special communication

Estimation of ventilatory capacity during submaximal exercise

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BABB, T. G., AND J. R. RODARTE. *Estimation of ventilatory capacity during submaximal exercise.* J. Appl. Physiol. 74(4): 2016–2022, 1993.—There is presently no precise way to determine ventilatory capacity for a given individual during exercise; however, this information would be helpful in evaluating ventilatory reserve during exercise. Using schematic representations of maximal expiratory flow-volume curves and individual maximal expiratory flow-volume curves from four subjects, we describe a technique for estimating ventilatory capacity. In these subjects, we measured maximal expiratory flow-volume loops at rest and tidal flow-volume loops and inspiratory capacity (IC) during submaximal cycle ergometry. We also compared minute ventilation ($\dot{V}\text{E}$) during submaximal exercise with calculated ventilatory maxima ($\dot{V}\text{E}_{\max\,\text{Cal}}$) and with maximal voluntary ventilation (MVV) to estimate ventilatory reserve. Using the schematic flow-volume curves, we demonstrated the theoretical effect of maximal expiratory flow and lung volume on ventilatory capacity and breathing pattern. In the subjects, we observed that the estimation of ventilatory reserve with use of $\dot{V}\text{E}/\dot{V}\text{E}_{\max\,\text{Cal}}$ was most helpful in indicating when subjects were approaching maximal expiratory flow over a large portion of tidal volume, especially at submaximal exercise levels where $\dot{V}\text{E}/\dot{V}\text{E}_{\max\,\text{Cal}}$ and $\dot{V}\text{E}$/MVV differed the most. These data suggest that this technique may be useful in estimating ventilatory capacity, which could then be used to evaluate ventilatory reserve during exercise.

maximal ventilation; lung volumes; breathing pattern; lung mechanics; ventilatory reserve; airflow limitation

THERE IS PRESENTLY no precise way to determine ventilatory capacity for a given individual during exercise; however, this information is necessary to adequately evaluate the ventilatory reserve during exercise, especially when the effect of maximal expiratory flow on exercise ventilation is investigated (3, 4) or when the ventilatory results of a diagnostic exercise test are determined (7, 23, 27). Usually ventilatory capacity is estimated from the maximal voluntary ventilation (MVV), and the MVV is then used to determine ventilatory reserve by calculating the minute ventilation- ($\dot{V}\text{E}$) to-MVV ratio. However, the use of the MVV is limited as an estimate of ventilatory capacity, because it is performed voluntarily for only a few seconds and then extrapolated to 1 min, and it is performed with high breathing frequencies (f) and small tidal volumes ($V\text{T}$) near total lung capacity (TLC), where one rarely breathes during exercise. Although we consider ventilatory capacity and ventilatory reserve to be important to exercise tolerance, it is very difficult to estimate.

In this report, we describe a technique for estimating ventilatory capacity, where ventilatory capacity is calculated ($\dot{V}\text{E}_{\max\,\text{Cal}}$) from the maximal expiratory flow-volume curve (5, 6, 12, 17). To illustrate this technique, we use schematic representations of maximal expiratory flow-volume curves and individual maximal expiratory flow-volume curves from four subjects with supernormal to slightly reduced pulmonary function. Also, we compare $\dot{V}\text{E}$ during submaximal exercise with $\dot{V}\text{E}_{\max\,\text{Cal}}$ and MVV to estimate ventilatory reserve.

METHODS

Subjects. All four subjects were men familiar with pulmonary testing and exercise (Table 1). All the subjects were physically active, participating in activities such as tennis and recreational bicycling, but none was participating in regular exercise training programs. All the subjects were asymptomatic and considered themselves healthy. *Subject 3* was the only smoker. The study was approved by the Institutional Review Board, and informed consent was obtained from all subjects.

Pulmonary function data are presented in Table 1. The MVV was determined from the maximal ventilation obtained in five successive breaths and extrapolated to 1 min. The pulmonary function technician observed an analog display proportional to ventilation and coached subjects to achieve maximal values. Although this technique for calculation of MVV gives a slightly greater value than a 12-s test, all subjects would be affected equally.

Maximal exercise test. Graded cycle ergometry was performed on an electronically braked cycle ergometer with use of 1-min 25- or 30-W increments in work rate. Exercise continued until volitional termination of the test. Measurements of gas exchange were made over the last

TABLE 1. *Subject physical characteristics and pulmonary function*

Subj No.	Age, yr	Ht, cm	Wt, kg	TLC, liters	VC, liters	FEV_1, liters	FEV_1/ FVC, %	MVV, l/min
1	40	183	74.8	9.2 (127)	7.5 (135)	6.2 (139)	83	248 (143)
2	33	183	78.2	8.8 (123)	6.7 (117)	5.3 (114)	80	207 (113)
3	50	188	83.9	8.0 (106)	5.7 (106)	4.0 (95)	70	177 (109)
4	31	170	79.4	6.5 (105)	4.9 (102)	3.1 (78)	64	127 (74)

Values in parentheses represent percent predicted. TLC, total lung capacity (determined by plethysmography); VC, vital capacity; FEV_1, forced expiratory volume in 1 s; FVC, forced vital capacity; MVV, maximal voluntary ventilation.

20 s of each work increment by use of an on-line breath-by-breath system. Electrocardiogram and blood pressure were monitored at each work rate during the exercise test.

Lung mechanics studies. On a separate day, maximal flow-volume loops, isovolume-pressure flow curves (22), and lung volumes were determined in a pressure-corrected volume-displacement body plethysmograph to eliminate the gas compression artifact (9, 15, 19). Transpulmonary pressure (Ptp) was estimated by subtracting airway opening pressure from esophageal pressure, which was measured using an esophageal balloon placed 45 cm from the nostril (Statham transducer). Validity of the balloon pressure was checked by having the subjects blow through a small orifice; if Ptp remained constant while oral pressure increased, placement was considered appropriate. Flow, volume, and Ptp were displayed on a strip chart recorder (HP-7758A) and sampled in real time (66 Hz) on a computer (DEC 11/73) for subsequent analysis. The maximal expiratory flow-volume curves were used for calculation of ventilatory capacity, and the other data were used to determine when maximal expiratory flow was achieved during exercise.

Breathing mechanics during submaximal exercise. Immediately after the lung mechanics studies, the subjects were asked to sit on the cycle ergometer while baseline measurements were made. All measurements at rest and during exercise were made with the subjects seated in the same body position. After 2 min of baseline measurements, the subjects performed progressive submaximal cycle ergometry on a mechanically braked cycle ergometer (Monark). Exercise began with 1.5–3 min of loadless cycling; thereafter the work rate was increased by 30 or 60 W every 1.5–3 min. A pedal rate of ~60 rpm was maintained using a cadence metronome.

At rest and during exercise, the subjects breathed through a mouthpiece attached to a two-way valve (MR-1) with an approximate dead space of 105 ml. Inspiratory and expiratory flows were determined by separate linearized hot wire pneumotachographs (Datametrics series 1000, MR-1). The separate inspiratory and expiratory flow signals were summed, and volume was determined from the integration of the summed flow signal. The flow resistances of the inspiratory and expiratory circuits were $<1.0\ cmH_2O \cdot l^{-1} \cdot s$ for flows of ±10 l/s. The esophageal balloon used in the lung mechanics studies remained in place for baseline measurements and during the submaximal exercise test. Balloon volume and position were checked before baseline measurements. Ptp was determined using a Statham transducer (PM131 ±5 psi). Flow, volume, and Ptp were displayed on a strip chart recorder (HP-7414A) and sampled in real time (66 Hz) on a computer (DEC 11/73).

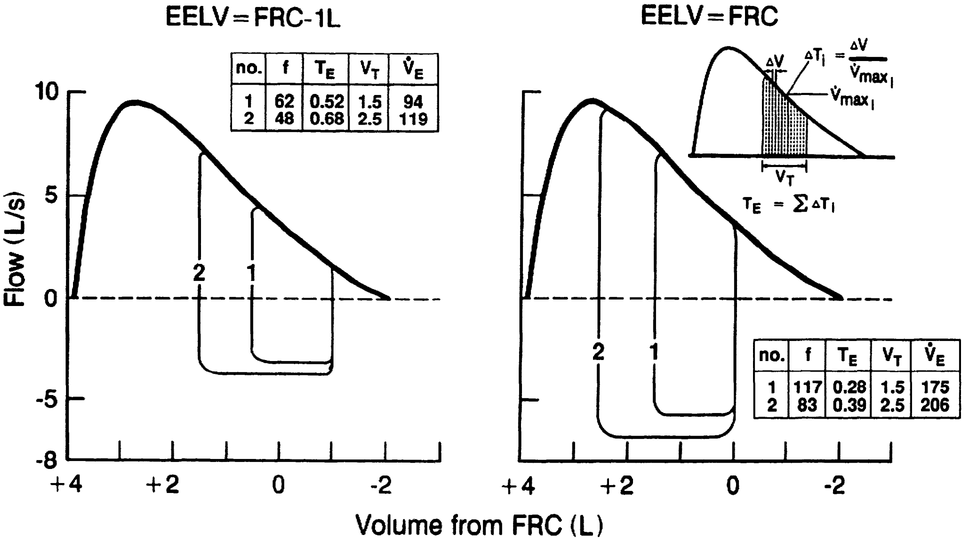
End-expiratory lung volume (EELV) was estimated at rest and during submaximal exercise from measurement of inspiratory capacity (IC), which we determined was an accurate estimate of EELV in earlier work (2). IC was measured during the last few seconds of each work load. Measurement of IC was performed by having the subject, on cue from the investigator, inhale maximally to TLC. A maximal inspiratory effort was confirmed by comparing maximal Ptp during the IC maneuver with the maximal static recoil pressure determined at baseline. We assumed that TLC does not change significantly during exercise either in control subjects with normal lung function or in patients with airflow limitation (2, 25, 26, 28). The subjects in our study were able to perform the procedure without difficulty.

Data analysis. Maximal and tidal flow-volume and pressure-volume loops were determined at baseline, and tidal flow-volume and pressure-volume loops were determined during exercise. A typical exercise tidal flow-volume loop, as well as the corresponding pressure-volume loop, was chosen from the breaths preceding the maximal inspiration and was positioned within the maximal flow-volume loop by use of the measured IC. A breath was considered typical if it had approximately the same volume and flow characteristics as the other breaths before the IC.

Submaximal exercise data were obtained from the last 30 s of the exercise increment, before the IC maneuver. VT, f, $\dot{V}$E, inspiratory time (TI), and expiratory time (TE) were calculated from the volume signal by an interactive computer program developed for the study. The computer-stored data were screened by the investigator with the interactive computer program and played back on a graphics terminal to generate exercise tidal flow-volume loops and pressure-volume loops. Body plethysmograph and preexercise maximal flow-volume loops also were extracted using the same program. By overlaying the maximal flow-volume loop and exercise tidal flow-volume loops, flow characteristics could be compared between baseline conditions and exercise. The same was done for maximal and tidal pressure-volume loops.

Calculation of ventilatory maxima ($\dot{V}E_{max\,Cal}$). The method for calculation of ventilatory maxima uses a maximal expiratory flow-volume curve plus measured VT, EELV, and inspiratory duty cycle (TI/TT) for a given level of exercise ventilation. These measurements are used to calculate minimum TE ($TE_{min\,Cal}$), maximal f ($f_{max\,Cal}$), and $\dot{V}E_{max\,Cal}$ for a specified level of exercise (5, 6, 12, 16). If the measured $\dot{V}$E approaches $\dot{V}E_{max\,Cal}$, the subject has attained his mechanical ventilatory maximum.

Figure 1 shows schematic representations of a maximum flow-volume curve with various tidal expiratory flow-volume curves and lung volumes. $TE_{min\,Cal}$ for a specific tidal expiratory flow-volume curve and lung volume is calculated graphically by dividing measured VT into small equal increments (ΔV_i), which are then divided by



no.	f	T_E	V_T	$\dot V_E$
1	62	0.52	1.5	94
2	48	0.68	2.5	119

no.	f	T_E	V_T	$\dot V_E$
1	117	0.28	1.5	175
2	83	0.39	2.5	206

FIG. 1. Calculation of maximal ventilation from schematic representations of maximal expiratory flow-volume curves (heavy lines). These calculations represent various tidal expiratory flow-volume curves (*1* and *2*) at 1 liter below resting functional residual capacity (FRC; EELV = FRC − 1 liter; EELV, end-expiratory lung volume) and at resting FRC (EELV = FRC). *Inset*: procedure for calculating expiratory time (TE) for each tidal volume (VT). Tables indicate breathing frequency (f, breaths/min), TE (s), VT (liters), and minute ventilation ($\dot V$E, l/min). Inspiratory time (TI, s) was taken to be 82% of TE, which results in an inspiratory duty cycle of 0.46. [Adapted from Beck et al. (6).]

the average measured expiratory flow ($\bar{\dot V}max_i$) over the volume increment (Fig. 1)

$$TE_{min\,Cal} = [\Sigma_i(\Delta V_i/\bar{\dot V}max_i)]$$

where $\Delta V_i = V_i - V_{i-1}$ and $\bar{\dot V}max_i = (\dot V max_i - \dot V max_{i-1})/2$.

The maximal f for the measured VT and lung volume is calculated by

$$f_{max\,Cal} = [1/(TE_{min\,Cal}/1 - TI/TT)] \cdot 60$$

A TI/TT of 0.46 was used to calculate the values in Fig. 1.

$\dot V E_{max\,Cal}$ that is possible for a measured VT and lung volume is calculated by

$$\dot V E_{max\,Cal} = VT \cdot f_{max\,Cal}$$

Two potential sources of error in determining $\dot V E_{max\,Cal}$ are the measurement of maximal expiratory flow and the measurement of lung volume (EELV). With the assumption of errors in each method of ±5% (23) and ±134 ml (2), respectively, the greatest cumulative error in the determination of $\dot V E_{max\,Cal}$ could be ~12%.

In all calculations for the subjects, $TE_{min\,Cal}$ was increased to adjust for the time necessary to achieve maximal expiratory flow. It is not possible to reach maximal expiratory flow instantaneously, as depicted in the schematic representations shown in Fig. 1, because of the impedance of the respiratory system and the force-velocity relationship of the expiratory skeletal muscles. Therefore the following correction was made to $TE_{min\,Cal}$

$$TE_{min\,Cal} = [\Sigma_i(\Delta V_i/\bar{\dot V}max_i)]/0.9$$

This 11% increase in $TE_{min\,Cal}$ was estimated from the findings of Jensen and others (16), who reported that subjects approach but never achieve the minimum TE estimated from the maximal expiratory flow-volume curve. All other calculations ($f_{max\,Cal}$ and $\dot V E_{max\,Cal}$) for the subjects were made as outlined above, except measured values of VT, EELV, and TI/TT for a specified level of exercise and the individual's maximal flow-volume curve were used for the calculations.

RESULTS

Theoretical results. The data in the tables in Fig. 1 represent calculations from the schematic representations shown in Fig. 1, which represent a young healthy individual. The table on the *right* contains calculations for two VT (*1* and *2*) that initiate from a lung volume equal to functional residual capacity (FRC) − 1 liter. The calculations in the table on the *left* are for the same two VT (*1* and *2*), except they initiate from a lung volume equal to FRC (FRC = EELV). In both tables, as VT increases, TE also increases, but to a lesser degree than $\dot V$E, which increases markedly. This is because the increase in VT causes a less-than-proportionate increase in TE because of the relationship of maximal expiratory flow to lung volume. In the table on the *left*, a reduction in EELV increases $TE_{min\,Cal}$ and reduces $\dot V E_{max\,Cal}$, compared with the table on the *right*, for the same VT. This is because lower maximal expiratory flows result in a higher $TE_{min\,Cal}$ and a lower $f_{max\,Cal}$. $\dot V E_{max\,Cal}$ is markedly affected by EELV. The more concave the maximal expiratory flow-volume curve, the more TE and $\dot V$E are affected by decreasing EELV. The potential for increasing VT and EELV is limited by the encroachment of end-inspiratory lung volume (EILV) on TLC, as demonstrated in Fig. 1 (11, 18, 20).

In Fig. 2, $f_{max\,Cal}$ and $\dot V E_{max\,Cal}$ (hatched areas) are represented on a VT vs. f plot for the same VT range (1.5–2.5 liters) and EELV range (EELV = FRC − 1 liter and EELV = FRC) shown in Fig. 1. The calculations of $f_{max\,Cal}$ and $\dot V E_{max\,Cal}$ for Fig. 2 were made assuming TI/TT of 0.42 and 0.50 (10). The left side of the hatched area represents the $f_{max\,Cal}$ when TI/TT = 0.50. The right side of the hatched area represents the $f_{max\,Cal}$ for the same VT and $TE_{min\,Cal}$ when TI/TT = 0.42. By allowing TI/TT to vary, $f_{max\,Cal}$ is increased or decreased for the same VT and EELV (width of the hatched areas). Also, as $f_{max\,Cal}$ increases or decreases, so does $\dot V E_{max\,Cal}$ (hatched areas cross-ventilation isopleths). The ventilation isopleths, which outline the background of the VT and f plot, show the different ventilations that can be produced for the different combinations of VT and f.

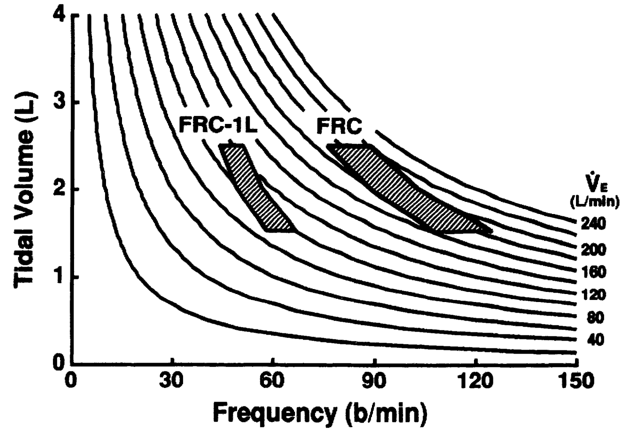


FIG. 2. Schematic representation of effect of EELV on calculated maximal ventilation ($\dot{V}E_{max\,Cal}$, hatched areas). $\dot{V}E_{max\,Cal}$ was calculated from maximal expiratory flow-volume curves shown in Fig. 1 for each of various VT and lung volumes. $\dot{V}E_{max\,Cal}$ as a function of VT (range 1.5–2.5 liters), f, and inspiratory duty cycle (TI/TT) at EELV = FRC and EELV = FRC − 1 liter. At a given VT, EELV, and TE, $\dot{V}E_{max\,Cal}$ can be increased by decreasing TI so that TI/TT is decreased.

Maximal exercise. All four subjects obtained or exceeded their age-predicted maximal O_2 uptake and maximal heart rate (Table 2). On the basis of maximal O_2 uptake ($ml \cdot kg^{-1} \cdot min^{-1}$), all the subjects would be considered fit. Their $\dot{V}E$/MVV was probably higher than reported in previous studies, because they were aerobically fit and because they were highly motivated to continue the maximum exercise test until complete exhaustion.

Breathing mechanics during submaximal exercise. The tidal flow-volume curves recorded during submaximal exercise are presented in Fig. 3 relative to the maximal flow-volume loop and tidal flow-volume loop determined during baseline. Tidal expiratory flow for *subject 1* never approached maximal expiratory flow at any level of exercise. *Subject 2* exceeded maximal expiratory flow only when there was a large increase in ventilation at the end of exercise. *Subjects 3* and *4* approached maximal expiratory flow at relatively low ventilatory demands (46 and 40 l/min, respectively). At greater ventilatory demands, *subjects 3* and *4* followed maximal expiratory flow over ~33 and 52% of VT, respectively. The results for *subjects 1–4* were similar to those reported in the literature for normal subjects (17, 22, 25) and for patients with mild-to-moderate airflow limitation (3, 4).

As evident from Fig. 3, all the subjects decreased their EELV during low-level exercise. Furthermore, most of the increase in VT during low-level exercise was at the expense of EELV. The response of EELV (1, 14, 21, 24, 28) and its contribution to the increase in VT during low-level exercise have been reported previously (2, 8, 14, 21, 24, 28). All the subjects continued to decrease EELV until higher levels of submaximal exercise were obtained. *Subjects 2–4* increased EELV at the higher levels of exercise when maximal expiratory flow was approached over a large percentage of VT. EELV in *subjects 3* and *4* was equal to or greater than baseline EELV at the highest level of ventilation. Johnson and others (17) reported a similar increase in EELV for physically active elderly subjects.

Ventilatory capacity and reserve. Ventilatory maxima were calculated for each work rate by use of the individual's own VT, TI/TT, EELV, and maximal expiratory flow-volume curve, as measured in the body plethysmograph. To determine the fraction of ventilatory capacity used by the subjects during submaximal exercise, we compared observed $\dot{V}E$ with $\dot{V}E_{max\,Cal}$ and with the MVV. $\dot{V}E/\dot{V}E_{max\,Cal}$ vs. ventilation is presented in Fig. 4 for each subject. Also shown in Fig. 4 is $\dot{V}E$ as a percentage of MVV.

On the basis of $\dot{V}E/\dot{V}E_{max\,Cal}$, *subject 1* used very little of his estimated ventilatory capacity during low-level exercise, as indicated from Fig. 3. For *subject 1*, $\dot{V}E$/MVV was very similar to $\dot{V}E_{max\,Cal}$. This is probably related to the fact that *subject 1* had such high flow reserves; his $\dot{V}E_{max\,Cal}$ was larger than MVV even at low lung volumes. *Subject 2* exceeds $\dot{V}E_{max\,Cal}$, presumably because bronchodilation caused an increase in maximal expiratory flow during exercise, which has been demonstrated by others (12, 15, 16). $\dot{V}E$/MVV reflected a large ventilatory reserve during the last level of exercise. *Subjects 3* and *4* used a large percentage of $\dot{V}E_{max\,Cal}$ at very low work rates because of the decrease in EELV and the lower maximal expiratory flow at low lung volumes. In *subject 3*, $\dot{V}E/\dot{V}E_{max\,Cal}$ actually decreased slightly at 180 W; this is because EELV increased slightly, which increased $\dot{V}E_{max\,Cal}$. Also in *subject 3*, $\dot{V}E/\dot{V}E_{max\,Cal}$ at the highest level of ventilation shows ventilatory reserve to be almost exhausted, whereas $\dot{V}E$/MVV shows ventilatory reserve to be normal. In *subject 4*, $\dot{V}E/\dot{V}E_{max\,Cal}$ and $\dot{V}E$/MVV are close at the last stage of exercise. This is because *subject 4* was breathing near TLC, where $\dot{V}E_{max\,Cal}$ and MVV are similar, and unlike *subject 3*, *subject 4* had a reduction in both peak flow and midvolume flow. Also, in *subject 4*, neither $\dot{V}E/\dot{V}E_{max\,Cal}$ nor $\dot{V}E$/MVV shows ventilatory reserve to be exhausted. However, from Fig. 3, we would suspect ventilatory reserve to be very small.

DISCUSSION

The purpose of this study was to describe a technique for estimating ventilatory maxima from the maximal expiratory flow-volume curve. On the basis of schematic representations of maximal expiratory flow-volume curves, we demonstrated the use of the technique and the

TABLE 2. *Maximal cardiorespiratory responses to graded exercise*

	Subj No.			
	1	*2*	*3*	*4*
$\dot{V}O_2$, $ml \cdot kg^{-1} \cdot min^{-1}$	53.1 (144)	46.3 (108)	42.5 (120)	44.3 (103)
HR, beats/min	178 (97)	165 (87)	174 (100)	186 (98)
$\dot{V}E$, l/min	147.3	184.5	176.1	113.6
f, breaths/min	32.0	56.1	61.8	39.0
VT, liters	4.6	3.3	2.8	2.9
$\dot{V}E$/MVV, %	59	89	99	89
TI/TT, %	38	41	39	41

Values in parentheses represent percent predicted. $\dot{V}O_2$, O_2 uptake; HR, heart rate; $\dot{V}E$, minute ventilation; f, breathing frequency; VT, tidal volume; TI/TT, inspiratory portion of duty cycle.

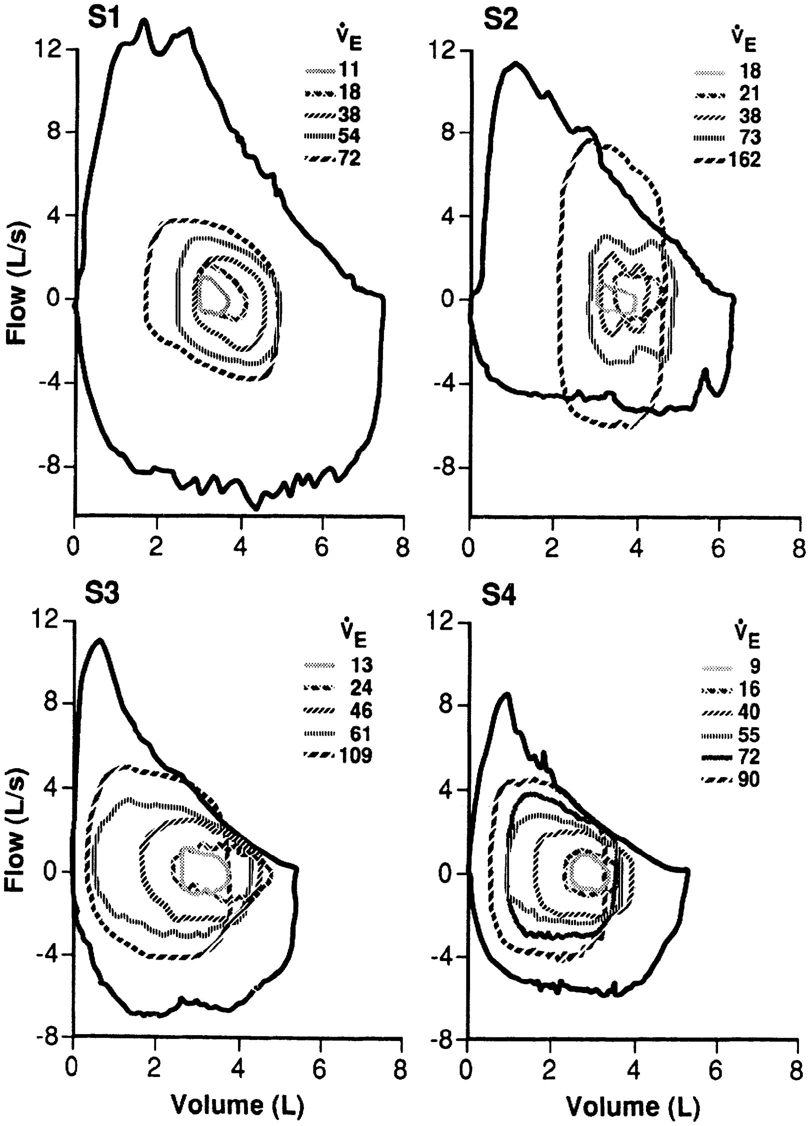


FIG. 3. Maximal flow-volume loop (heavy line), typical resting tidal flow-volume loop (smallest loop), and typical tidal exercise flow-volume loop for various ventilatory demands during submaximal exercise. S1, S2, S3, and S4, *subjects 1, 2, 3,* and *4*, respectively.

theoretical effect of maximal expiratory flow and lung volume on ventilatory capacity (Fig. 1). We also demonstrated the effect of breathing pattern and Ti/Tt on ventilatory capacity (Fig. 2). $\dot{V}E_{\max \mathrm{Cal}}$ is significantly affected by lung volume (EELV), maximal expiratory flow, and breathing pattern (Vt, f, Ti/Tt).

In four subjects with various degrees of maximal expiratory flow, we illustrated the use of this technique for estimating ventilatory capacity and calculating ventilatory reserve during submaximal exercise. We observed that the estimation of ventilatory reserve with use of $\dot{V}E/\dot{V}E_{\max \mathrm{Cal}}$ was most helpful in indicating when subjects were approaching maximal expiratory flow over a large portion of Vt during low-level exercise where $\dot{V}E/\dot{V}E_{\max \mathrm{Cal}}$ and $\dot{V}E$/MVV differed the most. Even small changes in lung volume and maximal expiratory flow at lower lung volumes were reflected in $\dot{V}E_{\max \mathrm{Cal}}$ during submaximal exercise. The MVV remained constant. At heavier exercise levels, $\dot{V}E/\dot{V}E_{\max \mathrm{Cal}}$ and $\dot{V}E$/MVV were closer because of the rise in EELV and EILV. We have not yet tried to estimate ventilation at maximal exercise with this technique, but these results would support such an attempt.

Others used the maximal expiratory flow-volume curve to describe the mechanical limits to maximal ventilation and to estimate ventilatory capacity, but they did not restrict their analyses to lung volumes and breathing patterns normally adopted during exercise (5, 12, 16). It is necessary to account for breathing pattern and lung volume when evaluating ventilatory capacity during submaximal exercise, because each has a profound effect on the maximum ventilation that can be generated at any particular level of exercise. As we have shown, it is possible for ventilation to approach a ventilatory maximum at lower lung volumes without approaching ventilatory maximum at higher lung volumes, because maximal expiratory flow is greater at higher lung volumes (Fig. 2). Therefore we based our calculations of ventilatory maxima on the actual lung volume adopted by our subjects at each level of exercise. Our technique is different, in that we can estimate ventilatory reserve for different levels of exercise as lung volume or breathing pattern is changing. The ability to adjust ventilatory maxima for physiological considerations allows us to determine whether subjects are experiencing flow limitation during exercise or whether unusual adjustments are needed in lung volume and breathing pattern to increase ventilatory supply. This is not possible with the MVV. On the basis of our

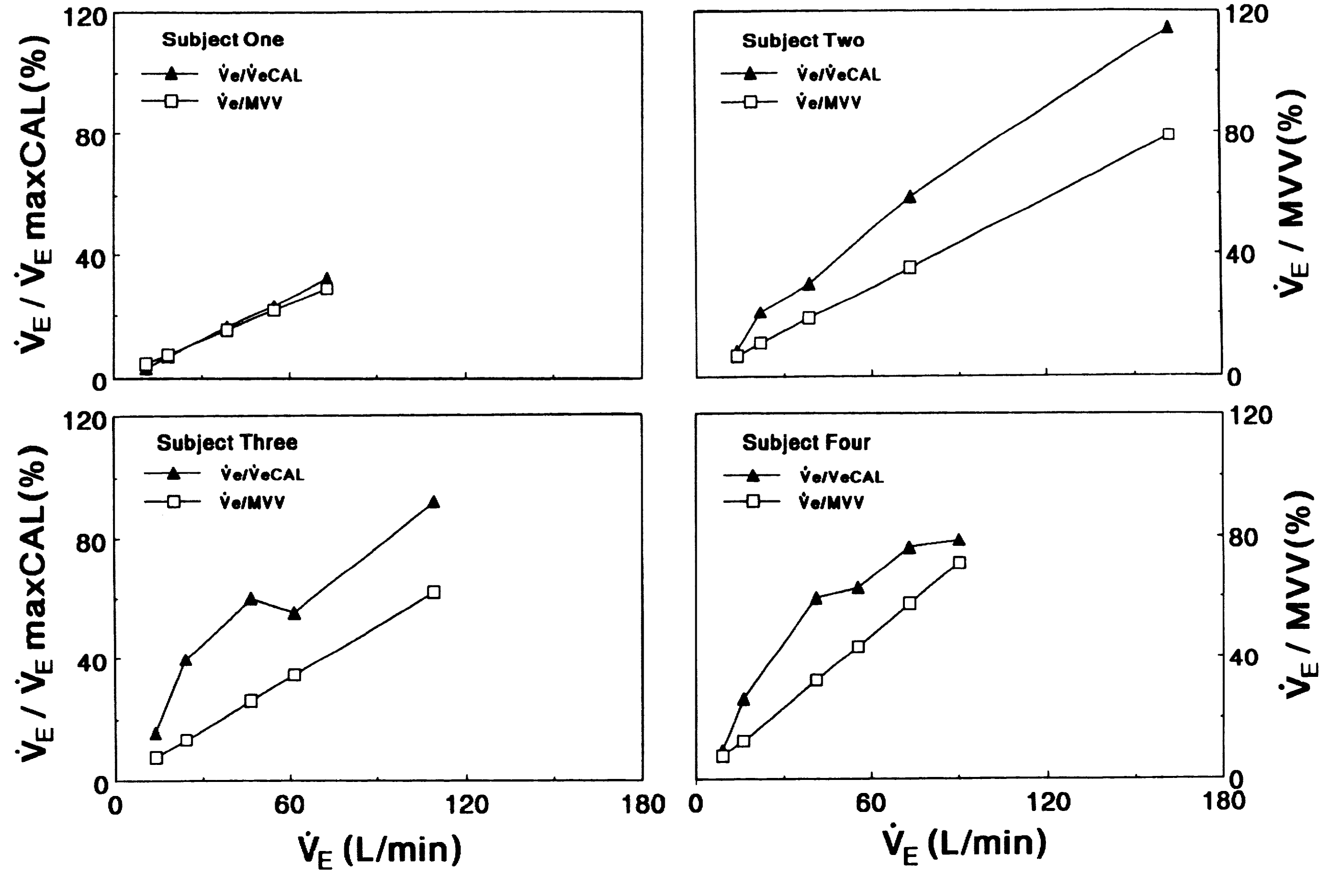


FIG. 4. $\dot{V}E$ as a percentage of $\dot{V}E_{\max\,Cal}$ during submaximal exercise for *subjects 1–4* plotted against $\dot{V}E$. $\dot{V}E_{\max\,Cal}$ was calculated from individual maximal expiratory flow-volume curves with use of subject's EELV, VT, and TI/TT observed at each level of submaximal exercise. Also shown is $\dot{V}E$ as a percentage of maximal voluntary ventilation ($\dot{V}E$/MVV).

illustrations, our technique shows promise as a method for estimating ventilatory capacity and calculating ventilatory reserve during exercise.

When ventilatory reserve is evaluated during submaximal exercise with use of $\dot{V}E/\dot{V}E_{\max\,Cal}$, it is lower than indicated by $\dot{V}E$/MVV (Fig. 4). This is not surprising, considering that the MVV is performed at higher lung volumes, smaller VT, higher f, and greater pressures than developed during exercise (16). Therefore the MVV is much larger than the actual breathing capacity at all lower lung volumes, where one would breathe during exercise. In *subject 1*, who had no flow limitation during exercise, either presentation indicated a large ventilatory reserve. Only in *subject 3* did the use of $\dot{V}E_{\max\,Cal}$ indicate a ratio ($\dot{V}E/\dot{V}E_{\max\,Cal}$ = 91%) at the higher levels of exercise that was consistent with the results in Fig. 3, where ventilatory reserve appeared quite limited; the $\dot{V}E$/MVV showed a much larger reserve. Only by markedly increasing peak tidal expiratory flow could this subject have increased ventilation greatly. In this and in other studies (3, 4), we observed that subjects do not utilize maximal expiratory flow in the upper portion of VT, even during heavy exercise, but would preferably increase EELV when expiratory flow is limited over a large portion of VT at least until EILV approaches TLC (4, 17). This subject probably had very little ventilatory reserve remaining, as indicated by $\dot{V}E/\dot{V}E_{\max\,Cal}$, unless he changed his breathing mechanics markedly.

In *subject 4*, both $\dot{V}E/\dot{V}E_{\max\,Cal}$ and $\dot{V}E$/MVV showed percentage of ventilatory reserve to be similar during heavy exercise ($\dot{V}E_{\max\,Cal}$ = 114 l/min, MVV = 127 l/min, and $\dot{V}E$ = 90 l/min). In this case, the use of $\dot{V}E_{\max\,Cal}$ and MVV gave the same estimate of ventilatory reserve. However, a greater correction to TE would decrease $\dot{V}E_{\max\,Cal}$ and make $\dot{V}E/\dot{V}E_{\max\,Cal}$ much larger, more in line with our conventional thinking of ventilatory limitation. Making $\dot{V}E_{\max\,Cal}$ smaller appears to make sense, because most subjects we have tested in this and in other studies (3, 4) increase EELV before they approach maximal expiratory flow over the entire VT, as mentioned above. No correction to TE in *subject 4* would yield a $\dot{V}E_{\max\,Cal}$ of 129 l/min (Fig. 5, *curve A*; maximal expiratory flow achieved over entire VT). Using the 11% correction to TE, we calculated a $\dot{V}E_{\max\,Cal}$ of 115 l/min (Fig. 5, *curve B*). A greater correction of TE (Fig. 5, *curve C*) would give a $\dot{V}E_{\max\,Cal}$ of 106 l/min ($\dot{V}E/\dot{V}E_{\max\,Cal}$ of 85%). Even this more conservative adjustment to $\dot{V}E_{\max\,Cal}$ does not yield a $\dot{V}E/\dot{V}E_{\max\,Cal}$ of 100%. However, approaching a ventilatory maximum does not imply that the subject was ventilatory limited, just as a lower percentage does not exclude the fact that breathing mechanics were not adjusted to generate the ventilatory output. Subjects and patients can generate very high ventilations just by altering breathing pattern and lung volume, as demonstrated by the MVV. Although we consider such adjustments to be abnormal during exercise, the subject is not technically

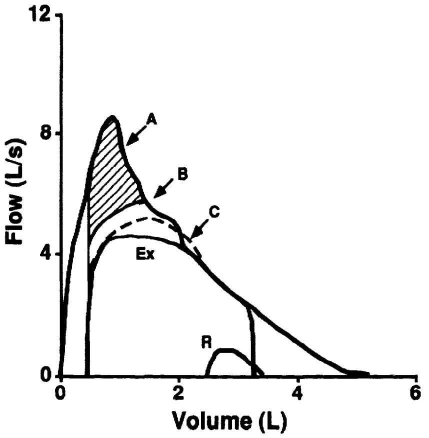


FIG. 5. Maximal expiratory flow-volume curve (*curve A*), resting tidal expiratory flow-volume curve (R), and exercise tidal expiratory flow-volume curve (Ex) for *subject 4. Curve A*, portion of maximal expiratory flow-volume curve used to calculate ventilatory maximum with no correction to T_E (129 l/min). Hatched area above *curve B* represents portion of flow-volume curve excluded to increase maximal T_E by 11% and decrease estimated ventilatory maximum to 114 l/min. Dashed line (*curve C*) represents expiratory flow-volume curve that would yield an estimated ventilatory maximum of 106 l/min. Exercise flow-volume curve denoted by Ex represents a $\dot{V}_E$ of ~90 l/min.

ventilatory limited. He has mechanical limitations to ventilation. Furthermore it is unclear whether these adjustments to breathing mechanics affect exercise tolerance.

Subject 2 exceeded his ventilatory maximum at the last stage of exercise, apparently because maximal expiratory flow had increased during exercise, which has been reported elsewhere (13, 16). This does interfere with our calculations but does not make them invalid. It may be necessary to measure maximal expiratory flow-volume curves immediately after exercise, although these curves would not be corrected for gas compression.

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