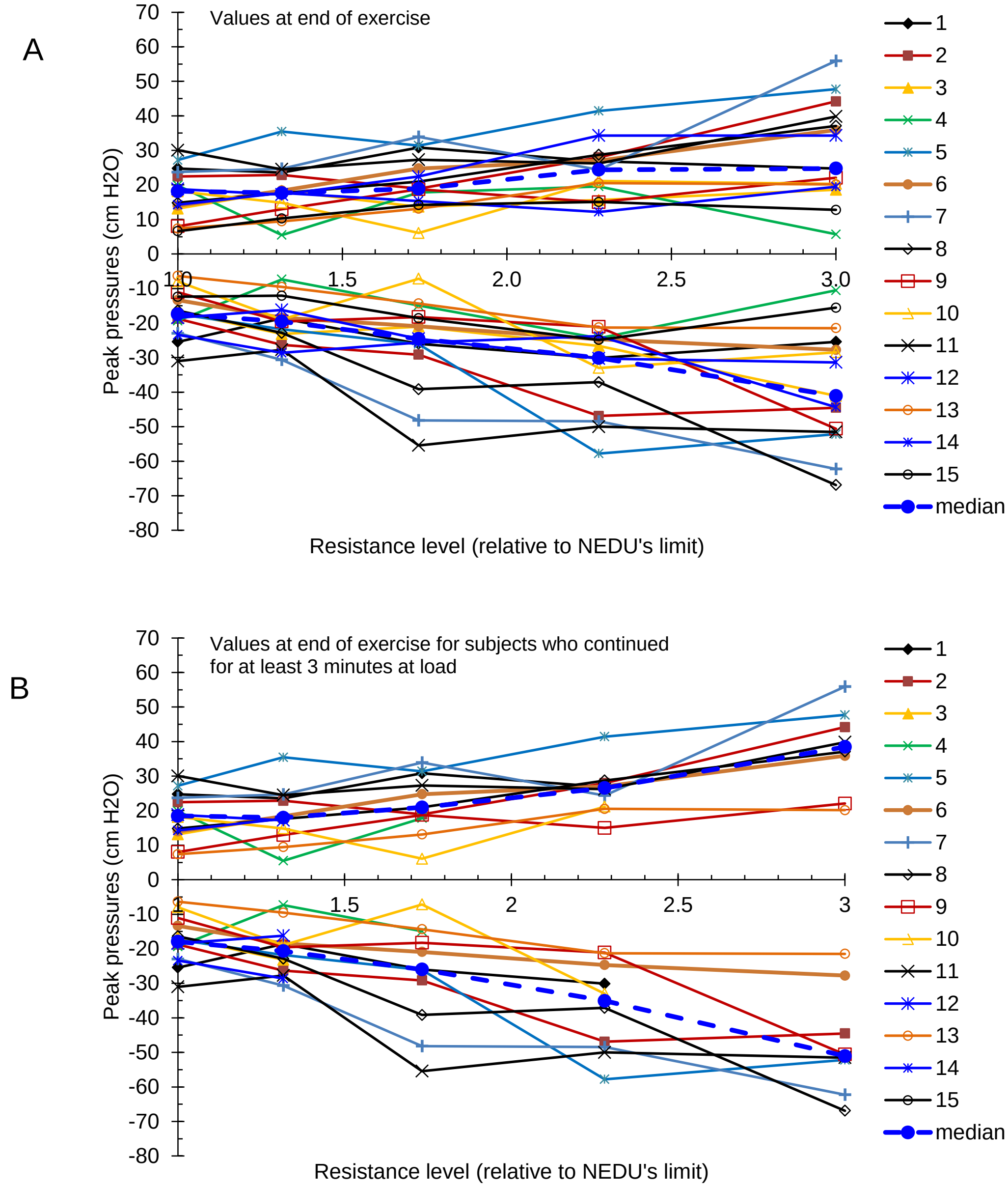


Figure 10. One minute average peak mask pressures at the end of exercise. Panel A shows values for all subjects. Panel B shows values for subjects who continued for at least 3 minutes at load.

For the inspiratory pressures for all subjects the magnitude of change was (mean ±SE) 0.37 ±0.06 kPa per kPa of nominal WOB/V_T ($p<0.0001$). For the subjects who exercised for at least three minutes at load, it was 0.41 ±0.08 kPa per nominal kPa of WOB/V_T ($p<0.001$). For the subjects who exercised for at least three minutes at load but less than 60 minutes overall, the slope of inspiratory pressure with R was 0.49 ±0.15 kPa CO_2 per kPa of nominal WOB/V_T ($p<0.01$).

For the expiratory pressures for all subjects the magnitude of change was (mean ±SE) 0.20 ±0.04 kPa per kPa of nominal WOB/V_T ($p<0.0005$). For the subjects who continued for at least three minutes at load it was 0.25 ±0.05 kPa per kPa of nominal WOB/V_T ($p<0.001$). For the subjects who exercised for between three minutes at load and 60 minutes overall, it was 0.34 ±0.09 kPa per kPa of nominal WOB/V_T ($p<0.005$).

Heart rate

Figures 11A and 11B show the one-minute average HR at end of exercise. The average slope of HR *vs.* R-load (mean ±SE) for all subjects was -3.7 ±1.0 beats/min per kPa of nominal WOB/V_T ($p<0.005$). For the subjects who continued for at least three minutes at load, it was -5.9 ±1.8 beats/min per kPa of nominal WOB/V_T ($p<0.01$). For the subjects who exercised for between three minutes at load and 60 minutes overall the slope was -8.7 ±2.1 beats/min per kPa of nominal WOB/V_T ($p<0.05$).

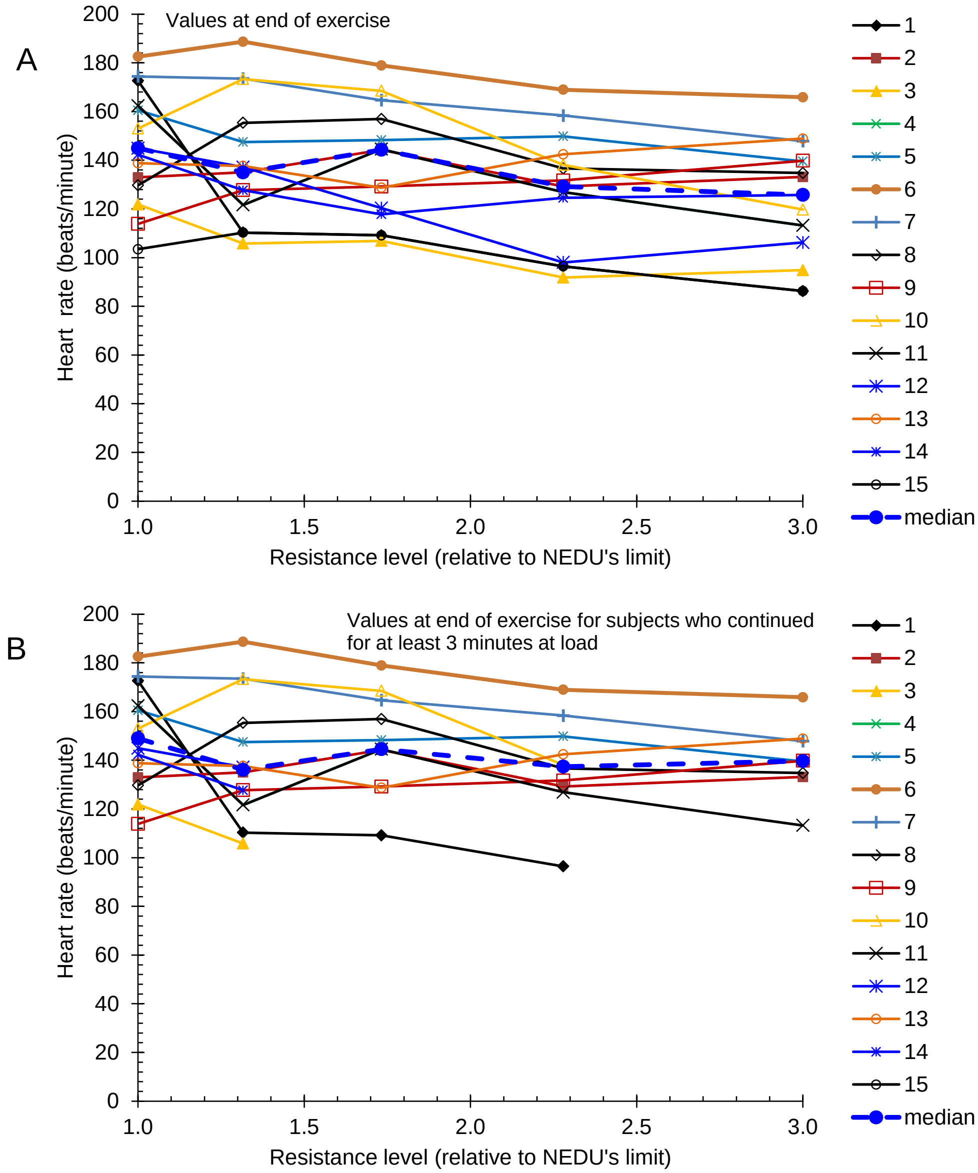
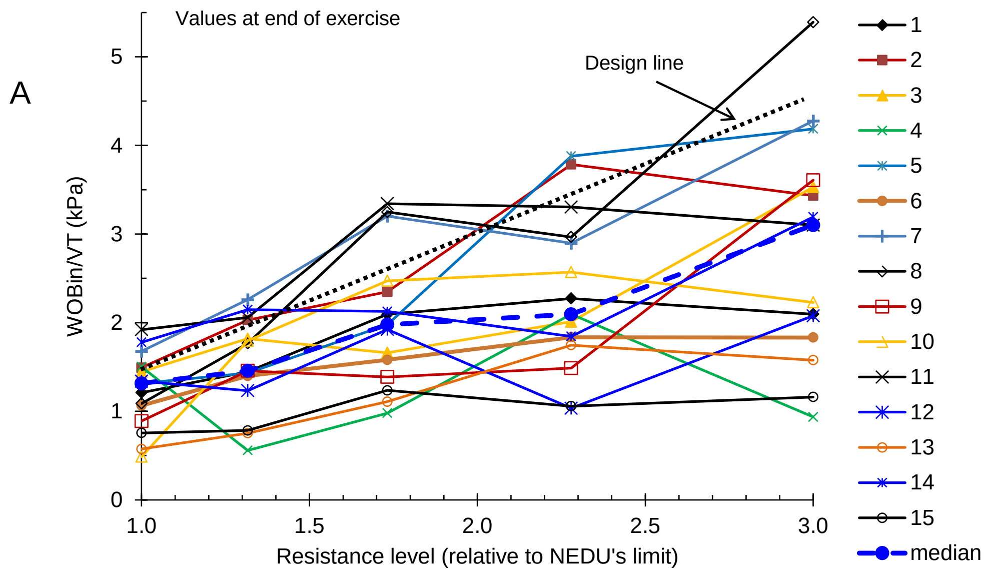


Figure 11. One-minute average heart rates at the end of exercise. Panel A shows values for all subjects. Panel B shows values for subjects who continued for at least 3 minutes at load.

Inspiratory work of breathing

Figures 12A and 12B show the average WOB_{in}/V_T during the last minute of exercise. The average slope of WOB_{in}/V_T *vs.* R-load for all subjects was (mean ±SE) 0.26 ±0.05 kPa per kPa of nominal WOB/V_T ($p<0.0001$). For the subjects who continued for at least three minutes at load it was 0.30 ±0.06 kPa per kPa of nominal WOB/V_T ($p<0.001$). For those who exercised between three and 57 min. at load, it was 0.27 ±0.08 kPa per kPa of nominal WOB/V_T ($p<0.01$). The ratio of median WOB_{in}/V_T to the nominal inspiratory value (half the total) was 83% for the subjects who exercised for at least 3 min. at load and 85% for those who exercised between 3 and 57 min. at load.



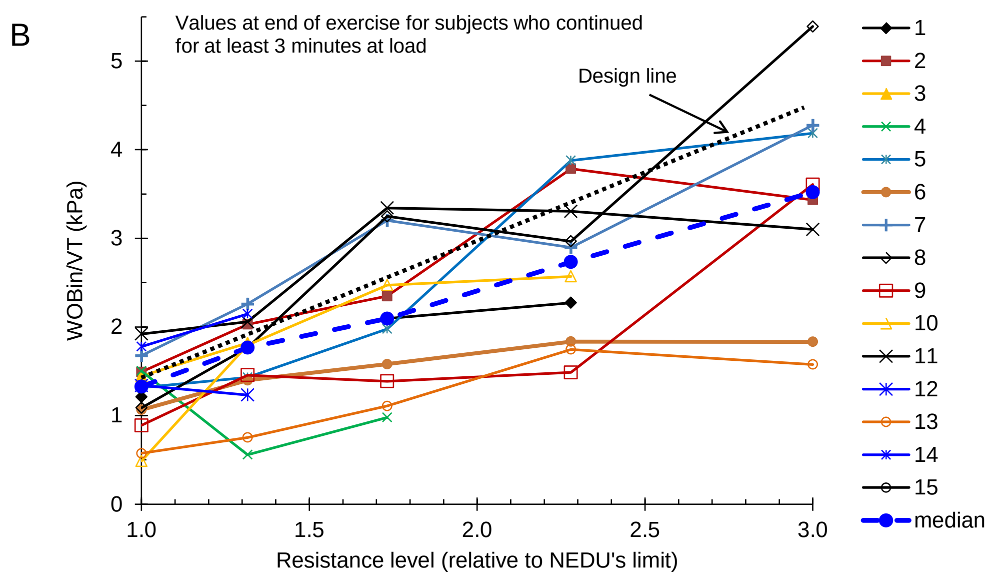
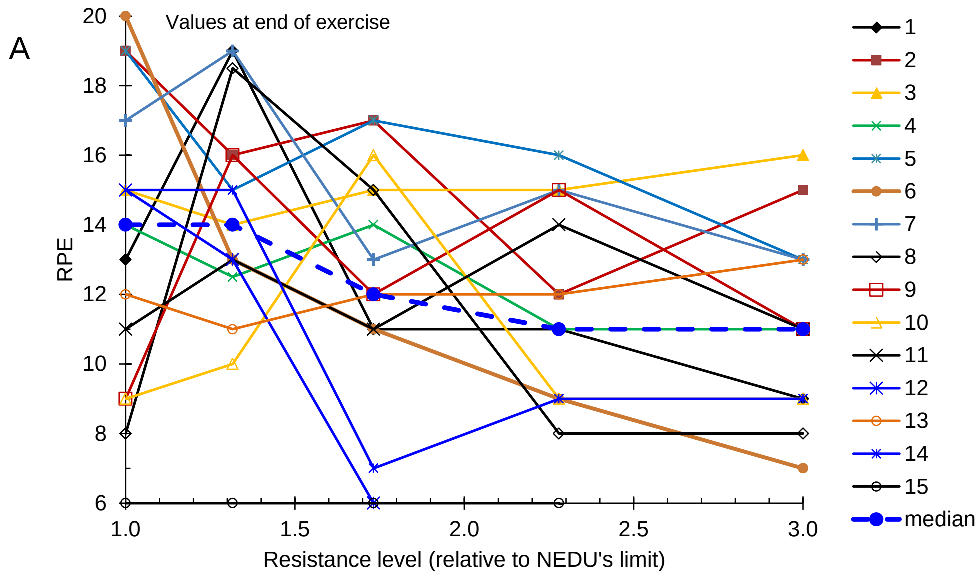


Figure 12. One minute average WOB_{in}/V_T at the end of exercise. Panel A shows values for all subjects. Panel B shows values for subjects who continued for at least 3 minutes at load. The dotted lines labelled "design line" shows $WOB_{in}/V_T = 0.5 \cdot WOB_{tot}/V_T$.

RPE and dyspnea

Figures 13A and 13B show the RPE at end of exercise, and Figure 14 shows dyspnea scores. The average slope of RPE *vs.* R-load (mean ±SE) for all subjects was -0.74 ±0.21 per kPa of WOB/V_T ($p<0.01$). For the subjects who continued for at least three minutes at load it was -0.58 ±0.20 per kPa of WOB/V_T ($p<0.05$). For the subjects who exercised between three minutes at load and 60 minutes overall, it was -1.1 ±0.40 kPa per kPa of WOB/V_T ($p<0.05$).



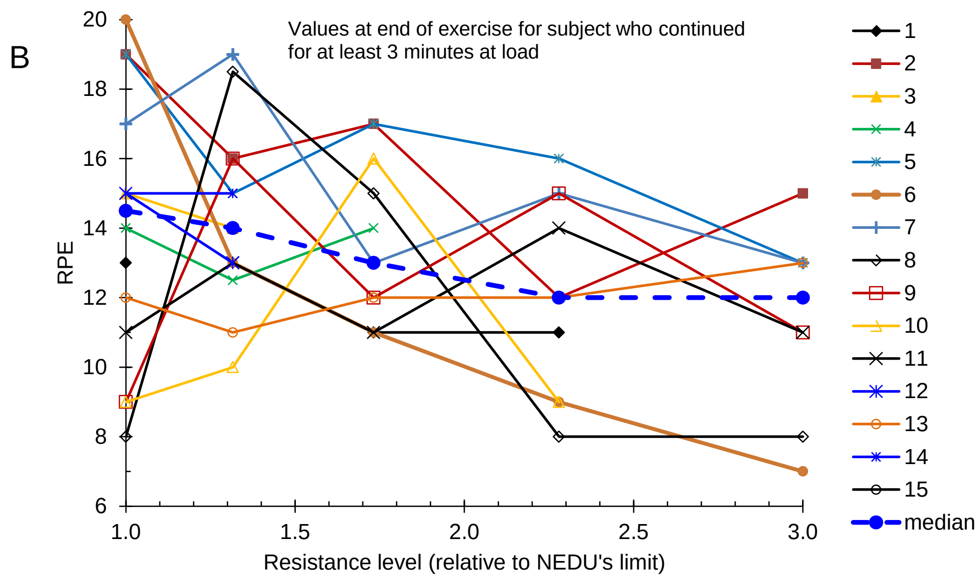


Figure 13. RPE at the end of exercise for all subjects at the end of exercise. Panel A shows values for all subjects. Panel B shows values for subjects who continued for at least 3 minutes at load.

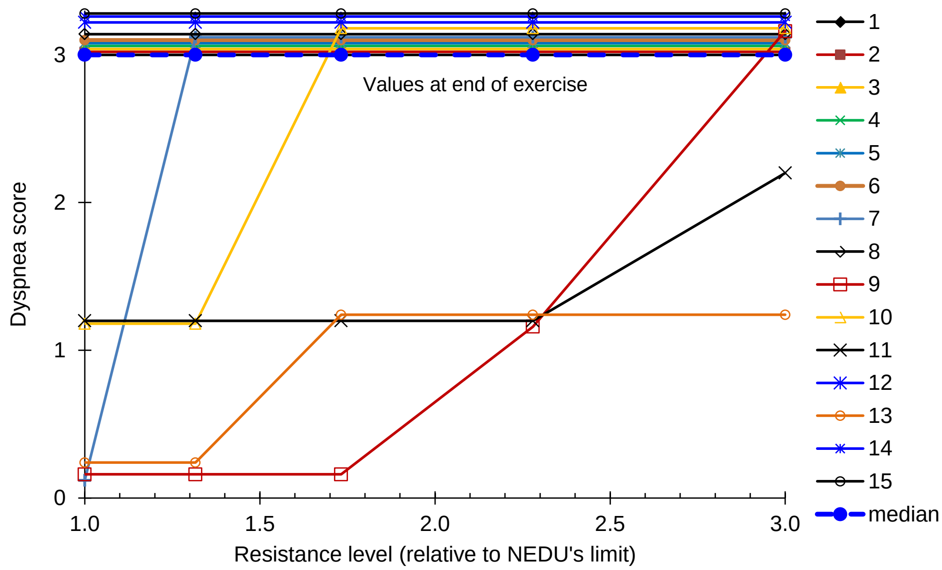


Figure 14. Dyspnea scores reported by each subject at the end of exercise. A score of 3 was assigned unless they reported that something other than breathing stopped them. For clarity, lines are separated vertically (the possibilities were 0, 1, 2 or 3).

<u>Examples of responses to very high breathing resistance</u>

In terms of $etCO_2$ values, and RPE and dyspnea scores, the subjects showed very different reactions to the breathing resistances. Figure 15 illustrates changes in a subject who managed 60 minutes with all levels of R. In early exercise (warmup ended at minute 3) the $etCO_2$ gradually climbed, leveled off and remained fairly constant after about 5 minutes. The $etCO_2$ plateau levels clearly increased from about 6.2% with R1 to about 7.2% with R5. Figure 15 also shows that the RPE scores increased gradually with time, but never became higher than 14 (“somewhat hard” to “hard”). The influence of R on RPE was less distinct than on $etCO_2$. The subject reported a dyspnea score of 1 for all resistances except R5, where it was 0.

Figure 16 shows a second person’s reaction to the resistance loads. This subject managed the full 60 minutes with R1 and R2, but the endurance time decreased slightly with R3, and very considerably with R4 and R5. The $etCO_2$ levels tended to increase with the magnitude of R (the influence of R was already noticeable during warmup), but $etCO_2$ decreased gradually after approximately 15 minutes. The RPE score for R3 reached a peak (16, “hard) after about 15 minutes, but then actually dropped two steps before the subject stopped exercise. The dyspnea scores stayed at 1 until the subject stopped with an assigned dyspnea score of 3 (for R3 and R4), except for R5 where the need to stop became urgent and the score jumped from 0 to an assigned value of 3.

Figure 17 shows a third person’s reaction, a subject who exercised for 60 minutes with the lowest resistance load, but stopped exercise much earlier with the more elevated resistances. With R1, $etCO_2$ increased at the start of exercise to about 6.9%, but decreased after about 7 minutes to about 6.3% after 60 minutes of exercise. RPE scores were moderate mid-exercise and were at 17 at the end of the hour. Dyspnea scores were 0 throughout. With R2, the $etCO_2$ increased considerably to about 7.2% at the start of exercise, but dropped quickly and was about 6% at the end of exercise. RPE scores climbed until exercise ended with a very high RPE score of 19, and dyspnea scores were 2 for about 9 minutes until exercise ended with an assigned dyspnea score of 3. With R3, $etCO_2$ increased similarly to that with R2 but remained slightly higher, with RPE scores distinctly lower than with R2, while dyspnea scores were similar to those with R2. With R4, $etCO_2$ followed a pattern similar to that of R2, RPE scores remained only slightly higher than with R3, and the subject reported a dyspnea score of 2 at 15 minutes, but then reduced it to a 1 while also lowering the $etCO_2$ values. With R5, $etCO_2$ increased similarly to R3 and R4, but stayed slightly higher for longer and then abruptly dropped before the subject quit with a RPE score of 13.

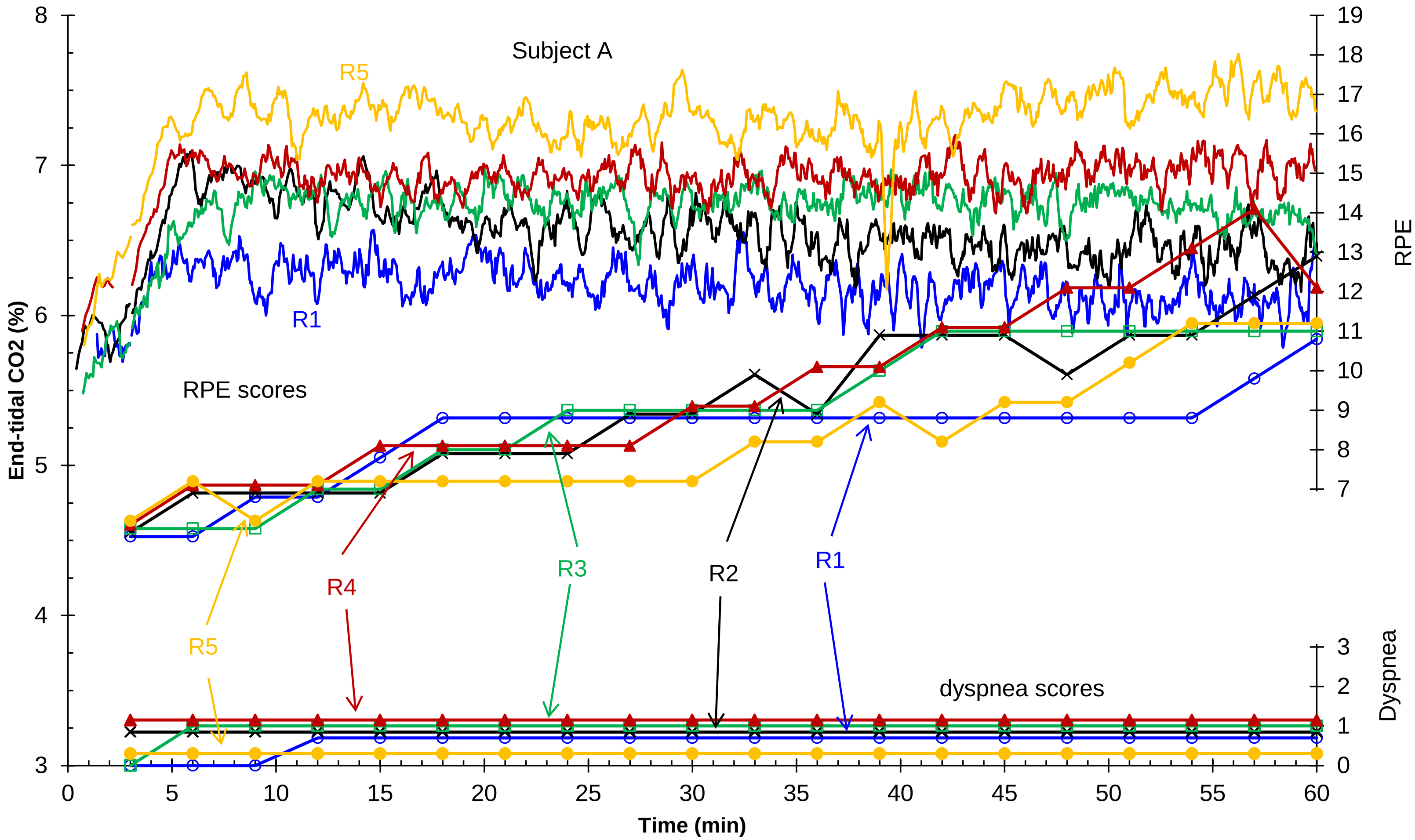


Figure 15. Time plot of subject A's end-tidal CO_2 (a nine-breath moving average), RPE and dyspnea scores for each of the resistance loads. For clarity, the lines for RPE and dyspnea have a slight vertical separation (only whole numbers were reported).

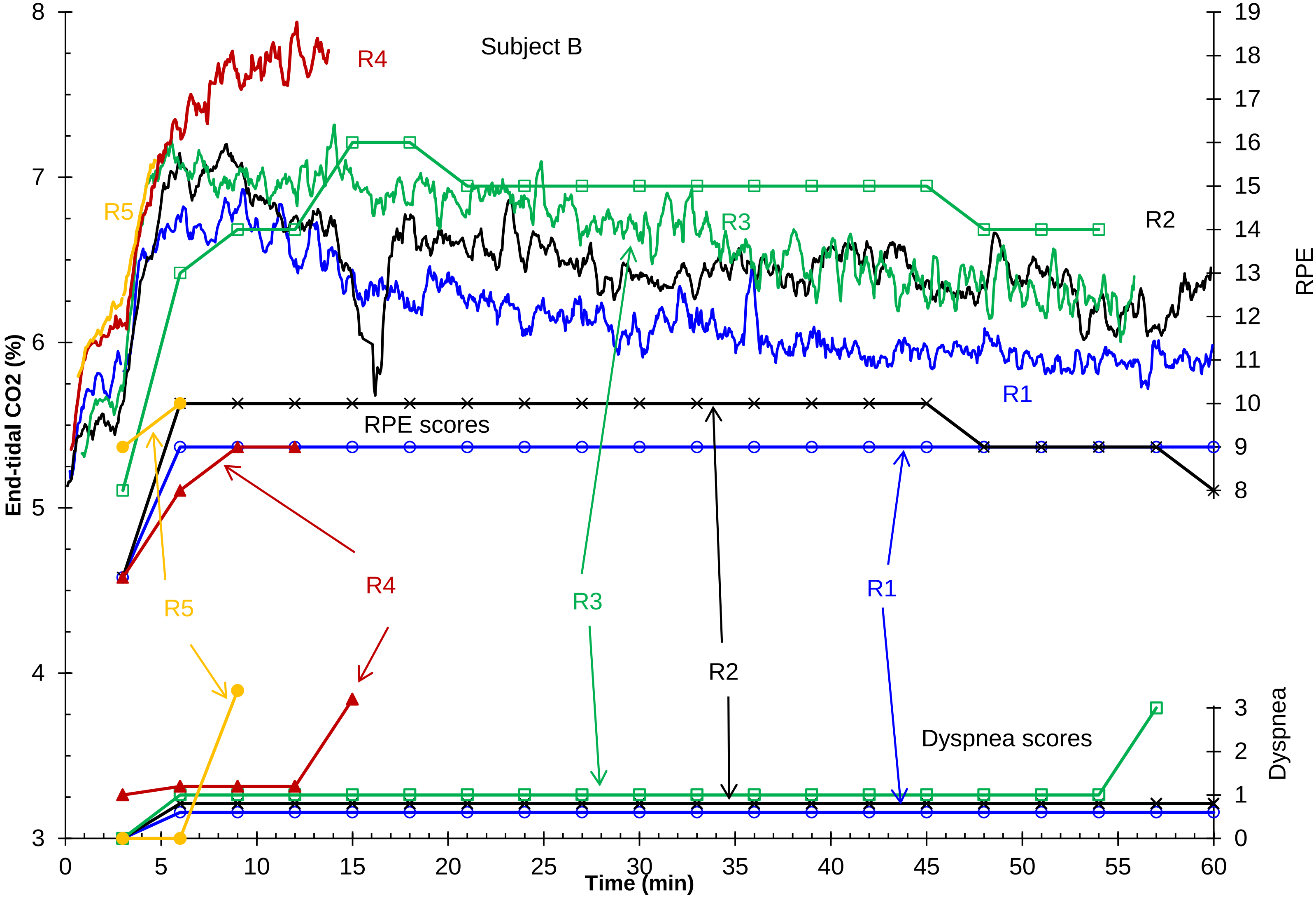


Figure 16. Time plot of subject B's end-tidal CO_2 (a nine-breath moving average), RPE and dyspnea scores for each of the resistance loads. For clarity, the lines for dyspnea have a slight vertical separation (only whole numbers were reported).

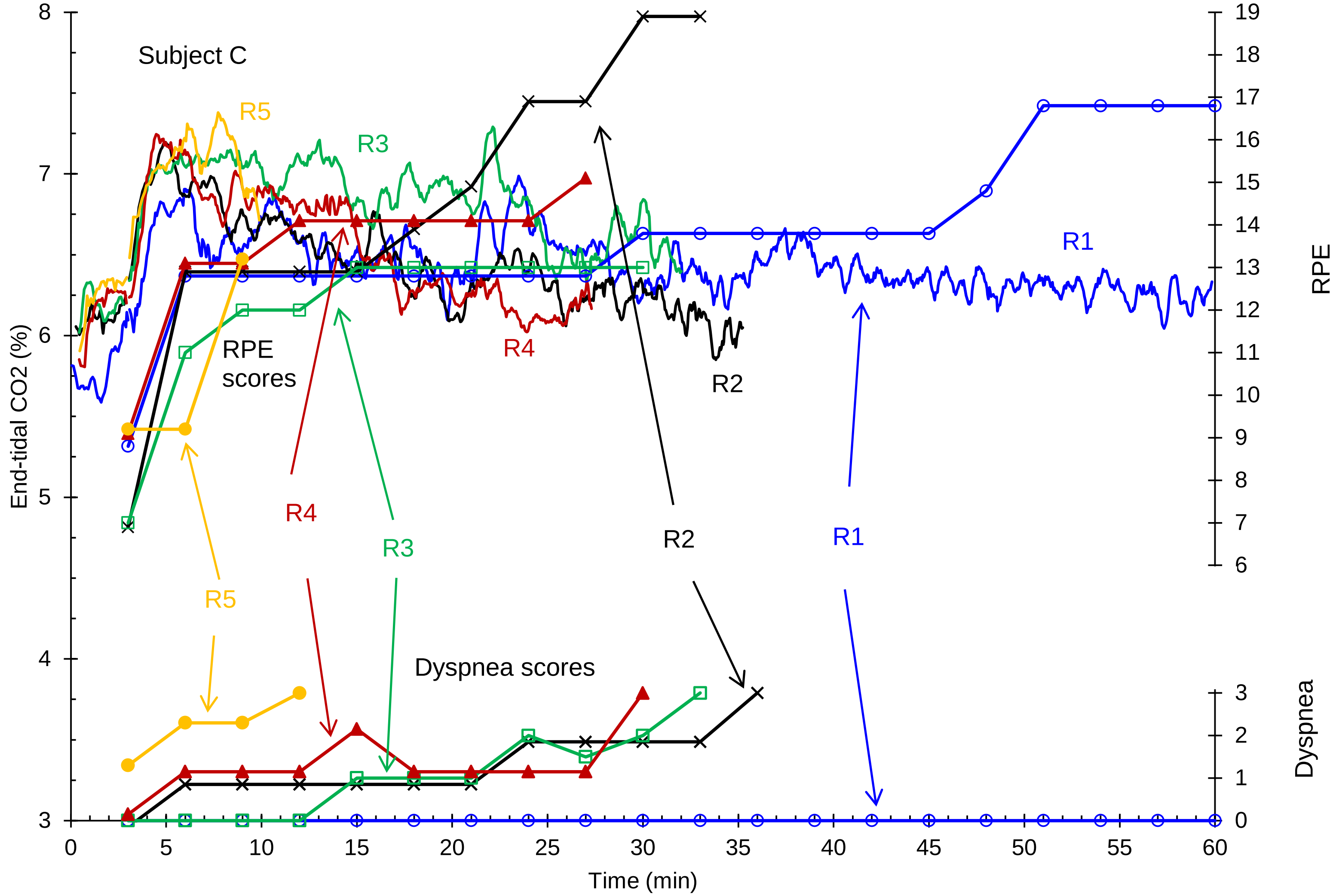


Figure 17. Time plot of subject C's end-tidal CO_2 (a nine-breath moving average), RPE and dyspnea scores for each of the resistance loads. For clarity, the lines for RPE and dyspnea have a slight vertical separation (only whole numbers were reported).

DISCUSSION

The average response is often a good descriptor for a response. However, in some circumstances, like this study where tolerance is measured, the average does not tell the whole story. Similarly, it is not sufficient when limits are set. Hence, results will be discussed mostly as averages, but some values, such as endurance times, will also be expressed as a value that the vast majority of the subjects could tolerate.

<u>Endurance times</u>

The average change in exercise endurance was -3.1 min/kPa of nominal WOB/V_T, which would mean an average decrease in endurance time of about 28 minutes if a change of WOB/V_T from 3 to 9 kPa could be tolerated. This calculation does not reflect the subjects' actual endurance time (many did not even make 28 minutes with R1). In fact, the subjects' responses to these very high breathing resistances varied drastically; some subjects managed to endure all the resistances for the full hour, while others endured them only for minutes. With R1, the endurance time met or exceeded by 75% of the subjects (calculated as the 75th percentile) was 16 minutes and for the 90th percentile it was just over 12 minutes. With R5, the 75th percentile of the endurance it was four minutes and for the 90th percentile it was less than three minutes. Overall, the endurance at a higher R was shorter than at a lower R (Figure 4), but this was not always the case. A subject's endurance at one R level is not necessarily a good predictor for the endurance at a different breathing load.

Most subjects showed a gradual reduction in endurance with increasing R. Two subjects were able to put in enough respiratory effort to last the entire 60-minute period with all levels of R. Their minute ventilations decreased with increased R, resulting in an increase in $etCO_2$. Their RPE scores increased with R and show that these two subjects sensed the necessary increase in respiratory effort as a component of total body exertion. The subject with the shortest endurance showed a minimal change in endurance when the R varied.

Based on a sample of 15 subjects of varying stature and fitness, 90% of the population can be expected to continue moderate exercise for at least 3 minutes at the warmup load of 50W with a nominal WOB_{tot}/V_T of 9 kPa. Put differently, 10% of the population will have endurance times of less than 3 minutes, and those at only the warm-up load. With a nominal WOB_{tot}/V_T of 6.8 kPa, 90% of the subjects could exercise for 4 minutes or more, a nominal WOB_{tot}/V_T of 5.2 kPa for 5 minutes or more, a nominal WOB_{tot}/V_T of 3.9 kPa for about 7 minutes or more and a nominal WOB_{tot}/V_T of 3 kPa for about 12 minutes or more. A summary of these values is shown in Table 4.

Simulated failure modes (e.g. kinked hoses, low supply pressure) can be imposed on a breathing apparatus and the resulting WOB/V_T measured. These values and values from existing breathing apparatus can be compared to the endurance times in Table 4 to judge how long wearers may last.

Table 4. The minimum time that at least an estimated 90% of the subjects could endure. The times stated include the 3 minute warmup period before the workload was increased to 60% of each subject's capacity.

Nominal WOB/V_T (kPa)	3.0	3.9	5.2	6.8	9.0
time (minutes)	12	7	5 to 6	4	3

End-tidal CO_2 levels

At no time did any subject show an $etCO_2$ close to the abort criterion of 65 Torr. This is in contrast to previous studies with lower resistances but with inspired CO_2 and heavier exercise either underwater [9] or dry [10].

The slope of 0.31 kPa CO_2/kPa WOB/V_T (90% confidence interval: 0.09 to 0.54) for the group that exercised at least 3 minutes at load would indicate that, when the nominal WOB/V_T increased by 6 kPa (from R1 to R5), the $etCO_2$ would increase by about 1.9 kPa. Thus, the $etCO_2$ would go from 6.2 to 8.1 kPa, a value not seen. The reason for this apparent impossibility is that 4 out 11 subjects had only two data points each for the calculation of the slope. For two of these four, the slope was 0.93 and for the third it was 0.52 and for the fourth it was 0.02 kPa CO_2/kPa. When the four were excluded, the slope became 0.14 kPa CO_2/kPa ($p<0.001$).

Subjects for whom the $etCO_2$ increases steeply with increasing R cannot tolerate the higher R; the climb in $etCO_2$ represents respiratory failure in face of the load.

Ventilatory patterns

On the average, $\dot{V}_E$ decreased by 10-15% when the intended WOB/V_T increased three-fold (R1 to R5). The decrease was caused by reduced breathing frequencies, as V_T did not change. The lack of influence of R level on the duty cycle may be because the imposed inspiratory and expiratory resistances were symmetrical. The large variations in duty cycle within a subject may reflect attempts to somehow ease the breathing difficulty, but as one subject put it, he “hunted for a good breathing pattern, but didn't find one”.

Inspiratory work of breathing

The calculated WOB_{in}/V_T was lower than the intended value. The calculated value was about 83% to 85% of the intended one, Figure 12. This is an expected phenomenon since subjects typically reduce their $\dot{V}_E$ when challenged by increased R (Figure 6). Individuals who lower their WOB/V_T from the designed value do so at the expense of increased $etCO_2$.

The values for WOB_{in}/V_T (Table A1) are the ones that must be used to compare breathing resistances across breathing apparatus, because that is how those are characterized during unmanned testing.

Inspiratory and expiratory peak pressures
On the average, peak inspiratory pressures increased more with increasing R than did the expiratory pressures.

Population values for maximum expiratory pressures for single breaths have been reported by one source as 14.9 (SD=3.5) kPa in women, 24.2 (SD=4.6) kPa in 29 year-old men and 15.6 (SD=6.4) kPa in 59 year-old men [11]; and by another source, as 13 ± 2.6 kPa in men and 10 ±1.8 kPa in women [12]. Maximum inspiratory pressures have similarly been reported at -10.2 (SD=1.9) kPa in women, -13.6 (SD=4.0) kPa in 29 year-old men and -11.1 (SD=3.1) kPa in 59 year-old men [11]; and in gender-mixed subjects as -15 kPa [13].

Maximum voluntary inspiratory and expiratory pressures during dive experiments [1] were about ±10 kPa, independent of depth (15 and 190 fsw, 4.5 and 57 fsw). In this study, the subject's individual, single-breath, maximum pressures were not measured, but the highest inspiratory and expiratory mask pressures seen for R5 (±6 to 7 kPa, ca ±60 to 70 cm H_2O), Figure 10, were below 70% of the lowest pressures reported in the literature. A large expiratory pressure makes the mask try to lift off the face, limiting possible expiratory pressures. The straps holding the masks had to be very tight, but even so, for one subject in particular the seal was hard to maintain during expiration.

Dyspnea, RPE scores and symptoms
One might think that an increasing R would always induce the same or increasing dyspnea, akin to the dyspnea scores shown for one subject in Figure 17. However, this is contradicted by the scores shown in Figure 15 where the subject had the lowest dyspnea scores with the highest R. Thus, a report of low dyspnea does not necessarily correspond to low or moderate breathing resistance. What individuals detect as dyspnea is not as straight-forward as simply the pressure needed to move air or the ability to maintain desired CO_2 levels. In fact, the sensation of dyspnea is possibly related to the ability to match respiratory drive with ventilation, and respiratory drive may be decreased in the presence of large WOB/V_T [9].

For some subjects the need to stop exercise came on very quickly.

Some subjects noticed inspiratory R more than expiratory R, while for others it was the opposite, although resistance was always symmetrical.

Even R1 provided high enough WOB_{tot}/V_T that subjects had a minimal chance to "catch up" on $\dot{V}_E$ after a short breathing interruption due to a cough or a sniffle.

If the limitation to exercise as R increases, becomes the difficulty in breathing, one might expect that the RPE scores at the end of exercise would decrease with increasing R. This appears to be the case; the median RPE score at the end of exercise with R5 in those subject who completed at least 3 minutes at load corresponded to "somewhat hard" and only one subject exceeded an RPE of 14. Two people scored the effort "very light" after stopping. A factor other than perceived effort is causing subjects to stop exercise.

Comparison to published limits on breathing resistance

The National Institute for Occupational Safety and Health (NIOSH) certifies respiratory protective devices for the U.S. [14], including those for Navy non-diving applications. The Navy has some 200,000 non-diving units for escape from ships. Many of the tests use a constant flow to judge breathing resistance, but for the closed-circuit escape respirators like those owned by the U.S. Navy, testing is done with sinusoidal breathing generated by a breathing machine (subpart O of 42 CFR 84). Subpart O includes two limits: "the peak expiratory-to-inspiratory pressure swing shall not exceed 200 mm H_2O" (ca. 2 kPa) and "excursions (lasting less than 1 minute) shall not exceed -300 to +200 mm H_2O" (ca. -3 to +2 kPa). For the subjects in this study the first limit was exceeded with R1. However, the much larger excursion range was not exceeded below R4. Thus, according to NIOSH, R3 and lower would be acceptable for use for less than 1 minute. For R3 the minimum endurance time was 5 minutes and 90% of the present group of subjects managed 6 minutes.

The physiologically acceptable values [3] adopted by the International Standards Organization [5] allow a maximum WOB_{tot}/V_T of 1.8 kPa from breathing apparatus designed for extended use. That limit was, by design, exceeded in this study. The short endurance times achieved confirm that the R levels used in this study are indeed excessive for long term exposure. However, for short term exposures the present results can provide guidance for minute ventilations in the range tested here. This range was 36 to 63 L/min (10 to 90% of measured values) for subjects who exercised for at least three minutes at load. These minute ventilations can be expected from a 70 kg man who works "full work shifts including breaks" to "continuous work for up to 2 h without breaks" [14].

Thus, if an endurance time of 10 minutes is needed for moderate work, then a WOB_{tot}/V_T of 3.2 kPa is likely to be manageable by at least 90% of wearers (using linear interpolation between adjacent values). Similarly, a 5-minute endurance time can be expected to be achieved with a WOB_{tot}/V_T of up to 5.5 kPa. Linear extrapolation to an R lower than R1 and R2 indicates that a WOB_{tot}/V_T of 2.6 kPa is likely to be manageable by 90% of the population for 15 minutes. A summary of these values is shown in Table 5.

Table 5. The maximum WOB/V_T that is likely to allow a desired endurance time (estimated from the 50, 75 and 90th percentiles). The times stated include the 3 minute warmup period before the workload was increased to 60% of each subject's capacity.

maximum desired time (minutes)		5	10	15
maximum, nominal WOB/V_T (kPa)	50th	-	6.8	5.8
	75th	6.7	4.7	3.4
	90th	6.0	4.0	2.6‡

‡see text

NEDU's limits for work of breathing, the current Navy diving standards, allow higher WOB_{tot}/V_T than do the NIOSH and ISO standards. The acceptable WOB/V_T under the NEDU limits varies with depth, but R1 for this study was designed to match the 1 atm (surface) limit, 3.0 kPa [6] [15]. NEDU's limits originate from a set of 96 diving experiments [1] conducted at two depths at the University at Buffalo. Those limits were set such that all of the subjects could manage 25 minutes of moderate exercise without excessive end-tidal CO_2 or excessive dyspnea. In this non-diving situation, the median endurance time with R1 exceeded 30 minutes. Only 9 of 15 subjects managed 25 minutes of moderate exercise. Calculated as the 90th percentile the endurance time was only 12 minutes or more. Thus, by the criteria used to determine the diving limits, the present study finds that a WOB_{tot}/V_T of 3.0 kPa is too high for use in the dry at 1 atm. However, any suggested changes for diving standards should await results of the second phase of this study which will be carried out under water.

Demographics

The subjects represented a large variety in age, size and physical fitness. Due to the population of potential subjects that we could draw from, only one woman took part.

SUMMARY

The response to high R varied greatly from subject to subject. On the average, the high breathing resistance reduced the endurance time. However, the spread in endurance times with any R ranged from a few minutes to the maximum permitted time of one hour.

NEDU's diving limit for WOB_{tot}/V_T of 3 kPa at the surface cannot be extrapolated for use in the dry at 1 atm. The NIOSH and ISO limits may fit better.

The high breathing resistance reduced the $\dot{V}_E$ through a reduction in breathing frequency with unchanged V_T. There was no consistent change in respiratory duty cycle.

On the average, the expired CO_2 levels increased with increased R, with a slope of 0.1 kPa per kPa of nominal WOB/V_T. The inter-individual spread in end-tidal CO_2 was large, ranging from 5% to 7.7%. There was no more serious CO_2 retention.

Even with R being imposed equally on inspiration and expiration, some subjects noticed R more on one phase than on the other. Some subjects reported that they couldn't breathe fast enough and stopped exercise, while some reported that leg fatigue made them stop. One subject was close to removing the mask, while another felt claustrophobic after 2 minutes but recovered and continued to exercise for the maximum time of an hour.

CONCLUSIONS

The purpose of this study was to determine the effects of different levels of very high breathing resistance on endurance exercise at a moderate work rate. These values that can be estimated are listed in Table 5. However, individual reactions to very high breathing resistance are not predictable. If breathing resistance increases beyond normal limits, exercise endurance at moderate work will be severely restricted for the vast majority of people, but there may be some people who can overcome even very high breathing resistance.

RECOMMENDATIONS

Existing values from unmanned tests of breathing apparatus can be compared to the results found in this study to judge likely endurance times of wearers. Similarly, possible failure modes can be imposed on existing breathing equipment and the resulting WOB_{tot}/V_T values used to judge likely endurance times.

NEDU's limits for acceptable breathing resistance should not be relaxed; they may need to be tightened.

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APPENDIX A

Table A1. Work of breathing values per tidal volume in kPa (i.e. the volume average pressure, WOB/V_T) for each combination of minute ventilation and opening size.

Minute ventilation	V_T	f	Size of opening in the resistance element (inches and mm)														
L/min	L	breaths/ minute	0.40 10.2	0.38 9.7	0.36 9.1	0.34 8.6	0.32 8.1	0.30 7.6	0.28 7.1	0.26 6.6	0.24 6.1	0.22 5.6	0.20 5.1	0.18 4.6	0.16 4.1	0.14 3.6	0.12 3.0
15	1.5	10	0.20	0.22	0.25	0.29	0.33	0.39	0.50	0.62	0.76	1.00	1.31	1.62	2.12	2.59	3.30
22.5	1.5	15	0.35	0.40	0.48	0.56	0.64	0.77	1.01	1.25	1.54	2.01	2.62	3.16	4.00	4.74	5.74
34	1.9	18	-	-	-	-	-	1.61	2.07	2.58	3.13	3.93	4.93	5.77	6.88	7.58	-
40	2.0	20	0.91	1.03	1.27	1.53	1.73	2.14	2.73	3.35	4.01	4.96	6.08	6.95	7.91	-	-
50	2.5	20	-	-	-	-	2.57	3.06	3.84	4.64	5.49	6.53	7.64	8.29	-	-	-
62.5	2.5	25	2.02	2.30	2.81	3.28	3.76	4.47	5.56	6.61	7.63	-	-	-	-	-	-
75	3.0	25	2.77	3.13	3.77	4.38	4.99	5.85	7.10	8.24	-	-	-	-	-	-	-
85	2.5	34	3.41	3.87	4.64	5.37	6.07	6.99	8.09	-	-	-	-	-	-	-	-
90	3.0	30	3.82	4.27	5.14	5.94	6.72	7.78	-	-	-	-	-	-	-	-	-
105	3.0	35	4.73	5.26	6.19	7.03	7.68	-	-	-	-	-	-	-	-	-	-
135	3.0	45	6.92	7.62	8.52	-	-	-	-	-	-	-	-	-	-	-	-

Note. The purpose of the measurements was to obtain values close to the desired range of 3 to 9 kPa. Hence no data was collected at some minute ventilations. The breathing simulator has an automatic system that stops it if the instantaneous pressure is high enough (ca 7 kPa) to risk causing damage to the simulator system. This safety feature restricts the WOB values to less than approximately 8.5 kPa. Extrapolation was used to get values of 9 kPa.

Table A2. Mean and standard deviation (SD) of respiratory parameters and heart rate for all subjects.

		Resistance level									
		R1		R2		R3		R4		R5	
Parameter	units	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
$etCO_2$	%	6.18	0.48	6.44	0.62	6.53	0.63	6.65	0.53	6.69	0.49
$\dot{V}_E$	$L \cdot min^{-1}$ ‡	55.4	10.7	50.7	12.9	43.6	11.8	40.0	14.0	33.0	10.5
VT	L‡	2.44	0.51	2.31	0.48	2.32	0.65	2.50	0.75	2.05	0.52
f	min^{-1}	23.9	5.6	21.6	4.4	19.7	4.8	16.5	4.1	15.9	4.3
duty cycle		0.48	0.03	0.48	0.03	0.50	0.05	0.46	0.06	0.46	0.06
$P_{mask,ex}$	kPa	17.5	7.2	18.2	7.4	20.6	7.8	23.7	7.9	29.2	14.1
$P_{mask,in}$	kPa	-17.4	6.6	-20.1	6.9	-26.0	12.9	-33.4	11.9	-38.3	16.9
Heart rate	min^{-1}	146	23	138	25	138	23	128	23	124	24
WOB_{in}/V_T	kPa	1.24	0.43	1.53	0.53	2.05	0.77	2.32	0.90	2.84	1.27
RPE		13.5	4.3	14.1	3.5	12.2	3.7	10.8	4.2	9.7	4.7

‡Volumes are given in BTPS.

Table A3. Mean and standard deviation (SD) of respiratory parameters and heart rate for all subjects who continued exercise for at least 3 minutes at load.

		Resistance level									
		R1		R2		R3		R4		R5	
Parameter	units	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
$etCO_2$	%	6.14	0.46	6.36	0.55	6.33	0.60	6.60	0.60	6.78	0.58
$\dot{V}_E$	L·min^{-1} ‡	57.0	9.0	52.4	11.9	47.8	10.4	47.9	9.2	39.1	8.0
V_T	L‡	2.45	0.53	2.24	0.40	2.36	0.74	2.67	0.84	2.23	0.56
f	min^{-1}	24.5	5.3	22.4	3.4	21.1	4.6	18.5	3.0	17.9	2.5
duty cycle		0.48	0.03	0.48	0.03	0.50	0.05	0.44	0.06	0.45	0.06
$P_{mask,ex}$	kPa	18.3	6.8	18.8	7.4	22.2	8.5	25.9	6.9	37.9	12.2
$P_{mask,in}$	kPa	-17.8	6.7	-20.7	6.7	-27.2	14.9	-37.0	13.1	-47.1	15.7
Heart rate	min^{-1}	149	21	143	24	147	20	138	20	140	15
WOB_{in}/V_T	kPa	1.27	0.42	1.59	0.52	2.16	0.85	2.67	0.84	3.43	1.27
RPE		14.0	3.9	14.3	2.6	13.5	2.4	12.1	2.8	11.4	2.7

‡Volumes are given in BTPS.

Table A4. Mean and standard deviation (SD) of respiratory parameters and heart rate for all subjects who continued exercise for at least 3 minutes at load, but less than 60 minutes.

		Resistance level									
		R1		R2		R3		R4		R5	
Parameter	units	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
$etCO_2$	%	6.12	0.57	6.35	0.66	6.17	0.63	6.60	0.70	6.70	0.60
$\dot{V}_E$	L·min^{-1} ‡	57.3	8.1	47.1	20.9	47.2	12.2	48.3	11.2	39.7	9.3
VT	L‡	2.61	0.52	1.98	0.77	2.29	0.85	2.89	0.93	2.35	0.56
F	min^{-1}	23.3	5.6	22.0	3.6	21.6	5.2	17.0	1.9	17.1	1.5
duty cycle		0.50	0.03	0.48	0.03	0.52	0.04	0.46	0.05	0.46	0.07
$P_{mask,ex}$	kPa	18.8	5.1	20.1	7.6	23.1	9.2	28.2	6.4	40.5	11.6
$P_{mask,in}$	kPa	-18.8	3.7	-21.4	6.7	-26.5	13.0	-39.7	11.7	-50.7	13.9
Heart rate	min^{-1}	150	21	140	27	152	21	140	23	143	12
WOB_{in}/V_T	kPa	1.36	0.23	1.46	0.72	2.24	0.77	2.89	0.75	3.79	1.18
RPE		15.3	3.7	13.6	5.3	14.3	2.4	11.4	3.1	11.2	3.1

‡Volumes are given in BTPS.

Table A5. Compiled list of subject comments related to breathing and exercise. The order is not related to the subject order, nor consistent across columns. Some subjects had no comments.

Resistance level				
R1	R2	R3	R4	R5
Legs stopped the subject. Felt exactly like the MK16 diving rebreather. Got behind on breathing and couldn't catch up when sniffling condensation through nose. Respiratory muscle ache. Could feel the muscle workload from the previous test (which was two days earlier, with R5). Suspects that this is the easiest R. Easier to exhale than to inhale. You can always push it out.	Nose was runny, couldn't clear nose fast enough. Inhalation was hard, got a headache behind the right eye in phase with inhalation. Went away when mask was removed. Exercise was steady, not limiting. Legs were 100% of reason for stopping. Tried different breathing patterns and pedal speeds. After 2 min felt claustro-phobic, but improved and continued for 60 minutes. Easier to exhale than to inhale, just couldn't get enough.	Could inhale. Couldn't exhale enough. Would have removed mask after another 2 min. Inspiration is a pain. Couldn't exhale fast enough before he needed to inhale. Couldn't breathe enough.	Harder to exhale than to inhale. Was able to inhale. Exhalation was much harder. Couldn't catch up. Couldn't catch up after yawning. Harder to inhale. Hunted for a good breathing pattern, but didn't find one. Couldn't exhale enough before subject needed to inhale. Workload was very easy. Felt panicky.	A sudden onset of need to stop. Inhalation was harder than exhalation. Ears kept popping. Couldn't inhale enough. Swallowed and couldn't catch up. Harder to exhale. Couldn't exhale fast enough before I had to breathe in. Thought that this was the hardest. Couldn't exhale enough before subject had to inhale again. "Definitely the hardest so far". Slightly harder to exhale than to inhale. Harder to exhale.