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EFFECT OF POSTURE ON VENTILATORY RESPONSE TO STEADY-STATE HYPOXIA AND HYPERCAPNIA

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Abstract. The ventilatory response to steady-state normocapnic hypoxia and hypercapnia was measured in eight normal subjects after 15 min inhalation of 10.5% oxygen (with added CO_2) or 4.2% CO_2 in air through a loose-fitting high-flow Venturi mask. The erect (sitting) and the supine postures were studied. Ventilation was measured with inductance coils around the chest and the abdomen (Respitrace). Oxygen saturation was measured with an ear oximeter and P_{CO_2} was measured transcutaneously on forearm skin using a modified pH electrode (Radiometer). In the erect posture (without stimulation), compared to supine, $\dot{V}E$ (21%) and VT/TI (32%) were greater but TI (19%) and TE (8%), abdominal contribution to tidal volume (24%) and 'arterial' P_{CO_2} (0.6 mm Hg) were less. The mean ventilatory response to hypoxia at an 'arterial' P_{CO_2} of 41 ± 4 mm Hg (SD) was 0.61 ± 0.34 L · min^{-1} · $Sa_{O_2}^{-1}$ erect and 0.84 ± 0.58 supine and to hypercapnia 2.89 ± 1.4 L · min^{-1} · mm Hg^{-1} erect and 3.73 ± 2.35 supine. The postural differences did not reach statistical significance. The pattern of response to both stimuli was similar, with doubling of VT, constant TI and slight shortening of TE. The abdominal contribution to tidal volume decreased by 9% with both forms of stimulation. In the steady state, the response to peripheral and central chemoreceptor stimuli was identical and essentially independent of position.

Chemoreceptor	Hypoxia
Control of ventilation	Inductance plethysmography
Human	Posture
Hypercapnia	Transcutaneous P_{CO_2}

In the supine posture, end-expiratory lung volume is reduced and there is significant cranial displacement of the relaxed diaphragm. Because of its length and curvature the diaphragm has a greater mechanical advantage at supine compared to erect FRC and will generate more force for any given stimulation. Measurements with magnetometers or inductance coils show that the abdominal wall displacement relative to rib cage displacement during tidal breathing is considerably greater in the supine than in the erect

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posture (Chadha *et al.*, 1982). Nevertheless, in spite of the relative mechanical disadvantage of the diaphragm in the erect position, total ventilation is some 20% greater than supine (Anthonisen *et al.*, 1965; Weissman *et al.*, 1982) even though the level of arterial P_{CO_2} is slightly lower. The explanation is that the intensity of activation of the diaphragm (from oesophageal EMG recordings) for the same P_{CO_2} is some 300% greater in the upright than in the supine position (Druz and Sharp, 1981). The neural mechanism which compensates for changes in diaphragm length has not yet been identified in man.

Changes in the operating length of the diaphragm might affect the ventilatory response to hypoxia or hypercapnia, either under transient or steady-state conditions or both. Slutsky *et al.* (1980) showed that the ventilatory response to isocapnic hypoxia (closed-circuit rebreathing) was similar in erect and supine postures, but the pattern of breathing was not analysed nor has the effect of posture on the steady-state response to hypoxia been investigated. Hypercapnic ventilatory responses appear to be similar in both postures with rebreathing (Lederer *et al.*, 1977; Rigg *et al.*, 1974) and steady-state (Weissman *et al.*, 1982) techniques. Only one of these studies (Weissman *et al.*, 1982) has been performed without a mouthpiece and noseclip, and none of them has reported the separate contributions to tidal volume of rib cage and abdominal motion.

Steady-state ventilatory response to hypoxia and hypercapnia were measured with respiratory inductance plethysmography (RIP). This device measures changes in thoracic and abdominal cross sectional areas by means of inductance coils attached to the body surface (Chadha *et al.*, 1982). With appropriate calibration ventilation and tidal volume can be measured leaving the mouth and face undisturbed. In addition, the individual contribution of rib cage and abdominal displacement in both postures and with resting and stimulated breathing can be observed. The measurements were performed in the supine and the erect (sitting) postures. Hypoxic and hypercapnic gas mixtures were breathed through a loose-fitting face mask (Ventimask). Oxygen saturation and P_{CO_2} were measured with transcutaneous devices as described below.

Methods

Eight normal subjects (4 male, 5 female) drawn from laboratory personnel, were studied twice, on separate days. Mean ($\pm$ SD) age, height and weight were 32 $\pm$ 6.7 years, 1.7 $\pm$ 0.08 m and 66 $\pm$ 14 kg, respectively. All had normal values for spirometry. On each study day, a hypercapnic or a hypoxic response was measured sitting upright in a purpose-built chair and, at least 30 min later, lying supine on a bed. Approval was obtained from the Research Ethics Committee, Hammersmith Hospital, and all subjects gave informed consent. The order hypoxia/hypercapnia between days, and erect/supine within a day was randomized. The subjects were unaware of which gas mixture they were receiving.

On a study day, subjects had a light breakfast but no tea or coffee. The studies were performed in a quiet room. Abdominal and rib cage inductance coils were attached and taped in position to prevent slipping. Arterial oxyhaemoglobin saturation (Sa_{O_2}%) was

measured with an ear oximeter (Hewlett-Packard 47201A). The level of carbon dioxide tensions was monitored via a transcutaneous pH probe on lightly abraded skin (Radiometer, Copenhagen – TCM 20) on the forearm. An ECG was attached via standard electrodes to measure heart rate.

A commercially available respiratory inductance plethysmograph (RIP) (Respitrace, Ambulatory Monitoring Inc.) measured tidal volume. The RIP device consists of two coils of insulated wire sewn onto elastic belts encircling rib cage (RC) and abdomen (ABD) connected to an oscillator module. Several methods have been described for calibrating the summed outputs of RC and ABD coils in terms of tidal volume (Chadha *et al.*, 1982) but the method used here was a modification of the technique of Stagg *et al.* (1978). The general approach, as originally suggested by Konno and Mead (1967) is via the equation:

$$SP = a \cdot RC + b \cdot ABD + E$$

where SP refers to the volume change measured simultaneously with a spirometer, a and b are the volume–motion coefficients for rib cage and abdominal movement respectively and E is a constant. The calibration manoeuvre was performed during spontaneous breathing over the expected tidal volume range (up to 1.0 L) using one posture only. Subjects rebreathed from a spirometer (SP) for 20 sec. RC and ABD excursions were displayed on an X–Y oscilloscope. A satisfactory solution for the volume motion coefficients can be obtained during tidal breathing if the relative contributions of RC and ABD vary sufficiently, either within a breath (looping) or from breath to breath (a change of slope). All subjects learnt quickly how to change the slope of the RC – ABD plot, displayed on the oscilloscope in front of them, by concentrating on expansion of the chest keeping the abdomen still and *vice versa*, alternating, in effect, 'chest' and 'abdominal' breaths. The voltage signals from SP, RC and ABD passed, at 100 msec intervals, via an ADC to an Apple II microcomputer. The best fit for the exponents a and b for the 200 sets of data was found using a least-squares multiple linear regression technique. The statistical consistency of these relationships was checked by regressing separately $SP-(b \cdot ABD)$ against $a \cdot RC$ and $SP-(a \cdot RC)$ against $b \cdot ABD$. If 95% of the individual readings were within 10% of the identity line values for both regressions the calibration was considered satisfactory.

A further check was carried out before and after each run, while breathing from the spirometer for two periods of 10 breaths each. The tidal volume (V_T) derived from RIP ($a \cdot RC + b \cdot ABD$) was compared with that from the spirometer (L BTPS). The RC and ABD tidal volumes were detected separately to allow for any phase shift between body surface movements and volume changes at the mouth. The mean (before and after) V_T ratio (SP/RIP) was used to adjust the V_T, minute ventilation ($\dot{V}_E$) and mean inspiratory flow (V_T/T_I) values calculated from RIP; in practice, the corrections were small ($< 5\%$). The standard deviation of the SP/RIP ratio which represents breath to breath accuracy of VT computed by RIP was also calculated.

From the calibrated spirogram, respiratory frequency (f), inspiratory and expiratory

times (TI, TE), fractional inspiratory time (TI/TTOT), VT/TI and $\dot{V}E$ were calculated by the computer in a standard way by searching for V (volume)$_{min}$ and t_{min} and V_{max} and t_{max} where max and min refer to maximum and minimum values of volume (V) and the corresponding time (t). Threshold values (variable but generally 100 ml) were inserted into the recognition of V_{min} and V_{max} so that small irregularities or 'hiccoughs' would not count as separate breaths. Every 6 sec the value for each variable was transferred to an 8-channel chart recorder using a switching technique which plotted two variables per channel. The values were ranked means of the current breath and the three immediately preceding and following in which the middle (median) value was taken. The heart rate (from ECG), arterial saturation (oximeter) and unprocessed RC and ABD signals were recorded continuously on the remaining four channels.

The transcutaneous P_{CO_2} electrode was attached to the forearm skin, after a previous two-point calibration with dry gases with P_{CO_2} values of 37 and 72 mm Hg. The probe was heated to 42 °C. In each study the response time was measured after vigorous hyperventilation for 15 sec. The initial fall in P_{CO_2} (> 2 mm Hg) occurred between 35 and 45 sec for all subjects. The transcutaneous CO_2 reading (Ptc_{CO_2}) was converted to give an approximate measurement of arterial P_{CO_2} using the equation:

$$Pa_{CO_2} = Ptc_{CO_2} \times 0.63 + 2.9 \text{ (mm Hg)}$$

In a series of 78 simultaneous comparisons of Ptc_{CO_2} with arterial CO_2, carried out in this laboratory, this equation predicted Pa_{CO_2} with 95% confidence limits of ± 6.7 mm Hg and a correlation coefficient (r) of 0.95 (Stradling *et al.*, 1983).

Protocol

Subjects wore loose-fitting face masks (Ventimask, Vickers Medical Ltd.) supplied with air, nitrogen or CO_2 which entrained known amounts of air using the Venturi principle (fig. 1). For the hypoxic study, masks with 1 : 1 entrainment ratios were used. Mask inflow was 20 L · min^{-1} of 100% N_2 plus 1.5–2.5 L · min^{-1} of 100% CO_2, which *in toto* entrained an equal flow of air, giving an inspired oxygen concentration of 10.5% and inspired CO_2 of 3.5–5.5%. The total mask inflow of 43–45 L · min^{-1} was in excess of the mean inspiratory flow rate of all subjects, during normal or stimulated breathing. The CO_2 flow in hypoxia was continuously adjusted to keep the transcutaneous CO_2 level constant. For hypercapnic studies, masks with 1 : 23 entrainment ratios were used with 2 L · min^{-1} of 100% CO_2 being added, giving a total flow of 48 L · min^{-1} with an inspired CO_2 concentration of 4.2%.

After calibration and checking of the RIP subjects breathed through the Ventimask with air supplied at the appropriate flow (43 and 48 L · min^{-1}). After a 10 min control period the inspired gas was changed to 10.5% oxygen or 4.2% CO_2. This mixture was inspired for 15 min before returning to control for a further 10 min. A radio programme was played to distract the subjects. Values for all variables were averaged over the last one minute of the control period and for 1 min at the 5th, 10th and 15th minutes of the hypoxic or hypercapnic period.

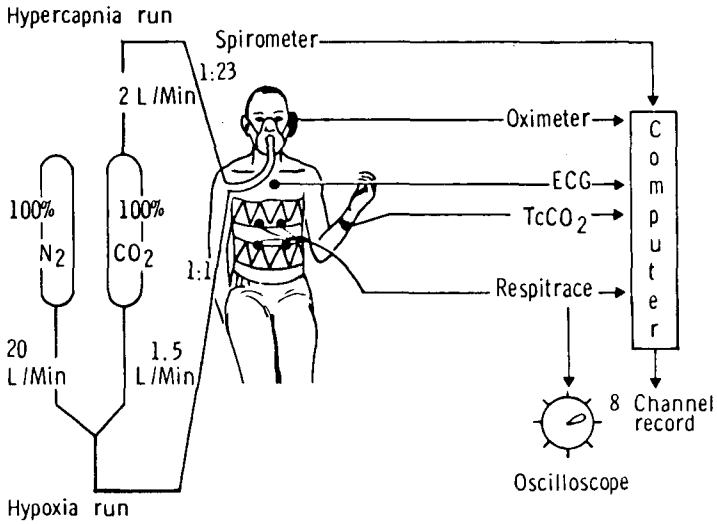

Fig. 1. Diagram of the set-up showing inductance coils around rib cage and abdomen, Ventimask with 1:23 CO_2–air entrainment for hypercapnic studies, and 1:1 nitrogen–air (with 1.5 L/min CO_2 enrichment) entrainment for hypoxic studies. Subject breathed on a spirometer for calibration and checking of Respitrace.

Results

The mean inspiratory capacity (IC) was 3.2 ± 0.56 (SD) L BTPS erect and 4.0 ± 0.97 supine. As a percentage of the erect vital capacity the increase in IC from erect to supine was 10.0 ± 2.5% in the males and 18.5 ± 4.4% in the females.

Validation of respitrace. The volume motion coefficients for rib cage and abdominal coils and the spirometer/inductance plethysmograph ratio for tidal volume are shown in table 1. These coefficients did not alter from day to day (from the hypoxic to the hypercapnic study). For the 200 sets of data from the spirometer, RC and ABD coils in each calibration, 95% of the points fell within 8% (range 7–9%) of the identity line when erect and 5.5% when supine (table 1:95% confidence) calculated from a multiple linear regression analysis (see Methods). For two sets of ten breaths each, the ratio of spirometer to calibrated RIP volume deviated by less than 3% from unity. For each set of 10 breaths, the mean SD of the SP/RIP ratio for both runs was 0.06 ± 0.05; thus 95% of *individual* RIP tidal volumes were within 11% of the spirometric value. The change of the SP/RIP ratio from beginning to end of each hypoxic or hypercapnic challenge averaged 4%. The worst 10 breath SP/RIP ratio was 1.16 (SD 0.05) and the largest SD was 0.15 (ratio 1.015).

Posture and resting ventilation. Table 2 plots mean data for the control studies in erect and supine postures with hypoxic and hypercapnic control runs combined. $\dot{V}_E$ and

TABLE 1

Mean values in 8 subjects in erect and supine postures for hypoxic and hypercapnic studies of volume–motion coefficients (arbitrary units) for rib cage (RC) and abdomen (ABD) with 95% confidence limits from multiple linear regression analysis, ratio of spirometer (SP) to calibrated Respitrace (RIP) tidal volume, SD of this ratio over 20 breaths, and change in SP/RIP ratio from beginning (pre) to end (post) of each run.

	Erect		Supine	
	Hypoxia	Hypercapnia	Hypoxia	Hypercapnia
RC	136 ± 36	133 ± 45	126 ± 38	134 ± 36
95% confidence	± 4	± 5	± 5	± 6
ABD	63 ± 25	68 ± 26	59 ± 16	74 ± 16
95% confidence	± 7	± 9	± 6	± 5
SP/RIP ratio (Pre)	1.009 ± .01	0.98 ± .05	1.037 ± .06	0.98 ± .05
Mean SD (SP/RIP ratio)	0.046 ± .02	0.041 ± .02	0.053 ± .02	0.041 ± .02
ΔSP/RIP (Pre-Post)	0.04 ± .026	0.034 ± .029	0.03 ± .04	0.052 ± .03

* Without regard to sign.

TABLE 2

Mean values (± SD) in control runs (hypoxic and hypercapnic studies combined, n = 16) in 8 subjects in erect (sitting) and supine postures for resting ventilation ($\dot{V}_E$) and its subdivisions (see text for details), abdominal displacement contributing to tidal volume (ABD%), Pa_{CO_2} (from transcutaneous measurements) and arterial oxygen saturation (Sa_{O_2}) from ear oximetry.

	Erect	Supine
$\dot{V}_E$ ($L \cdot min^{-1}$)	5.88 ± 1.15**	4.85 ± 1.13
V_T (L)	0.380 ± 0.077	0.360 ± 0.078
f (min^{-1})	15.3 ± 1.2*	13.8 + 1.8
T_I/T_{TOT}	0.39 ± 0.03*	0.42 ± 0.04
T_I (sec)	1.53 ± 0.22**	1.89 ± 0.32
T_E (sec)	2.39 ± 0.25	2.60 ± 0.45
V_T/T_I ($L \cdot min^{-1}$)	15.0 ± 2.8**	11.4 ± 2.1
ABD%	39.6 ± 10**	63.8 ± 11
Pa_{CO_2} (mm Hg)	40.5 ± 3.7	41.1 ± 3.1
Sa_{O_2} (%)	96.1 ± 1	96.6 ± 1

* $P < 0.05$;** $P < 0.01$.

V_T/T_I were significantly greater in the erect posture; V_T and f were also greater but the changes were smaller and less significant. The respiratory duty cycle (T_I/T_{TOT}) and the abdominal contribution to V_T were significantly larger supine. T_I was also greater supine but T_E was unaltered by posture (fig. 2). Pa_{CO_2}, from transcutaneous measurements, was slightly higher supine but the change was not significant.

Posture and hypoxic/hypercapnic responses. Figure 3 plots the spirogram in erect and supine postures under control conditions and when stimulated by normocapnic hypoxia

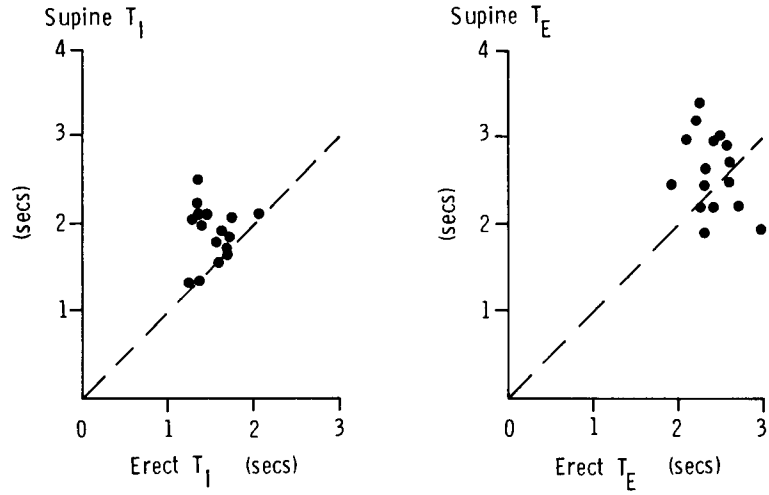

Fig. 2. Individual values for inspiratory (TI) and expiratory (TE) times comparing supine with erect posture (line of identity shown) in the unstimulated (control) state. Two comparisons (n = 16) are available for the eight subjects, from the control runs for hypoxic and hypercapnic studies.

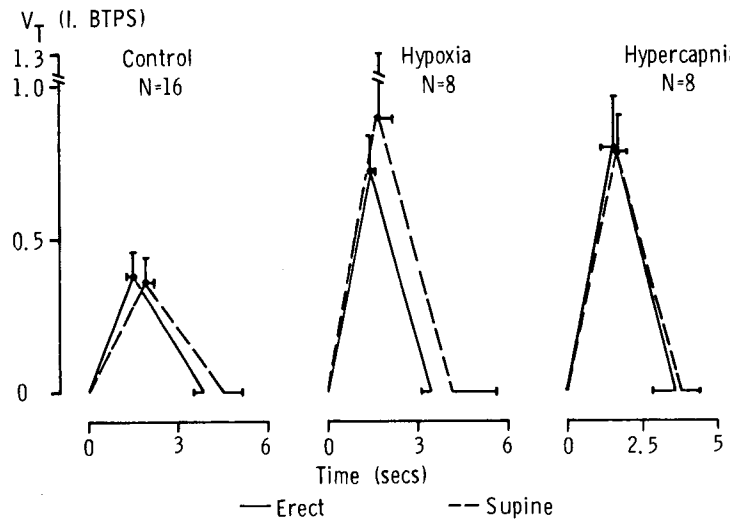

Fig. 3. Spirograms for eight subjects comparing mean (± SD) tidal volume (VT) and inspiratory and total cycle times in erect and supine positions for control (hypoxic and hypercapnic runs combined) and stimulated (hypoxic and hypercapnic) states.

or hypercapnia. The response to hypoxia and hypercapnia is similar and little affected by the postural change. Table 3 outlines the values during stimulated breathing in absolute terms and as a percentage of control. In relation to control values the increase of $\dot{V}E$ and VT/TI was significantly greater supine than erect for both hypoxic and hypercapnic stimulation. There were no other posturally related differences.

TABLE 3

Mean values for all subjects at 15 min (and as % control in parentheses) for hypoxic and hypercapnic steady-state responses in erect (E) and supine (S) postures. Ventilatory abbreviations as in Table 2. Sa_{O_2} % is oxygen saturation (ear oximeter).

	Hypoxia (E)	Hypoxia (S)	Hypercapnia (E)	Hypercapnia (S)
$\dot{V}E$ ($L \cdot min^{-1}$)	12.32 (216)	**13.0 (266)	13.3 (230)	*12.7 (277)
VT (L)	0.71 (196)	0.88 (248)	0.79 (209)	0.78 (211)
f (min^{-1})	17.4 (112)	15.8 (111)	17.0 (111)	16.3 (125)
TI (sec)	1.43 (96)	1.7 (94)	1.56 (100)	1.66 (86)
TI/TTOT	0.41 (107)	0.42 (102)	0.43 (110)	0.44 (103)
TE (sec)	2.05 (94)	2.4 (93)	2.07 (87)	2.11 (82)
VT/TI ($L \cdot min^{-1}$)	29.6 (201)	**30.6 (264)	31.3 (214)	*28.2 (260)
ABD%	34.9 (92)	60.0 (92)	36.8 (91)	62.1 (96)
Pa_{CO_2} (mm Hg)	41.2 (101)	40.8 (100)	43.3 (107)	44.2 (107)
Sa_{O_2} (%)	83.8 (87)	84.6 (87)	96.6 (101)	97.5 (101)

* $P < 0.05$, ** $P < 0.01$, comparing erect % control with supine % control.

Figure 4 shows the time course of the ventilatory response to changes of P_{CO_2} and Sa_{O_2} throughout the 15 min period of stimulated breathing in relation to control values. There are no significant changes with time in relation to the hypercapnic response, but with hypoxia $\dot{V}E$ and Sa_{O_2} are less tightly linked over the 15 min period. In the supine posture the response is steady between the tenth and fifteenth minute, but there is a progressive fall with time in hypoxic sensitivity in the erect posture.

Figure 5 plots the individual results for hypoxic and hypercapnic responses after 15 min stimulation in each case. There is a trend for the responses to hypercapnia and hypoxia to be greater in the supine position but the change was too small to be

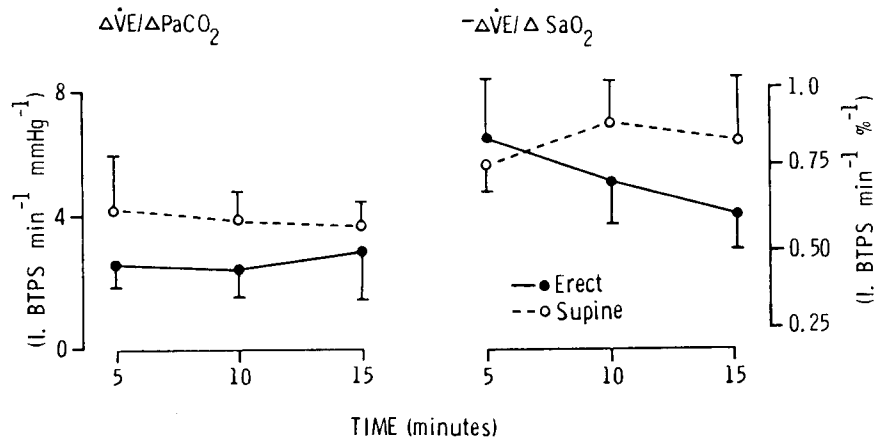

Fig. 4. Mean (± SEM) values for ventilatory response to hypercapnia ($\Delta\dot{V}E/\Delta Pa_{CO_2}$) and normocapnic hypoxia ($-\Delta\dot{V}E/\Delta Sa_{O_2}$) in eight subjects in erect and supine postures at 5, 10 and 15 min during the steady-state response.

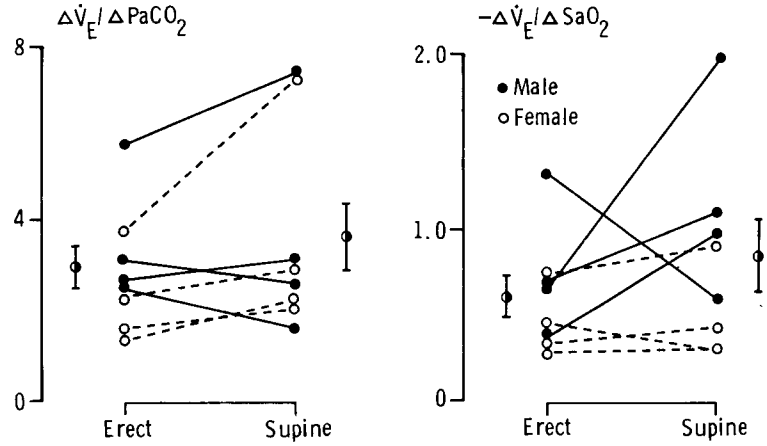

Fig. 5. Individual values at 15 minutes for ventilatory response to hypercapnia ($\Delta\dot{V}E/\Delta Pa_{CO_2}$) and normocapnic hypoxia ($-\Delta\dot{V}E/\Delta Sa_{O_2}$) in erect and supine postures.

significant. Those who showed the largest postural change to hypercapnic stimulation were not the same as those who showed the largest postural change with hypoxic stimulation. When $\dot{V}E$ was normalised to the vital capacity (VC) of each subject, the ventilatory response to hypoxia $-\Delta\dot{V}E/(VC \cdot \Delta Sa_{O_2})$ was $0.119 \pm 0.06\ min^{-1} \cdot \%^{-1}$ (SD) erect and 0.179 ± 0.09 supine, a difference which just reached significance ($P = 0.049$) on a paired t-test. For hypercapnic stimulation, erect ($0.58 \pm 0.3\ min^{-1} \cdot mm\ Hg^{-1}$) and supine ($0.78 \pm 0.65$) differences for $\Delta\dot{V}E/(VC \cdot \Delta P_{CO_2})$ were not significantly different. In a recent study (Chapman and Rebuck, 1984a) with progressive hypercapnia (rebreathing) values of 0.67 ± 0.3 (seated) and 0.61 ± 0.2 (supine) were obtained– a difference which was not significant. There were no significant postural differences between changes of mean inspiratory flow per unit Sa_{O_2} or P_{CO_2} change [$\Delta VT/(TI \cdot \Delta Sa_{O_2})$, $\Delta VT/(TI \cdot \Delta P_{CO_2})$].

Reproducibility. The responses were reproducible from day to day; $-\Delta\dot{V}E/\Delta Sa_{O_2}$ was 0.75, 0.8, 0.73 on separate occasions in one and 0.42 and 0.33 in another subject. $\Delta\dot{V}E/\Delta P_{CO_2}$ was 2.07, 1.75, 1.86 on separate days in one and 5.79 and 5.4 in another subject. When two levels of hypoxia (10.5 and 13% inspired O_2) or four levels of inspired CO_2 (4.5, 5.5, 6.4, 7.3%) were inhaled sequentially the relationship between $\dot{V}E$ and Sa_{O_2} and $\dot{V}E$ and P_{CO_2} was linear (two subjects for each study).

Discussion

Calibration. The inductance coils were calibrated separately in each posture; the accuracy and stability of the calibrations were similar erect and supine (table 1). From the pre-post SP/RIP ratio change (table 1) mean tidal volumes were estimated with a maximum error of about 5%. The postural change from erect to supine produces a large

shift in the ABD/RC ratio (see ABD% in table 2) and a change of posture itself has been used as a method for calculating RC and ABD volume motion coefficients and calibrating RIP (Chadha *et al.*, 1982). Volume–motion coefficients might in themselves alter with postural shifts and differences have been reported for the semirecumbent *vis à vis* the erect or supine posture (Zimmerman *et al.*, 1983). The volume–motion coefficients, calculated separately in each posture, were the same in this instance (table 1).

Resting values. Control values, shown in table 2, were stable from day to day and there was no difference between hypoxic and hypercapnic studies. The pattern and depth of breathing at rest is similar to that reported in other studies without mouthpieces, *i.e.* with inductance plethysmography (Tobin *et al.*, 1983) or with a canopy (Weissman *et al.*, 1982). In measurements made in ten subjects on two occasions, using the system described in this paper, a noseclip and mouthpiece and 80 ml instrumental dead space increased ventilation and tidal volume by 26–27% compared to breathing without them; the high-flow Ventimask system, as used in this study, eliminated the instrumental dead space and caused no significant changes in the amount of ventilation or its timing (D.L. Maxwell and J.M.B. Hughes, unpublished observations).

Effect of posture on resting values. It is well known that $\dot{V}_E$ is about 20% greater in the erect posture in spite of an arterial P_{CO_2} which is 1–3 mm Hg lower (Anthonisen *et al.*, 1965). The pattern of breathing has been analysed by Weissman *et al.* (1982) using the head canopy and the results using inductance plethysmography (table 2) are broadly similar including the increase in TI when subjects were supine. The abdominal contribution to the tidal volume increased from 40 to 64% when supine. Chadha *et al.* (1982), also using RIP, reported an increase in ABD% from 28 to 70%.

The increase in ventilation (total and alveolar) in the erect posture at rest compared to supine is not easily explained. It is accompanied by a substantial increase in electrical activation of the diaphragm (Druz and Sharp, 1981) despite the lower Pa_{CO_2}, presumably as compensation for the reduction in diaphragm fibre length at the larger end-expiratory lung volume when erect (Green *et al.*, 1978). The increase in $\dot{V}_E$ when erect is abolished by water immersion to the level of the xiphoid cartilage (Anthonisen *et al.*, 1965). This eliminates venous pooling in the legs and might prevent the 20% decrease in cerebral blood flow which occurs when the erect posture is assumed (Lassen, 1959).

Ventilatory response to hypoxia. The values for hypoxic sensitivity ($-\Delta\dot{V}_E/\Delta Sa_{O_2}$) are in line with recent studies (table 4) using closed systems and progressive hypoxia once the level of arterial or end-tidal P_{CO_2} has been taken into account. There is an important interaction between P_{CO_2} and $-\Delta\dot{V}_E/Sa_{O_2}$ (Rebuck and Woodley, 1975) so that measurements are usually made under isocapnic conditions maintaining a constant end-tidal P_{CO_2}. Ideally, the arterial rather than end-tidal P_{CO_2} should be held constant. While this difference is small in normal subjects, it will be larger in patients with $\dot{V}_A/\dot{Q}$

TABLE 4

Results in normal subjects (n = number) for hypoxic ($-\Delta\dot{V}E/\Delta Sa_{O_2}$) and hypercapnic ($\Delta\dot{V}E/\Delta P_{CO_2}$) ventilatory responses ($\pm$ 1 SD) in erect and supine postures. Under Methods, closed and open refer to the breathing circuit.

Author(s)	Method	(n)	P_{CO_2} (mm Hg)	$-\Delta\dot{V}E/\Delta Sa_{O_2}$ ($L \cdot min^{-1} \cdot Sa_{O_2}^{-1}$)	
				Erect	Supine
Slutsky *et al.* (1980)	Closed: mouthpiece	(7)	45 ± 1	1.21 ± 0.7	1.07 ± 0.5
This study	Open: respitrace	(8)	41 ± 4 (E) 41 ± 2.7 (S)	0.61 ± 0.34	0.84 ± 0.58
Rebuck and Woodley (1975)	Closed: mouthpiece	(11)	39 ± 1.4 52 ± 1.6	0.56 ± 0.4 2.0 ± 0.65	
				$\Delta\dot{V}E/\Delta P_{CO_2}$ ($L \cdot min^{-1} \cdot mm\ Hg^{-1}$)	
				Erect	Supine
Chapman and Rebuck (1984a)	Closed: mouthpiece	(8)		3.37 ± 1.31	3.07 ± 0.71
Lederer *et al.* (1977)	Closed: mouthpiece	(10)		3.03 ± 0.4*	2.98 ± 0.3*
Rigg *et al.* (1974)	Closed: mouthpiece	(8)		4.01 ± 1.4	4.2 ± 1.6
Weissman *et al.* (1982)	Open: canopy	(5)		2.8 ± 1.6	2.9 ± 1.9
This study	Open: respitrace	(8)		2.89 ± 1.4	3.73 ± 2.35

* SEM.

inhomogeneity; hence, the interest in a transcutaneous measurement of 'arterial' P_{CO_2}.

The pattern of ventilatory response in steady-state hypoxia differs from the response to transient or progressive hypoxia (Rebuck *et al.*, 1976; Gardner, 1980). The increase in $\dot{V}E$ in the transient response is characterized by a greater increase in f (shortening of TI and TE) than tidal volume but the reverse occurs with the steady-state isocapnic response as seen in this study and previously (Gardner, 1977, 1980). The steady-state response to hypoxia in man differs from that seen in the awake cat where substantial shortening of TI as well as TE is observed (Gautier, 1976).

There was a significant difference between the steady-state response after 10 compared to 15 min of hypoxia (fig. 5). This was caused by a progressive fall of Sa_{O_2} while $\dot{V}E$ remained constant. Weil and Zwillich (1976) observed that the steady-state response diminished with increasing exposure to hypoxia, due to a fall in $\dot{V}E$ rather than Sa_{O_2}. Presumably both findings represent adaptation to the stimulus. Nevertheless, no changes between the tenth and the fifteenth minutes were observed for the steady-state response to hypercapnia in erect or supine nor to hypoxia in the supine posture.

Ventilatory response to hypercapnia. The ventilatory response ($\Delta\dot{V}E/\Delta P_{CO_2}$) in this study was similar to that reported for the steady state by Weissman *et al.* (1982) with a canopy system and Lederer *et al.* (1977) for the non-steady state (rebreathing) with mouthpiece and noseclip (table 4). In terms of the pattern of breathing (f, TI and TE), the results are similar to those of Weissman *et al.* (1982) except that the shortening of

TE in the present study did not reach significance. The response to hypercapnia during rebreathing is characterized by two phases (Clark and von Euler, 1972); in range 1, during which the tidal volume is approximately two to three times control values (as in this study), TI remains constant but at greater VT (range 2) increasing vagal activity leads to progressive shortening of TI.

Relation between hypoxic and hypercapnic response. The steady-state responses to a predominantly peripheral chemoreceptor stimulus (normocapnic hypoxia) and a largely central stimulus (hypercapnia) were not significantly different (fig. 3, table 3). Thus, results with respiratory inductance plethysmography and transcutaneous O_2 and CO_2 measurements are in agreement with previous work (Hey *et al.*, 1966; Gardner, 1977, 1980). Nevertheless, the responses to a transient or non-steady-state stimulus are different for hypoxia and hypercapnia (Rebuck *et al.*, 1976; Gardner, 1980).

Postural effects on hypoxic and hypercapnic responses. Table 4 summarizes the findings of various groups who have used a variety of techniques. There is no evidence that the postural change from erect to supine has a very significant effect on the ventilatory response to either stimulus, though there was a trend towards a greater response in the supine posture in this study in terms of $\dot{V}E$ and VT/TI (fig. 5, table 3). The pattern of response in terms of the spirogram (fig. 3), TI and TE and abdominal contribution to tidal volume (table 3) was essentially independent of posture and of the nature of the chemical stimulus.

Partitioning of tidal volume. Although there were large differences in the abdominal contribution to tidal volume in the supine as opposed to the erect posture (64% *vs* 40%, table 2) in the resting state, there was no significant change in its relative contribution during stimulated breathing in either posture or with either stimulus. On the other hand, the increase in tidal volume to non-steady-state stimuli, either progressive hypoxia (Chapman and Rebuck, 1984b) or CO_2 rebreathing (Pengelly *et al.*, 1979) was achieved almost entirely by enhancement of rib cage motion, irrespective of posture (Chapman and Rebuck, 1984b). The explanation for these differences probably relates to the larger VT in the Pengelly and the Chapman studies which placed their subjects in Clark and von Euler's 'range 2' (1972). At the lower VT in this study the small decrease in abdominal contribution was similar for hypoxic and hypercapnic stimulation and was not related to the magnitude of VT change.

Conclusion. The resistance of the respiratory system is greater in the supine position (Granath *et al.*, 1959); on the other hand, the mechanical efficiency of the diaphragm in terms of trans-diaphragmatic pressure change per unit integrated EMG signal (Pdi/Edi ratio) is about three times greater supine than erect (Druz and Sharp, 1981). Nevertheless, the respiratory system is so finely tuned, presumably via proprioceptive feedback, that for a given chemical stimulus the change of total ventilation remains essentially unaffected by the combination of mechanical loading and unloading which accompany postural change from seated to supine.

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