Undersea Biomedical Research, Vol. 19, No. 2, 1992

Static lung load and posture effects on pulmonary mechanics and comfort in underwater exercise

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Derion T, Reddan WG, Lanphier EH. Static lung load and posture effects on pulmonary mechanics and comfort in underwater exercise. Undersea Biomed Res 1992; 19(2):85–96.—Static lung load (SLL), or transrespiratory pressure gradient, imposed by underwater breathing apparatus can affect breathing comfort and mechanics, especially during exertion. We examined the effects of body position and SLL on two factors known to affect or limit exertion: a) tidal flow-volume limitation, i.e., the percentage of the tidal volume that meets the boundary of the maximum expiratory flow-volume curve; and b) breathing discomfort. Eight healthy male scuba divers (28 ± 4 yr) performed cycle ergometry to exhaustion during immersion in each of four combinations of body position and SLL: upright, prone, +10 cmH_2O, −10 cmH_2O. SLL was referenced to the sternal notch. Tidal flow-volume limitation was significantly greater with the negative SLL ($P < 0.05$). In the prone position, higher expiratory flows were achieved ($P < 0.01$) and flow limitation was not significantly increased. Respiratory discomfort was quantified with a psychophysical rating scale and increased significantly as exercise intensity increased ($P < 0.01$). No effect of posture or SLL on discomfort was found. We conclude that, although respiratory comfort is unaffected, positive static lung loading and the prone body position minimize adverse changes in respiratory mechanics during exercise in immersion.

immersion
pressure breathing
respiration
posture
dyspnea
breathing apparatus
ventilation
flow limitation

A transrespiratory pressure gradient or static lung load (SLL) exists when inspired gas pressure differs from the hydrostatic pressure on the chest. Immersion in water engenders a negative SLL and decreases the expiratory reserve volume (ERV) (1). This effect is most profound when a diver is in the upright position (2) because the chest is subjected to a vertical hydrostatic pressure gradient that is absent when the diver is prone.

Hydrostatic pressure imbalance is inherent also in underwater breathing apparatus; the SLL imparted by a diver's breathing apparatus must be both physiologically and subjectively tolerable. This is especially important during exertion when increases in ventilation can cause expiratory flow to approach or reach the effort-independent portion of the maximal expiratory flow-volume (MEFV) curve. Such perturbations could prevent further increases in ventilation (3) and limit exertion. However, increases in the ERV produced by a positive SLL (4) or by postural changes may facilitate increases in expiratory flow and ventilation.

Breathing discomfort (dyspnea) is another factor that may limit exertion underwater (5–7). Respiratory comfort is affected by the hydrostatic pressure imbalance of breathing apparatus, especially as the diver's activity level increases (5, 8, 9) or as the diver changes body position (9). Through use of a psychophysical scale (10) for quantification of breathing discomfort, we previously found a significant increase in dyspnea for SLLs greater than ± 10 cmH_2O (referenced to the sternal notch) during submaximal exercise (11). Furthermore, at rest, dyspnea was significantly greater in the upright position at the extreme negative SLLs (-15 and -20 cmH_2O) (11).

The purpose of the present study was to examine, during immersion, the effects of body position and SLL during moderate and exhaustive exercise on two factors known to affect or limit exertion: a) tidal flow-volume limitation, i.e., the percentage of the tidal volume (V_T) that meets the boundary of the MEFV curve; and b) breathing discomfort. We used the extremes of the SLL "comfort range" (± 10 cmH_2O referenced to the sternal notch) (11) to investigate these factors in 8 normal male divers performing cycle ergometry in the upright and prone body positions during immersion at 1 atm abs (3.063 kPa).

METHODS

Subjects

Eight nonsmoking, healthy male, certified scuba divers with no history of cardiopulmonary disease served as subjects. On the first visit to the laboratory, each subject was informed of the design and possible hazards of the study and signed a consent form approved by the University of Wisconsin-Madison Committee for the Protection of Human Subjects. In addition, anthropometric and standard pulmonary function data were gathered, and a maximal oxygen consumption ($\dot{V}O_2max$) test was administered on land (Table 1). The $\dot{V}O_2max$ test was conducted using a modified Balke

TABLE 1
PHYSICAL AND FUNCTIONAL CHARACTERISTICS OF THE SUBJECTS

Subject	Age, yr	Height, cm	Weight, kg	FVC, l BTPS	MVV, $l \cdot min^{-1}$ BTPS	$\dot{V}O_2max$, $l \cdot min^{-1} \cdot kg^{-1}$ STPD
1	31	189	82	6.6	195	59.9
2	30	188	80	6.7	214	44.5
3	25	180	77	5.2	216	41.3
4	22	173	63	4.9	191	65.4
5	33	183	79	6.2	210	46.9
6	28	178	80	5.2	197	51.9
7	23	173	71	4.8	182	38.3
8	30	183	80	5.2	190	44.5
Mean	28	181	77	5.6	199	49.1
SD	4	6	6	0.8	13	9.4

Key: FVC = forced vital capacity; MVV = maximum voluntary ventilation; $\dot{V}O_2max$ = maximal oxygen uptake, upright on land.

protocol (12), with the subject seated upright on the same cycle ergometer used for exercise during immersion. Each subject subsequently returned to the laboratory on each of four different (nonconsecutive) days for the immersion experiments, which are explained below.

Experimental design

In the immersion experiments, each subject performed moderate and exhaustive exercise (*see* below) on the cycle ergometer in a 3.0 × 1.8 × 1.5-m water tank (Fig. 1). Each day, a subject exercised in only one of the following four combinations of posture and SLL (referenced to the suprasternal notch): U+: upright position with +10 cmH_2O (+0.99 kPa); U−: upright position with −10 cmH_2O; P+: prone position with +10 cmH_2O; P−: prone position with −10 cmH_2O. The order of the conditions was randomized for each subject. Water temperature was regulated to provide optimal comfort: 35.0° ± 0.5°C during rest, 31.0°C or less during exercise.

For the upright conditions, the subject was seated on the ergometer with a weighted belt across the lap to counteract positive buoyancy. In the prone conditions, the subject was held in place by a standard scuba backpack attached to the frame of the ergometer (Fig. 1). The backpack could pivot vertically, allowing the subject to stand upright with his head above water when necessary. Each subject wore his own dive mask.

At the start of the experiment, the subject was positioned comfortably on the ergometer in the immersion tank in the condition (posture and SLL) for that day and was given a 2-min rest period before the exercise bout. During the rest period, three maximal flow-volume (F-V) maneuvers were performed. In addition, two maximal

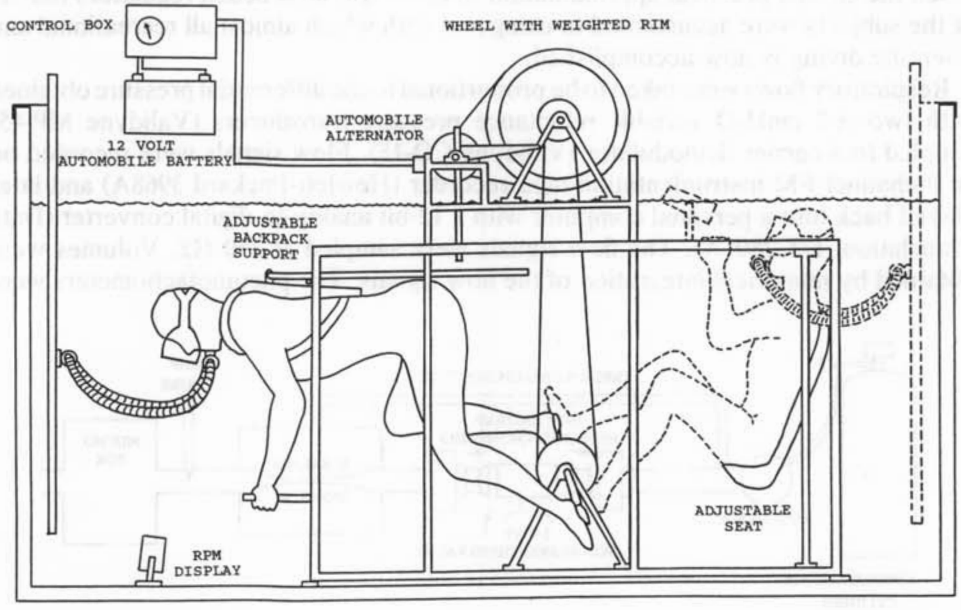

Fig. 1. Submersible cycle ergometer used for upright *(dashed line)* and prone *(solid line)* underwater exercise experiments.

inspirations from end-expiration (hereafter referred to as inspiratory capacities) and a respiratory discomfort rating were obtained. Inspiratory capacity maneuvers were separated by at least 30 s. The subject then pedaled for 2 min with no load on the ergometer. After this warm-up period, he pedaled at 65% of his dry land $\dot{V}O_2max$ for 6–8 min. During the last minute at this workload, two inspiratory capacity measurements and a respiratory discomfort rating were obtained. He then pedaled at 95% of his dry land $\dot{V}O_2max$ for at least 2 min. When the subject signaled that he could continue exercise for only about 1 more min, two final inspiratory capacity measurements and a final respiratory discomfort rating were obtained.

The subjects maintained a pedal frequency at or near 65 rpm throughout the exercise period by observing an rpm meter positioned inside the immersion tank (Fig. 1). Previous work in our laboratory (13) showed the hydrodynamic work to be 60.8 W at a pedal frequency of 65 rpm on this ergometer. This level of hydrodynamic work was equivalent to 15.8% of the dry land $\dot{V}O_2max$. The ergometer workload was governed by the field current supplied to the alternator that constituted the load. Work was kept constant automatically, compensating for variations in pedal frequency.

Breathing apparatus

Figure 2 illustrates the breathing system used during the immersion experiments. The subject breathed compressed air from a cylinder located outside the immersion tank. The demand regulator (Dacor Pacer) was attached to a vertically movable assembly located at the end of the water tank (*see* Fig. 1). Inspiratory and expiratory flows were measured by two linear pneumotachometers (Hans-Rudolph, model 3800) positioned on either side of a two-way, non-rebreathing valve (Hans-Rudolph, model 2700). A large-bore mouthpiece was attached to the Hans-Rudolph valve. This provided the closest practical approximation to the single-hose scuba regulators that all of the subjects were accustomed to using and with which almost all recreational and scientific diving is now accomplished.

Respiratory flows were taken to be proportional to the differential pressure obtained with two ± 2 cmH_2O variable reluctance pressure transducers (Validyne MP-45) coupled to a carrier demodulator (Validyne CD-18). Flow signals were recorded on an 8-channel FM instrumentation tape recorder (Hewlett-Packard 3968A) and later played back into a personal computer with a 12-bit analog-to-digital converter (Data Translation, DT-2801A). The flow signals were sampled at 250 Hz. Volumes were obtained by numerical integration of the flow signals. The pneumotachometers were

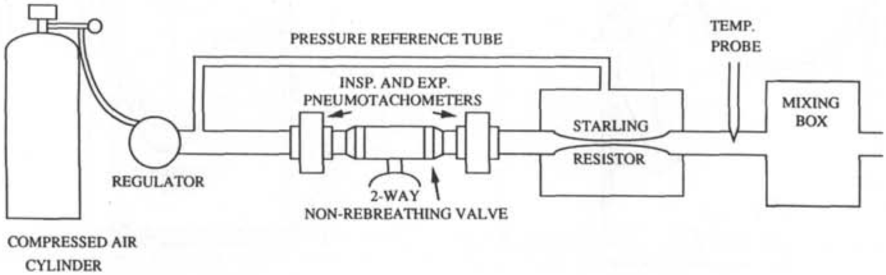

Fig. 2. Breathing system used during underwater exercise experiments. "Starling resistor" keeps inspiratory and expiratory pressures equal (*see* text).

calibrated before and after each experiment by flowing air at various rates through them and into a calibrated rotameter.

To keep the subject's airway pressure equal for both phases of respiration, and to prevent regulator free-flow, a large, modified Starling resistor secured inside an airtight acrylic cylinder was placed on the expiratory side of the breathing system, out of the water. Tygon tubing (7 mm i.d.) connected a port near the regulator to a port on the acrylic cylinder (Fig. 2). Submerging the regulator pressurized the air around the Starling resistor, thus equally pressurizing the inspiratory and expiratory sides of the system. The depth of the regulator below the water surface determined the air pressure delivered to the subject. Inspiratory resistance was approximately 2.0 $cmH_2O \cdot liter^{-1} \cdot s^{-1}$ at 5.0 liters $\cdot s^{-1}$ flow; expiratory resistance was approximately 1.5 $cmH_2O \cdot liter^{-1} \cdot s^{-1}$ at 6.0 liters $\cdot s^{-1}$ flow.

Static lung load selection

The SLL to which the subject was exposed was expressed as the pressure at the regulator minus the pressure at the level of the subject's suprasternal notch. A balloon catheter was placed at the level of the regulator (on the movable assembly) and another was taped to the subject's chest at the level of his sternal notch. The pressure difference between these two balloon catheters was obtained with a variable reluctance pressure transducer (Validyne MP-45), processed through a carrier demodulator (Validyne MC1-3), and displayed on a 6-channel polygraph (Gilson Medical Electronics, 5/6H). The differential pressure between the balloons was also displayed on an oscilloscope (Tektronix 5113) for viewing by an assistant in the immersion tank. The assistant was thus able to "fine tune" the SLL by adjusting the height of the regulator while watching the oscilloscope. Compliance curves were previously plotted for the balloons, and 10 ml of air was determined to be optimal balloon volume (14).

Measurements

All of the following measurements were obtained at rest and during the last minute at each of the two exercise levels.

Ventilation, O_2 uptake, and CO_2 production

Expired minute ventilation ($\dot{V}_E$) was assessed by adding V_T over a 1-min period. Breathing frequency was calculated by counting breaths over a 1-min period. Mixed expired gas was collected from a baffled mixing box, and the O_2 and CO_2 concentrations were immediately measured with an O_2 analyzer (Ametek, Inc., model S3A) and a CO_2 analyzer (Ametek, model CD39), respectively. The analyzers were calibrated with gases of O_2 and CO_2 concentrations that spanned the expected range.

Tidal flow-volume loops

Inspiratory and expiratory volumes were obtained by computer integration of the flow signals. To determine the position of a tidal F-V loop within the maximal loop, we used the inspiratory capacity preceding the tidal breath to align the tidal loop, along the volume axis, within the maximal loop. Thus tidal F-V limitation, if present, could be determined by measurement of the percentage of the tidal F-V loop that reached the boundary of the MEFV curve (15).

Respiratory discomfort

Respiratory discomfort was quantified by the use of a psychophysical rating scale (Table 2) (10). When asked, the subject was instructed to assign values to the amount of respiratory discomfort felt, and ratings between integers were accepted (e.g., 2.5). We previously estimated inter- and intra-subject reliability of the scale to be high (16).

Statistical analysis

To determine the effects of SLL, posture, exercise, and their interactions on each variable, an analysis of variance (ANOVA) with repeated measures was employed. If a significant main effect or interaction was observed, Duncan's Multiple Range Test was employed post hoc to compare the means. A significance level of $P \leq 0.05$ was used. All values are expressed as the mean ± SD.

RESULTS

Tables 3 and 4 show the mean ± SD of the variables for each activity level in each of the four experimental conditions. The results of the ANOVA performed on each variable are presented in Table 5.

Ventilation and lung volumes

Expired minute ventilation increased with exercise and during negative static lung loading but was not affected by posture. During exercise, V_T increased from the value

TABLE 2
PSYCHOPHYSICAL RATING SCALE FOR PERCEIVED RESPIRATORY DISCOMFORT

0	None
0.5	Very, very slight
1	Very slight
2	Slight
3	Moderate
4	Somewhat severe
5	Severe
6	
7	Very severe
8	
9	
10	Very, very severe
•	Maximal

TABLE 3

VENTILATION; O_2 UPTAKE, CO_2 PRODUCTION; RESPIRATORY DISCOMFORT RATING[a]

		U+	U−	P+	P−
$\dot{V}E$	R	12.1 ± 2.6	10.5 ± 3.3	13.3 ± 4.9	12.5 ± 3.0
	M	47.8 ± 11.1	57.4 ± 18.9	48.1 ± 13.5	59.4 ± 20.9
	E	81.7 ± 16.4	84.6 ± 22.1	84.6 ± 26.7	98.0 ± 24.6
V_T	R	1.35 ± 0.38	1.11 ± 0.31	1.24 ± 0.27	1.27 ± 0.44
	M	2.66 ± 0.66	2.77 ± 0.40	2.59 ± 0.48	2.95 ± 0.53
	E	2.93 ± 0.44	2.99 ± 0.53	2.92 ± 0.47	3.39 ± 0.66
f	R	9.3 ± 2.2	10.0 ± 3.7	11.0 ± 4.3	10.6 ± 3.7
	M	19.3 ± 7.3	21.1 ± 7.5	19.4 ± 7.4	20.3 ± 6.6
	E	28.9 ± 8.9	28.7 ± 7.6	29.1 ± 8.4	29.7 ± 8.2
ERV	R	0.89 ± 0.53	0.64 ± 0.33	2.41 ± 1.04	1.09 ± 0.79
	M	1.36 ± 0.46	1.24 ± 0.78	2.64 ± 1.41	1.40 ± 0.84[b]
	E	1.48 ± 0.54	1.47 ± 0.98	2.67 ± 1.07	1.28 ± 0.99
FVC	R	5.55 ± 0.70	5.05 ± 0.88	6.02 ± 0.84	5.63 ± 0.89
PIF	R	0.56 ± 0.18	0.55 ± 0.17	0.61 ± 0.22	0.59 ± 0.23
	M	1.72 ± 0.29	1.84 ± 0.38	1.94 ± 0.45	1.98 ± 0.54
	E	2.89 ± 0.50	2.79 ± 0.35	3.01 ± 0.74	3.00 ± 0.73
PEF	R	0.76 ± 0.27	0.64 ± 0.16	0.69 ± 0.31	0.81 ± 0.47
	M	2.28 ± 0.44	2.75 ± 0.58	2.51 ± 0.81	3.38 ± 0.97
	E	3.48 ± 0.42	4.22 ± 0.85	3.90 ± 0.88	5.68 ± 1.62
$\dot{V}O_2$	R	0.47 ± 0.11	0.40 ± 0.10	0.41 ± 0.08	0.45 ± 0.12
	M	2.46 ± 0.20	2.59 ± 0.23	2.39 ± 0.17	2.79 ± 0.38
	E	3.36 ± 0.35	3.33 ± 0.63	3.40 ± 0.35	3.91 ± 0.70
$\dot{V}CO_2$	R	0.40 ± 0.07	0.34 ± 0.11	0.38 ± 0.11	0.40 ± 0.10
	M	2.13 ± 0.26	2.48 ± 0.45	2.23 ± 0.40	2.64 ± 0.60
	E	3.33 ± 0.36	3.43 ± 0.64	3.49 ± 0.54	3.96 ± 0.72
RDR	R	1.29 ± 1.25	0.82 ± 1.05	1.07 ± 1.10	1.07 ± 1.06
	M	2.64 ± 1.35	2.50 ± 1.19	2.57 ± 1.24	2.57 ± 1.24
	E	4.21 ± 0.99	4.07 ± 1.24	4.21 ± 1.87	4.29 ± 1.87

[a]All values are mean ± SD (n = 8). *See* Table 5 for statistical significance. [b]n = 7.

Key: $\dot{V}_E$ = expired minute ventilation (liters · min^{-1} BTPS); V_T = tidal volume (liter BTPS); f = breathing frequency (breaths · min^{-1}); ERV = expiratory reserve volume (liters BTPS); FVC = forced vital capacity (liters BTPS); PIF = peak inspiratory flow (liters · s^{-1}); PEF = peak expiratory flow (liters · s^{-1}); $\dot{V}O_2$ = oxygen uptake (liters · min^{-1} STPD); $\dot{V}CO_2$ = carbon dioxide production (liters · min^{-1} STPD); RDR = respiratory discomfort rating; R = rest; M = moderate exercise; E = exhaustive exercise.

at rest, but values during moderate and exhaustive exercise were not different from each other. A significant interaction was observed between SLL and exercise such that V_T was greatest during exhaustive exercise with negative static lung loading. Respiratory frequency increased with exercise, but no effects of posture or SLL were observed.

Expiratory reserve volume was greater with the positive SLL. When values for a given activity level were averaged across all four conditions, ERV at rest was less than at either of the two exercise levels. In addition, a significant interaction of SLL

TABLE 4

FACTORS CONTRIBUTING TO MECHANICAL LIMITATION TO VENTILATION[a]

		U+	U−	P+	P−
$\dot{V}max_{50}$	R	5.5± 1.5	4.5± 1.0	5.7± 1.1	4.8± 1.4
TFVL	R	3.9±10.9	16.8±24.9	0.0± 0.0	9.3±17.2
	M	12.2±23.1	27.9±32.0	3.8± 9.5	19.0±36.0[b]
	E	18.5±31.1	25.8±33.5	11.6±30.6	34.7±38.3

[a]All values are mean ± SD (n = 8). *See* Table 5 for statistical significance. [b]n = 7.

Key: $\dot{V}max_{50}$ = maximum expiratory flow at 50% of the vital capacity (liters · s^{-1}); TFVL = tidal flow-volume limitation (%V_T), i.e., percentage of the tidal flow-volume loop that met the boundary of the MEFV curve. R = rest; M = moderate exercise; E = exhaustive exercise.

TABLE 5

RESULTS OF THE REPEATED MEASURES ANOVA PERFORMED ON EACH VARIABLE

Variable	Pos	SLL	E	Pos × SLL	Pos × E	SLL × E	Pos × SLL × E
$\dot{V}_E$	ns	*	***	ns	ns	ns	ns
V_T	ns	*	***	ns	ns	*	ns
f	ns	ns	***	ns	ns	ns	ns
ERV	ns	**	*	**	ns	ns	ns
FVC	ns	**	—	ns	—	—	—
PIF	ns	ns	***	ns	ns	ns	ns
PEF	ns	ns	***	ns	**	*	ns
$\dot{V}max_{50}$	ns	b	—	ns	—	—	—
TFVL	ns	*	ns	ns	ns	ns	ns
$\dot{V}O_2$	ns	ns	***	**	ns	ns	ns
$\dot{V}CO_2$	ns	*	***	ns	ns	ns	ns
RD	ns	ns	**	ns	ns	ns	ns

*$P \le 0.05$; **$P \le 0.01$; *** $P \le 0.001$; ns = not significant; b = borderline significance (P = 0.056).

Key: Pos = posture; SLL = static lung load; E = exercise level; $\dot{V}_E$ = expired minute ventilation (liters · min^{-1} BTPS); V_T = tidal volume (liters BTPS); f = breathing frequency (breath · min^{-1}); ERV = expiratory reserve volume (liters BTPS); FVC = forced vital capacity (liters BTPS); PIF = peak inspiratory flow (liters · s^{-1}); PEF = peak expiratory flow (liters · s^{-1}); $\dot{V}max_{50}$ = maximum expiratory flow at 50% of the vital capacity (liters · s^{-1}); TFVL = tidal flow-volume limitation (%V_T), i.e., the percentage of the tidal flow-volume loop that met the boundary of the MEFV curve; $\dot{V}O_2$ = oxygen uptake (liters · min^{-1} STPD); $\dot{V}CO_2$ = carbon dioxide production (liters · min^{-1} STPD); RD = respiratory discomfort ring.

and posture was observed such that the order of *decreasing* ERV (averaged across all activity levels) for the four experimental conditions was: P+, P−, U+, U−.

Forced vital capacity (the expired volume measured during the maximal F-V maneuvers performed pre-exercise) was greater with positive static lung loading. No effect of body position was observed.

Respiratory flows and flow limitation

Peak inspiratory flow increased with exercise level. No effects of SLL or posture were observed. For peak expiratory flow, significant interactions were observed between SLL and exercise level, and between posture and exercise level. Thus, peak expiratory flow was a) greater during prone than during upright exercise, and b) greater during exercise with the negative than with the positive SLL.

Figure 3 shows the maximal and tidal F-V loops for subject 1 in each of the four experimental conditions. Note that during tidal breathing this subject reached the boundary of his MEFV curve during both rest and exercise in the negative SLL

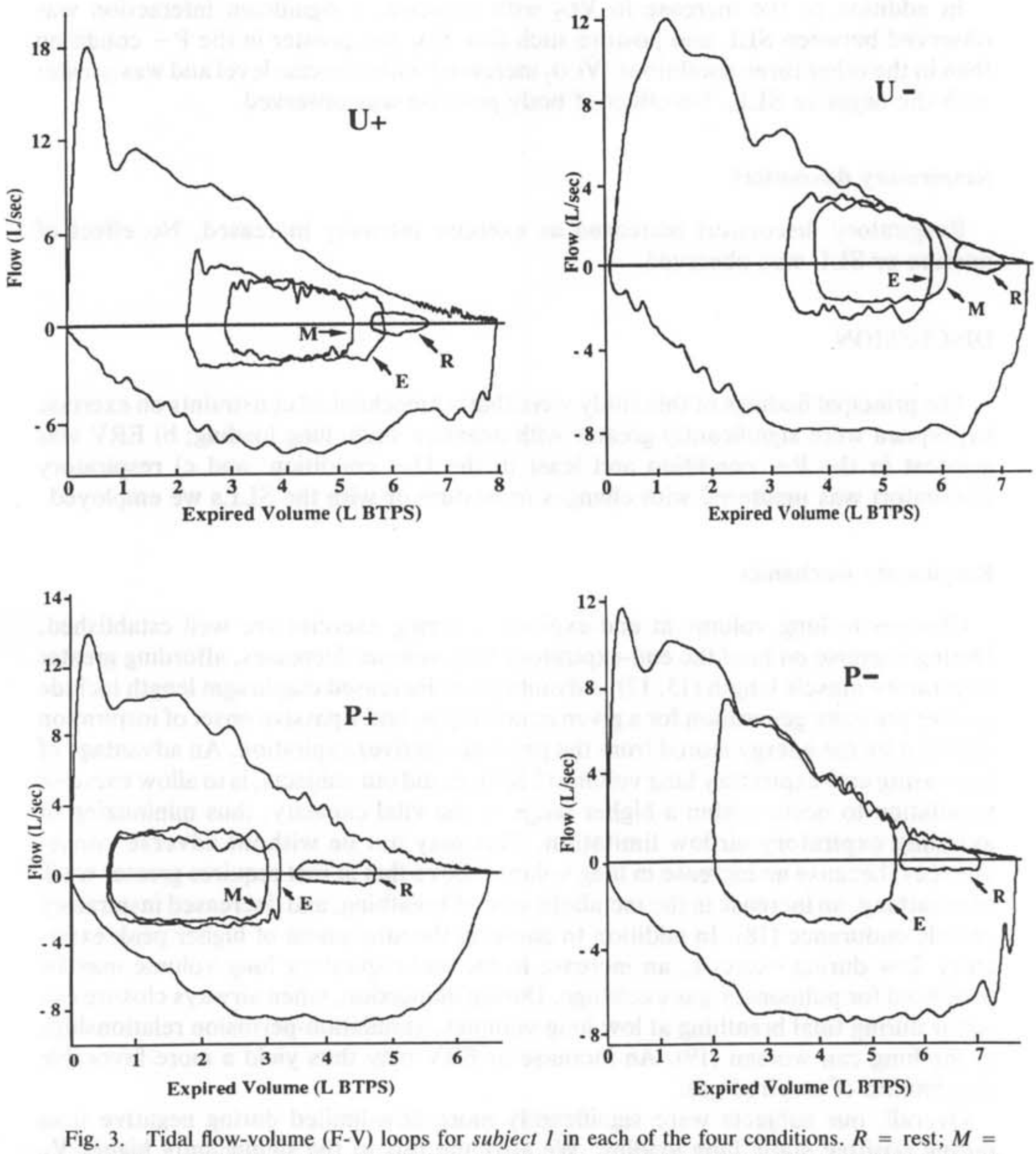

Fig. 3. Tidal flow-volume (F-V) loops for *subject 1* in each of the four conditions. R = rest; M = moderate exercise; E = exhaustive exercise. Tidal loops are plotted within the pre-exercise maximal F-V loops. Maximal loops were obtained under same experimental conditions as tidal loops. In this subject, no tidal F-V loop was obtained during moderate exercise in P−. *Note* that tidal loops met the boundary of the MEFV curve in the negative SLL conditions.

conditions. For all subjects, a borderline significant difference ($P = 0.056$) was found between SLLs in the maximum expiratory flow achieved at 50% of the vital capacity ($\dot{V}max_{50}$): $\dot{V}max_{50}$ was greater when subjects were breathing with the positive SLL. Tidal F-V limitation was significantly greater during negative static lung loading.

O_2 uptake and CO_2 production

In addition to the increase in $\dot{V}O_2$ with exercise, a significant interaction was observed between SLL and posture such that $\dot{V}O_2$ was greater in the P− condition than in the other three conditions. $\dot{V}CO_2$ increased with exercise level and was greater with the negative SLL. No effect of body position was observed.

Respiratory discomfort

Respiratory discomfort increased as exercise intensity increased. No effect of posture or SLL was observed.

DISCUSSION

The principal findings of this study were that: a) mechanical constraints on exercise hyperpnea were significantly greater with negative static lung loading; b) ERV was greatest in the P+ condition and least in the U− condition; and c) respiratory discomfort was unaltered with changes in posture or with the SLLs we employed.

Respiratory mechanics

Changes in lung volume at end-expiration during exercise are well established. During exercise *on land* the end-expiratory lung volume decreases, affording greater inspiratory muscle length (15, 17). Advantages of increased diaphragm length include greater pressure generation for a given neural input, and a passive onset of inspiration afforded by the energy stored from the previous (active) expiration. An advantage of *increasing* end-expiratory lung volume (ERV), as did our subjects, is to allow exercise ventilation to occur within a higher range of the vital capacity, thus minimizing or avoiding expiratory airflow limitation. This may not be without adverse consequences, because an increase in lung volume above that at rest requires greater work of breathing, an increase in the metabolic cost of breathing, and decreased inspiratory muscle endurance (18). In addition to allowing the attainment of higher peak expiratory flow during exercise, an increase in the end-expiratory lung volume may be beneficial for pulmonary gas exchange. During immersion, when airways closure can occur during tidal breathing at low lung volumes, ventilation-perfusion relationships in the lung can worsen (19). An increase in ERV may thus yield a more favorable distribution of inspired gas.

Overall, our subjects were significantly more flow-limited during negative than during positive static lung loading. We attribute this to the significantly higher $\dot{V}_E$ and significantly reduced $\dot{V}max_{50}$ (a reduction in the latter acting to constrain expiratory flow) during negative static lung loading. One potential source of error in our calculation of tidal F-V limitation is exercise-induced bronchodilation. This phenomenon has been demonstrated in subjects after maximal exercise (on land) by means of measured increases in $\dot{V}max_{50}$ and $\dot{V}max_{75}$ (15). We measured maximum expiratory flow parameters in our subjects only before exercise. Thus, our subjects may have actually had less airflow limitation during exercise than we measured.

Respiratory discomfort

Our subjects did not show a preference for either the positive or the negative SLL. Previous investigators (5, 20) studied dyspnea during exercise at depths ranging from 1.45 to 6.76 atm abs and found that their subjects preferred SLLs of +10 cmH_2O with respect to the mid-thoracic line when prone (5) or 0 to +10 cmH_2O with respect to the lung centroid when upright (20), over negative airway pressures. Referenced to the sternal notch, these SLLs were equal to about +4 to +24 cmH_2O. Earlier work at 1 atm abs in our laboratory (11) suggests that our subjects would have found +24 cmH_2O intolerable.

An explanation for such differences is that the hyperbaric studies (5, 20) employed a full face mask whereas ours (11 and present) were conducted with a mouthpiece. As Jarrett (21) has pointed out, use of a full mask makes a difference in tolerance for static lung loading. If the situation requires a positive SLL great enough to restore lung volumes to dry-land values during upright immersion, a mask or helmet is generally necessary. A SLL of such magnitude implies not only compensation for hydrostatic imbalance but also counteraction of the transfer of blood to the thorax from sites of gravitational pooling (22).

Our observation that respiratory comfort was unaffected by SLLs of ±10 cmH_2O reinforces the results of previous work in our laboratory: Carlson et al. (11) found no significant differences in respiratory discomfort for SLLs between and including ±10 cmH_2O during rest and submaximal exercise ($\dot{V}O_2$ = 1.76 liters · min^{-1}) in either the upright or prone postures. In addition, we previously found that SLLs of opposite sign but of equal magnitude produced the same degree of respiratory discomfort (14). This relationship held true at all activity levels in the present study.

Although respiratory discomfort increased with exertion, respiratory discomfort ratings were relatively low (Table 3). This may be because leg fatigue, as opposed to a sensation of excessive breathing effort, caused all of our subjects to terminate exercise. Kim et al. (23) report that subjects terminate underwater swimming of up to 2 h primarily because of local muscle fatigue.

We conclude that during immersion and graded exercise to exhaustion at 1 atm abs, changes in SLL, and to a lesser degree body position, influence respiratory mechanics in a distinct manner. Tidal flow-volume limitation occurred to a significantly greater extent with the negative than with the positive SLL. In the prone position, higher expiratory flows were achieved and flow limitation was not significantly increased. We found no relationship between respiratory discomfort and the amount of tidal flow-volume limitation, as discomfort significantly increased with exercise level but flow limitation did not. Adverse changes in respiratory mechanics during underwater exercise seem to be minimized with positive static lung loading and a prone body position. Respiratory comfort is unaffected with SLL values of ±10 cmH_2O.

The authors are grateful to Mr. Thomas W. Roberts for the design and construction of auxiliary instrumentation, Dr. Harold J.B. Guy for the data logging system, Mr. Jacks Lee and Ms. Marti Louther for help with data collection, the staff of the University of Wisconsin Biotron for assistance with the immersion facility, and to Dr. Charles E. Lehner for valuable advice. This work was supported by the University of Wisconsin Sea Grant Institute under grants from the National Sea Grant College Program, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, and from the State of Wisconsin. Federal grant (NA84AA-D-00065), project (R/NA-11).—*Manuscript received November 1988; accepted December 1991.*

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