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# Estimate of maximum expiratory flow based on the equal pressure point concept and Weibel's lung model

JAMES H. HAYNES and JOHANNES A. KYLSTRA

*F. G. Hall Laboratory for Environmental Research, Duke University Medical Center, Durham, North Carolina 27710*

Haynes, J. H., and J. A. Kylstra 1974. Estimate of maximum expiratory flow based on the equal pressure point concept and Weibel's lung model. Undersea Biomed. Res. 1(1): 45-58.–Using empirical flow equations from the engineering literature we have calculated expiratory pressure-flow relationships in Weibel's lung model. The computed maximum expiratory flow of air and oxygen-helium mixtures over a range of barometric pressures from 1 to 53 atmospheres was in good agreement with experimentally determined values. It is concluded that a diver's maximum expiratory flow at great depths can be estimated from measurements made at the surface and at shallow depths.

expiratory flow
EPP
lung model

Wood and Bryan (1969) have measured the maximum expiratory flow in healthy men who breathed air at pressures up to 10 atmospheres. They derived empirical equations which relate maximum expiratory flow at a given lung volume to the density of the gas breathed. The present paper is a report on attempts to predict maximum expiratory flow in divers using any conceivable breathing mixture at any depth. These predictions are based on the *equal pressure point* (EPP) concept and conventional fluid-flow equations, applied to Weibel's (1964) model of the human lung.

Fry et al. (1954) and Mead et al. (1964, 1967) have pointed out that maximum expiratory flow over most of the vital capacity is effort independent as a result of dynamic compression of airways.

$$\dot{V}\text{E max} = \frac{\text{Pst}}{\text{Rus}} = \frac{\text{Ppl}}{\text{Rds}} \qquad (1)$$

where Rus[1] and Pst are constant at a given lung volume. Here the lateral pressure drop in each generation of Weibel's (1964) dichotomously branching human lung model at increasing expiratory flow rates has been computed. It was assumed that expiratory flow would reach its maximum value whenever the cumulative lateral pressure drop in the airways

[1] Here and throughout this paper the symbols defined by Mead and Milic-Emili (1964) as well as a few simple abbreviations not included in that glossary have been used. For this reason a list of symbols and definitions is given at the end of this paper.

approached the static recoil pressure of the lung. Then computed maximum expiratory flows were compared with measured maximum expiratory flows reported in the literature (Schilder et al. 1963; Stubbs and Hyatt 1972; Varene and Vieillefond 1971; Wood and Bryan 1969). We found that, in general, there was good agreement.

## CALCULATIONS

It is assumed that changes in airway diameter and length upstream of EPP is negligible and gas density in the airways remains constant at physiologic pressures. The calculations were performed with the aid of a digital computer.

### FLOW EQUATIONS

The same four components have been considered responsible for the total drop in pressure within the airways as discussed previously by Rohrer (1915), Fry et al. (1954), and Permutt and Pride (1964) and Pride, Permutt et al. (1967): ΔP*in*(L) due to the inertia of the lung tissue; ΔPres(L) due to resistance to deformation of the lung tissue; ΔP*in*(aw) due to the inertia of the flowing fluid, and ΔPres(aw) due to resistive losses within the airways.

Flow of gas from the lung is caused by the difference in pressure between alveoli and the mouth. Under conditions of effort-independent maximum expiratory flow, the energy losses within the tissues (both inertial and resistive) must be balanced by the pleural pressure. Thus, at $\dot{V}_E$ max only energy losses within the airways need to be considered. Calculations were made of the frictional losses due to laminar flow, frictional losses due to turbulent flow, and the additional energy losses due to perturbations in the fluid caused by branching and contraction or expansion at the branch points. The latter factors were considered together as an entrance effect due to contraction or expansion. Kinetic energy of the gas was calculated. All flow equations were taken from the *Chemical Engineers' Handbook* (Perry 1963) and the units corrected to physiologic units where necessary.

Flow was assumed either fully laminar below a critical Reynolds number (Re) or fully turbulent above that Re. After considering a range of critical Reynolds numbers from 500 to 10,000, 2100 was selected as the critical Re (*see* DISCUSSION). Reynold's number is defined as:

$$\mathrm{Re} = \frac{\mathrm{d} \cdot U \cdot \rho}{\eta} \tag{2}$$

and describes the tendency of the flowing fluid to be in a laminar, turbulent, or transitional flow regime.

For Reynold's numbers equal to or less than 2100, flows were assumed to be laminar and pressure drops described by the Hagen-Poiseuille equation:

$$\Delta\mathrm{Pres(aw), lam} = \frac{32\,\mathrm{L} \cdot U \cdot \eta}{g \cdot \mathrm{d}^2} \tag{3}$$

Above the critical Reynold's number, resistive losses were assumed to be described by the Darcy-Fanning equation:

$$\Delta\mathrm{Pres(aw), turb} = \frac{2f \cdot \mathrm{L} \cdot \rho \cdot U^2}{\mathrm{d} \cdot g} \tag{4}$$

where $f$ is the Fanning friction factor which varies with the state of turbulence as follows:

$$f = 0.0014 + 0.125\,(\mathrm{Re})^{-0.32} \tag{5}$$

The entrance effects must be described by two separate equations, depending upon whether cross-sectional area for flow is contracting or expanding. For contracting cross-sectional areas:

$$\Delta Pc = 0.4\,(1.25 - Ax(k)/Ax(k+1)) \cdot \frac{\rho \cdot (U(k))^2}{2g} \tag{6}$$

For expanding cross-sectional areas:

$$\Delta P_E = (U(k+1) - U(k))^2 \cdot \rho/2g \tag{7}$$

As the expired gas travels through converging branches of the lung, it is accelerated, and the kinetic energy gained by the moving gas is reflected as a drop in the driving pressure, described by Bernoulli:

$$\Delta Pin(\text{aw}) = \frac{\rho \cdot U^2}{2g} \tag{8}$$

The kinetic energy of the flowing stream is not a loss of energy, since it can be regained upon deceleration as lateral pressure. The kinetic energy of gas in each airway was calculated individually, and independently of the kinetic energy in subsequent or previous airways.

## LUNG MODEL

All calculations of $\dot{V}_E$ max or $\Delta$Paw were made utilizing Weibel's dichotomously branching human lung Model A (Weibel 1964). The total cross-sectional area of each generation, *Ax(k)*, is plotted on a logarithmic scale versus accumulative lengths of the airways in Fig. 1.

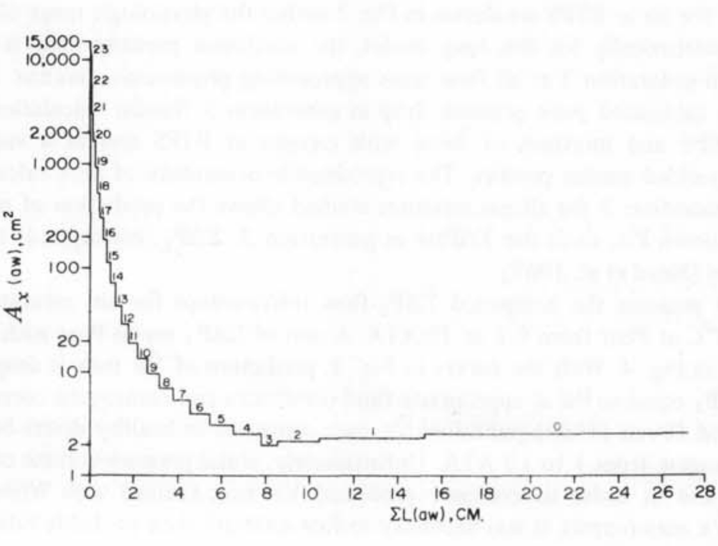


Fig. 1. Cross-sectional area of airway generations in the Weibel lung model (1964) vs. cumulative airway length from the periphery. Numbers on the figure identify the airway generation represented. Note logarithmic scale of ordinate (*Ax*).

## COMPUTER PROGRAM

The equations describing intra-airway resistive and inertial pressure drops were entered as subroutines in a computer program[2] in order to carry out the many iterative calculations necessary to calculate pressure profiles in the lung model. The program simply takes the dimensions of the lung model and the physical properties of the gas of interest, converts these physical properties into units useful for the calculations, and computes pressure losses in each generation from the most peripheral to the most central as flow rates are stepped from one-half liter per second to 20 liters per second. Resistive losses are accumulated from the periphery and added to the convective acceleration drop in each generation. Each component of the pressure drops, i.e. laminar losses, turbulent losses, entrance effects, and convective acceleration pressure equivalents are stored separately for each generation, and may be printed out individually.

## COMPARISON OF COMPUTED AND EXPERIMENTAL DATA

For corresponding experimental values of Pst and $\dot{V}_E$ max, direct comparisons of calculated and measured $\dot{V}_E$ max values are given (*see* Figs. 8 and 9). Where $\dot{V}_E$ max (exptl) values were available at several ambient pressure conditions but Pst (exptl) data were not available (Schilder et al. 1963; Varene and Vieillefond 1971; Wood and Bryan 1969), Pst (comp) was calculated from $\dot{V}_E$ max (exptl) at 1 ATA and used to calculate $\dot{V}_E$ max (comp) in Weibel's model for the other conditions reported (*see* Figs. 5-7). One datum point for each set of data is therefore forced to fall on the line of identity.

## RESULTS

Representative isoflow plots of calculated pressure profiles along subsequent airway generations for air at BTPS are shown in Fig. 2 within the physiologic range of ΔPus and $\dot{V}_E$ max. Characteristically for this lung model, the maximum pressure drop is seen to occur invariably in generation 3 at all flow rates approaching physiologic maxima. Increasing $\dot{V}_E$ accentuates calculated peak pressure drop in generation 3. Similar calculations for helium, neon and SF6 and mixtures of these with oxygen at BTPS and at a variety of other conditions yielded similar profiles. The reproducible occurrence of peak calculated pressure drops in generation 3 for all gas mixtures studied allows the prediction of maximum flow rates at a known Pst, since the ΣΔPaw in generation 3, $\Sigma\Delta P_3$, corresponds to ΔPus of the EPP concept (Mead et al. 1967).

Figure 3 presents the computed $\Sigma\Delta P_3$-flow relationships for air, saturated with water vapor at 37°C at Pbar from 0.1 to 10 ATA. A plot of $\Sigma\Delta P_3$ versus Pbar with flow isopleths is included as Fig. 4. With the curves in Fig. 3, prediction of $\dot{V}_E$ max is simply a matter of finding $\Sigma\Delta P_3$ equal to Pst at appropriate fluid conditions and reading the corresponding $\dot{V}_E$.

Wood and Bryan (1969) published $\dot{V}_E$ max measured in healthy divers breathing air at pressures ranging from 1 to 10 ATA. Unfortunately, static pressure-volume curves were not published, and in order to compare predicted $V_E$ max (comp) with Wood and Bryan's measured $\dot{V}_E$ max (exptl), it was necessary to first estimate their probable values of Pst. This

[2]This Fortran IV Program is on file with the American Society for Information Services, National Auxilliary Publications Service and reproductions are available upon request at moderate cost.

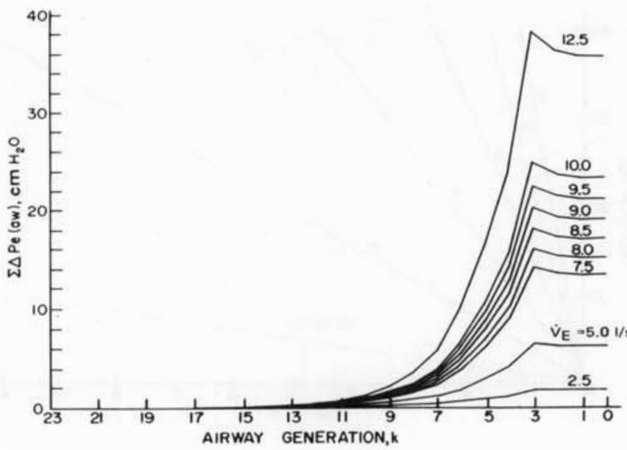


Fig. 2. Computed pressure profiles for air (BTPS) in Weibel's lung model. Note characteristic peak in generation 3 and negligible pressure drops in small, peripheral airways.

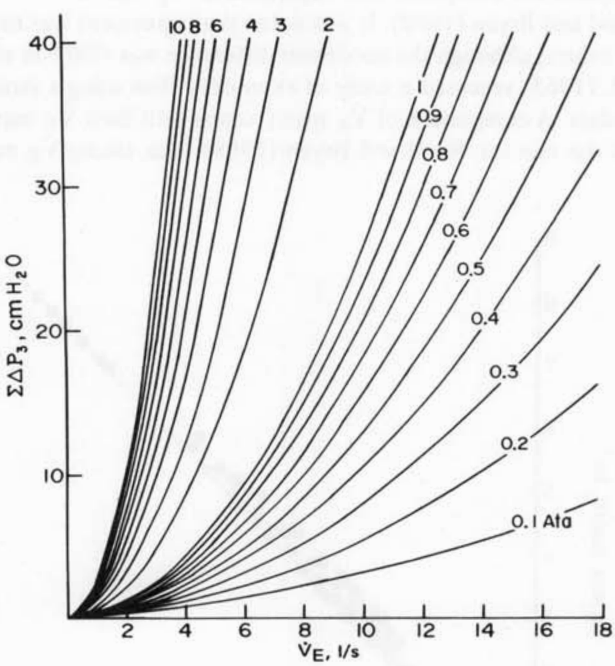


Fig. 3. Computed pressure drop-expiratory flow relationships in generation 3 of Weibel's lung model for air at 37°C, saturated with $H_2O$ vapor at Pbar values indicated.

was done by taking V̇E max (exptl) at 1 ATA and from Fig. 3 determining what value of Pst would set V̇E max (comp) equal to V̇E max (exptl). That value of Pst was then used to determine V̇E max (comp) for the other ambient pressures Wood and Bryan studied.

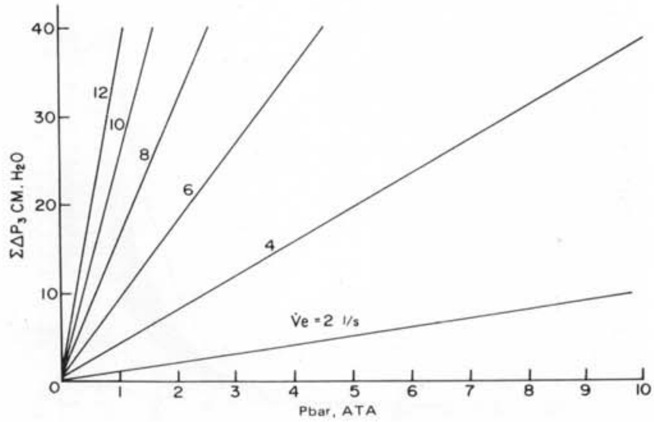


Fig. 4. Computed pressure drop-Pbar relationships for $\dot{V}_E$ values indicated. Conditions are the same as for Fig. 3. Note linear relationship of $\Sigma\Delta P_3$ with Pbar.

Figure 5 compares the computed and experimental $\dot{V}_E$ max at 75% VC. for all subjects reported by Wood and Bryan (1969). It was noted that agreement was much better for some individuals than others, although the maximum difference was <20% in all cases.

Schilder et al. (1963) reported a study of expiratory flow using a variety of gas mixtures, but without Pst data. A comparison of $\dot{V}_E$ max (comp) with their $\dot{V}_E$ max (exptl) values was made, similar to the one for Wood and Bryan (1969) data, taking $\dot{V}_E$ max (exptl) for air as

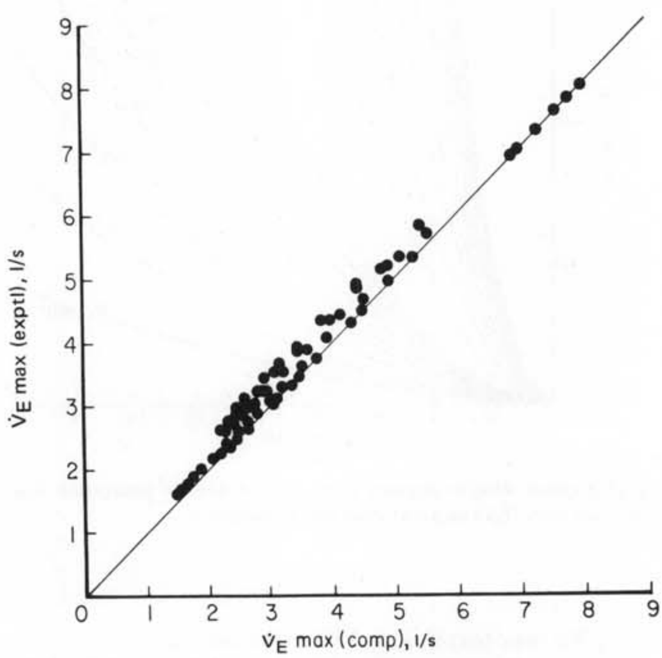


Fig. 5. Comparison of $\dot{V}_E$ max (exptl) at 75% VC in 8 healthy divers at Pbar = 1, 2, 3 ... 10 ATA (Wood and Bryan 1969) with $\dot{V}_E$ max (comp) at the same conditions.

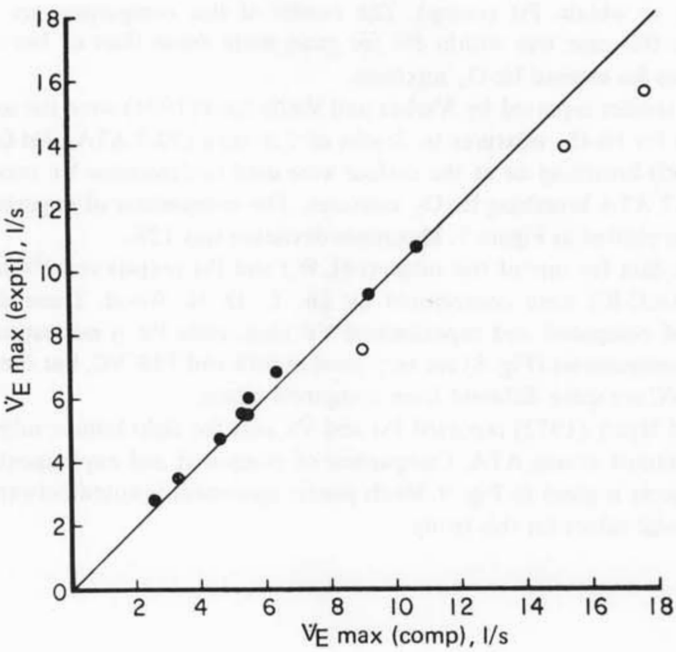


Fig. 6. Comparison of $\dot{V}_E$ max (exptl) for air and gas mixtures more dense (●) and less dense (o) than air. Experimental data from Schilder et al. (1963) at 40, 60, and 70% VC.

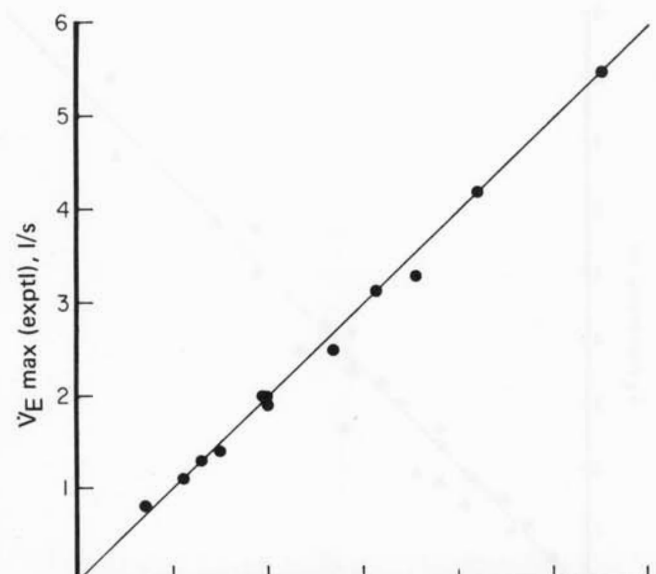


Fig. 7. Comparison as in Fig. 8 for data from Varène and Vieillefond (1971) for air at sea level and $HeO_2$ mixtures at 12.9 and 52.7 ATA. VC ranged from 30 to 60%.

the reference to obtain Pst (comp). The results of this comparison are given as Fig. 6. Agreement in this case was within 8% for gases more dense than air but differed by 20% from the values for expired He-$O_2$ mixtures.

Deep-dive studies reported by Varène and Vieillefond (1971) were the source of $\dot{V}$E max (exptl) values for He-$O_2$ mixtures to depths of 520 msw (52.7 ATA). Pst (comp) values for $\dot{V}$E max (exptl) breathing air at the surface were used to determine $\dot{V}$E max (comp) at 12.9 ATA and 52.7 ATA breathing He-$O_2$ mixtures. The comparison of experimental and computed values is plotted as Figure 7. Maximum deviation was 12%.

Pst (exptl) data for one of the subjects (L.W.) and Pst (exptl) and $\dot{V}$E max (exptl) data for another (A.C.B.) were contributed by Dr. L. D. H. Wood. These data allow direct comparison of computed and experimental $\dot{V}$E max, since Pst is not estimated. Results of these direct comparisons (Fig. 8) are very good at 50% and 75% VC, but the data for subject L.W. at 25% VC are quite different from computed values.

Stubbs and Hyatt (1972) reported Pst and $\dot{V}$E max for eight human subjects. All of their data were obtained at one ATA. Comparison of computed and experimental $\dot{V}$E max data for these subjects is given in Fig. 9. Much poorer agreement is noted between the computed and experimental values for this group.

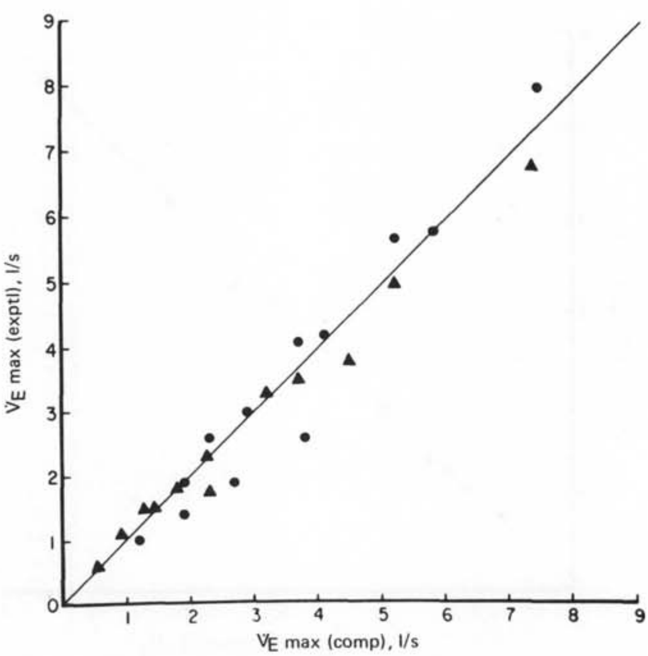


Fig. 8. Comparison of experimental and computed $\dot{V}_E$ max for two subjects studied by Dr. L. D. H. Wood. Respiratory gas was air at 1, 2, 4 and 10 ATA and measurements are at 25, 50 and 75% VC.

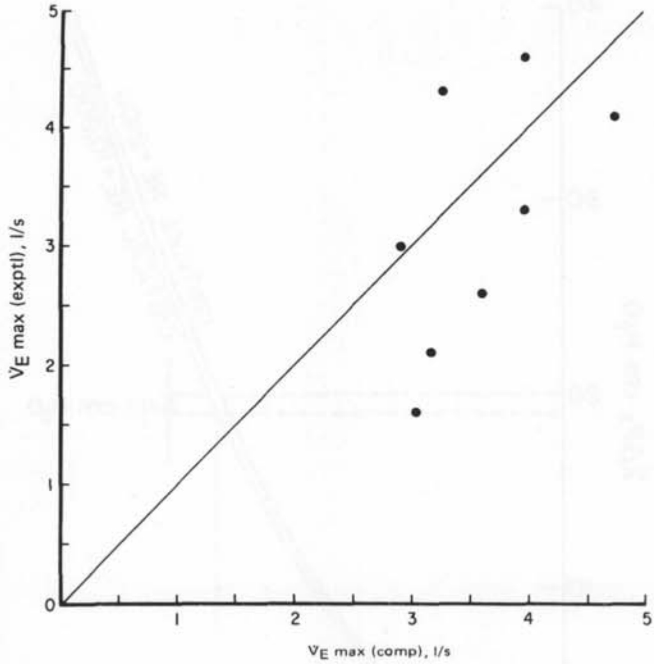


Fig. 9. Comparison of experimental and computed $\dot{V}_E$ max for 8 subjects studied by Stubbs and Hyatt (1972) breathing air at 1 ATA. Lung volume was 50% TLC.

## DISCUSSION

The EPP concept of Mead and coworkers (Mead and Milic-Emili 1964; Mead et al. 1964) explains the effort-independent flow maxima and dynamic airways compression during forced expiration in terms of pressure drops upstream of EPP. This approach is much simpler than the work of Rohrer (1915), Fry et al. (1954), Permutt and Pride (1964) and Pride et al. (1967), because the extremely complex pressure-flow relationships in the upper airways can be neglected. It also focuses attention on the primary importance of lung static recoil pressure in determining $\dot{V}_E$ max by defining $\dot{V}_E$ max in terms of Pst (L) and Rus.

The calculation of pressure-flow relationships in any lung model requires a proper application of the flow equations. Error in the assumption of abrupt transition to turbulent flow has little effect on the calculated profile or conclusions drawn, but it is important to remember that the transition is more gradual than implied in the calculations and figures reported here. Figure 10 illustrates the difference in $\Sigma\Delta P_3$ for assumed critical Reynold's numbers of 2100 and 10,000. At $\dot{V}_E = 9.0$ l/sec, the difference is 1.1 cm $H_2O$ or about 5% of the total. Figure 11 illustrates how the computed pressure drop for air at BTPS is distributed between kinetic energy (convective acceleration) entrance effects at branch points, turbulent flow losses (Re crit $> 2100$) and laminar flow losses. Even at very low flow rates, convective acceleration and entrance effects dominate, and their relative contributions increase with increasing $\dot{V}_E$. If compensating errors in the model, equations, EPP concept, and assumptions made allowed good agreement between computed and experimental $\dot{V}_E$ max for air at BTPS, one would expect significant deviations between computed and experimental values for hyperbaric conditions or other gas mixtures. The assumption of constant

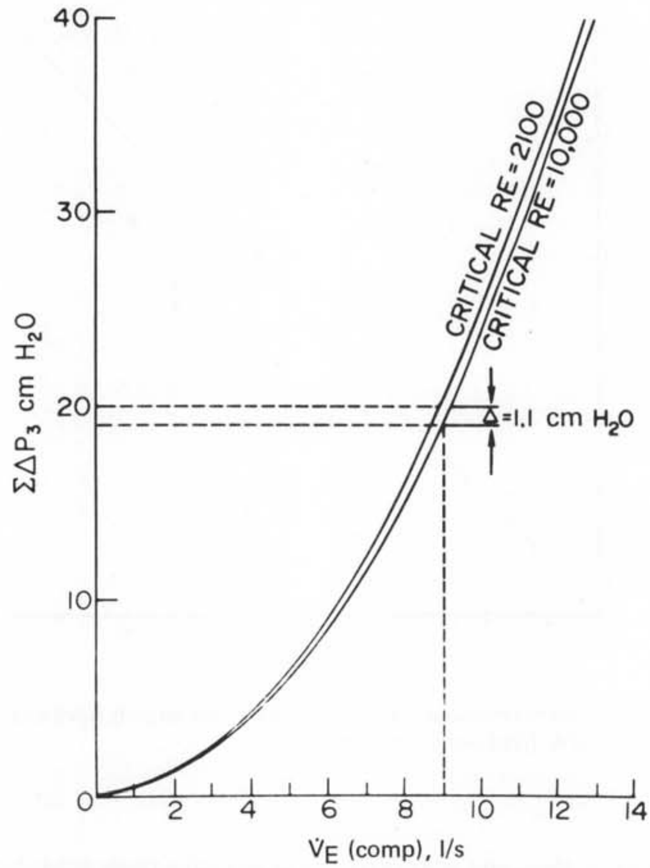


Fig. 10. The effect of the critical Reynolds number assumed to differentiate laminar and turbulent flow regimes. The fluid is air (BTPS).

gas density in the lung is one possible pressure-compensating variable, but it is not a large factor (see below). In fact, the agreement with the French deep-dive data (Varène and Vieillefond 1971) and Schilder et al. (1963) data for several gas mixtures of varying density and viscosity agree within expected limits of experimental error.

Airway dimensions negligibly variable with lung volumes upstream of EPP have been assumed. At EPP the Ptm is, by definition, zero, so that the airway diameter at EPP would remain constant. EPP are fixed over much of the FVC, but the length and diameter of the upstream segments would change with a change in lung volume. The agreement of computations assuming no change with experimental data at 25-75% VC (Schilder et al. 1963; Varene and Vieillefond 1971; Wood and Bryan 1969) and 50% TLC (Stubbs and Hyatt 1972) suggests that the changes of airways' geometry in the midrange of VC are functionally not very important in healthy lungs. Compressibility of gas in the lungs was also neglected. The error resulting from this simplification is about 10% at 1 ATA but decreases linearly with increasing Pbar to about 1% at 10 ATA and 0.2% at 53 ATA. The expired volumes reported by Wood and Bryan (1969) were measured at the mouths of their subjects by integrating the flow signal of a pneumotachograph and by Schilder et al. (1963) with a servo-spirometer.

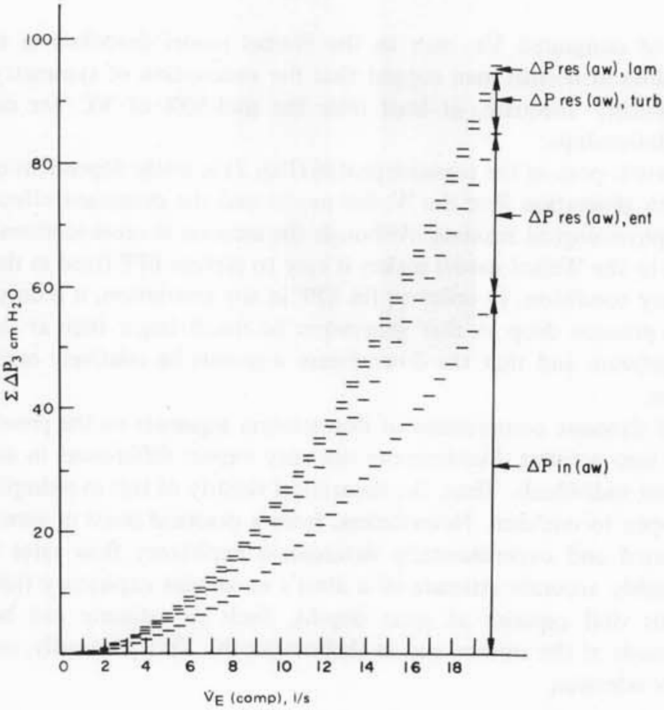


**Fig. 11. Partitioning of computed components of pressure drop in Weibel's lung model for air (BTPS).**

These methods estimate the true expired gas volume independent of intra-pulmonary compression, although estimates of lung volume and, by extension, Pst (L), are in error by the amount of gas compression neglected. The experimental error inherent in measuring $\dot{V}_E$ max is probably greater than the combined errors of assuming upstream airways' geometry constant and gas density within the airways constant.

The rigorous analysis by Olsen et al. (1970) of inspiratory pressure-flow relationships in the asymmetrical lung model of Horsfield et al. (1971) considered pressure drops due to partially developed flow regimes, the angle of branching, etc. All of these losses are density-dependent losses which can be simplistically attributed to added turbulence, as can the contraction and expansion losses considered under the term *entrance effects*. In considering the whole lung, all these effects are confounded and since the true flow regimes and branching angle effects are unknown and variable, pooling all losses due to perturbations of flow at the branch points into a single, empirical entrance effect seems a reasonable simplification. A rigorous analysis of the many factors operating at the branch points has been extremely enlightening but is not necessary for an understanding of the gross pressure-flow relationships in a lung model, nor for the practical task of predicting flows for most gases.

Weibel's lung model has been criticized by Olsen et al. (1970) and by Horsfield (1971) as being oversimplified, although the inspiratory pressure-flow relationships computed by Olsen and coworkers (1970) in the Horsfield assymmetrical lung model were within 10% of the values they computed in the Weibel symmetrical model. Their major objection to the Weibel model is that Weibel assumes symmetrical dichotomous branching. Weibel (1964) adequately defended the dichotomous branching assumption. The agreement of computed inspiratory pressure-flow relationships in the Weibel and Horsfield lung models (Olsen et al. 1970) and the agreement of computed $\dot{V}_E$ max in the Weibel model described in this paper with experimental values in normal men suggest that the assumption of symmetry in the Weibel model is functionally adequate, at least over the mid-50% of VC, for computing gross pressure-flow relationships.

The characteristic peak in the pressure profile (Fig. 2) is solely dependent on the *anatomical bottleneck* in generation 3 of the Weibel model and the dominant effect of convective acceleration at physiological maxima. Although the increase in cross-sectional area proximal to generation 3 in the Weibel model makes it easy to picture EPP fixed in the bottleneck, it is not a necessary condition. In order to fix EPP in any generation, it is only necessary that the cumulative pressure drop in that generation be much larger than at the branch point immediately upstream and that the downstream segments be relatively easily collapsed by external pressure.

The effect of dynamic compression of downstream segments on the pressure profiles has not been taken into account. Furthermore one may expect differences in airway geometry between different individuals. Thus, the theoretical validity of this oversimplified functional lung model is open to criticism. Nevertheless, from a practical point of view, the agreement between computed and experimentally determined expiratory flow rates would seem to permit a reasonably accurate estimate of a diver's maximum expiratory flow rate over the mid-range of his vital capacity at great depths. Such an estimate can be derived from measurements made at the surface and at shallow depths. This, obviously, could be of value in terms of diver selection.

## ABBREVIATIONS AND SYMBOLS

### VARIABLES AND CONSTANTS

$A$ = area, $cm^2$
d = diameter, cm
$f$ = Fanning friction factor, dimensionless
FVC = forced vital capacity, cc or liters
$g$ = acceleration of gravity, $cm/sec^2$
L = length, cm
P = pressure, cm $H_2O$ or as noted
R = resistance to flow, $\Delta P/\dot{V}$, cm $H_2O$/cc/sec
Re = Reynold's number, $d \cdot U \cdot \rho/\eta$, dimensionless
TLC = total lung capacity, cc or liters
$U$ = average linear velocity, cm/sec
V = volume of gas, cc
$\dot{V}$ = volume flow rate, dV/dt, cc/sec
VC = vital capacity
$\eta$ = viscosity, poises or as noted
$\rho$ = density, gm/cc

### IDENTIFYING SYMBOLS

ATA = atmospheres pressure, absolute
aw = airway
bar = barometric

BTPS = body temperature (37°C) and ambient pressure, saturated with water vapor
$c$ = contracting area for flow
comp = computed
crit = critical
ds = downstream from EPP
E = expiratory or expanding area for flow
ent = entrance effect of perturbations due to contraction, expansion, etc.
exptl = experimental
EPP = equal pressure point(s), intra- and extra-airways pressures equal
$in$ = inertial or kinetic energy component
IVPF = isovolume pressure-flow curves after Fry et al. (1954)
$k$ = order of airways generation in Weibel's lung model
L = lung tissues
lam = laminar flow condition
max = maximum (at a given lung volume)
pl = pleural space
res = resistive component
st = static condition (zero flow)
tm = transmural, across the wall of the airway
turb = turbulent flow condition
us = upstream from EPP
$x$ = cross-sectional
$\Delta$ = change or difference

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## REFERENCES

Fry, D. L., R. V. Ebert, W. W. Stead, and C. C. Brown. 1954. The mechanics of pulmonary ventilation in normal subjects and in patients with emphysema. Am. J. Med. 16:80-96.

Horsfield, K., G. Dart, D. E. Olson, G. F. Filley, and G. Cumming. 1971. Models of the human bronchial tree. J. Appl. Physiol. 31:207-217.

Mead, J., and J. Milic-Emili. 1964. Theory and methodology in respiratory mechanics with glossary of symbols. Pages 363-364 *in* W. O. Fenn and H. Rahn, eds. Handbook of physiology. Sect. 3: Respiration, I. American Physiological Society, Washington, D.C.

Mead, J., A. Bouhuys, J. Schwaber, and E. Motoyama. 1964. Factors influencing maximum expiratory flow-volume (MEFV) relationships. Fed. Proc. 23:155. (Abstr.)

Mead, J., J. M. Turner, P. T. Macklem, and J. B. Little. 1967. Significance of the relationship between lung recoil and maximum expiratory flow. J. Appl. Physiol. 22:95-108.

Olson, D. E., G. A. Dart, and G. F. Filley. 1970. Pressure drop and fluid flow regime of air inspired into the human lung. J. Appl. Physiol. 28:482-494.

Permutt, S., and N. B. Pride. 1964. The lung as a starling resistor. Fed. Proc. 23:155. (Abstr.)

Perry, J. H., ed. 1963. The chemical engineers' handbook, 4th ed. Pages 7-33, sect. 5. McGraw-Hill, New York.

Pride, N. B., S. Permutt, R. L. Riley, and B. Bromberger-Barnea. 1967. Determinants of maximal expiratory flow from the lungs. J. Appl. Physiol. 23:646-662.

Rohrer, F. 1915. Der Strömungswiderstand in den menschlichen Atemwegen und der Einfluss der unregelmässigen Vergzweigung des bronchial Systems auf den Atmungsverlauf in verschiedenen Lungenbezirken. Pfluegers Arch. Gesamte Physiol. Menchen Tiere 166:225-303.

Schilder, D. P., A. Roberts and D. L. Fry. 1963. Effect of gas density on the maximal expiratory flow-volume relationship. J. Clin. Invest. 42:1705-1713.

Stubbs, S. E., and R. E. Hyatt. 1972. Effect of increased lung recoil pressure on maximal expiratory flow in normal subjects. J. Appl. Physiol. 32:325-331.

Varène, P., and H. Vieillefond. 1971. Résultats de l'experience physalie V; mécanique ventilatoire en plongée profonde. Compte-Rendu D'étude No. 958, Centre D'essais en Vol., Laboratoire de Médecine Aerospatiale, Mars.

Weibel. E. R. 1964. Morphometry of the lung. Pages 285-307 *in* W. O. Fenn and H. Rahn, eds. Handbook of physiology. Sect. 3: Respiration, I. American Physiological Society, Washington, D.C.

Wood, L. D. H., and A. C. Bryan. 1969. Effect of increased ambient pressure on flow-volume curve of the lung. J. Appl. Physiol. 27:4-8.