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# Is Gas Density Independent of the Maximum Expiratory Flows at Low Lung Volumes?

Yasuyo OHTA, Yohnosuke YAMAZAKI* and Toshitada YAMAUCHI**

*Department of Physiology, School of Medicine, Tokai University*
**Department of Anesthesiology, School of Medicine, Tokai University*
***Department of Internal Medicine, School of Medicine, Tokai University*

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**MEFV and MIFV curves of six volunteer subjects were recorded while they were breathing He-$O_2$, air and $SF_6$-$O_2$, respectively, at 0.5, 1.0 or 2.0 ATA. MEFVs at lung volumes greater than 25% of vital capacity had a close relation with the density of inspired gas, and varied as an exponential function of density. The exponents were between − 0.35 and − 0.45 according to lung volumes.**

**Correlation coefficients of gas density to peak flow, $\dot{V}_{50}$ and $\dot{V}_{25}$ were − 0.987, − 0.986 and − 0.976, respectively. Even at a very low lung volume ($\dot{V}_{10}$) the coefficient was − 0.734. Statistical analysis of $\dot{V}_{10}$ revealed that the correlation coefficient of $\dot{V}_{10}$ with viscosity or with kinematic viscosity is almost identical to that with density and has a magnitude of − 0.73.**

**MEFV at very low lung volumes or flows in the peripheral airways is very unlikely to be laminar.**

**(Key Words: Gas Density, Gas Viscosity, Maximum Expiratory Flow, Flow-Volume Curve)**

## INTRODUCTION

Is gas density independent of the maximum expiratory flow rate at low lung volume?
Since the earlier study of Rohrer (10), the general belief is that airflow in the large airways is turbulent and density-dependent, whereas that in the peripheral airways is laminar and viscosity-dependent. Indeed, many works (2, 3, 4, 5, 7, 11, 13) showed close relations between gas density and maximum voluntary ventilation (MVV), maximum expiratory flow (MEF) and peak flow rate.

Vorosmarti et al.(1971) confirmed that gas flows with neon mixtures, which have a much higher viscosity than air, correspond to the density and do not differ from other gases in this respect.

On the other hand, Mead et al.(6) and Pride et al.(9) introduced an almost identical theory separately which states that the maximum expiratory flow at an equal pressure point is limited by static recoil pressure (Pst(l)) divided by upstream resistance (Rus). According to this important theory, the pressure drop in the upstream segments equals the sum of the frictional pressure losses, which are composed of turbulent and laminar pressure

Yasuyo OHTA, Department of Physiology, School of Medicine, Tokai University, Bohseidai, Isehara, Kanagawa 259 – 11, Japan

drops, and pressure losses due to convective acceleration of gas. Wood and Bryan (1969) observed that as the lung volume decreases below 25% of vital capacity, laminar flow becomes an increasingly large component of the flow regime. However, recent work (4, 8) suggests that gas flow in the peripheral airways, even in the vicinity of the gas exchange region, is unlikely to be laminar.

The present study is aimed at estimating the role of gas density in maximum expiratory flows at low lung volumes by means of statistical analysis of data obtained during breathing of various gas mixtures with different densities and viscosities.

## MATERIALS AND METHODS

Six healthy laboratory workers served as volunteer subjects. Table 1 shows their vital statistics at the time of the study.

The gas mixtures inhaled in the present study and their physical properties are shown in Table 2. To change the density of inspired gas, experiments were performed under hypo- (0.5 ATA) and hyperbaric (2.0 ATA) conditions as well as under ambient pressure using the facilities of the Hyperbaric Oxygen Therapy Unit of Tokai University Hospital.

The maximum expiratory and inspiratory flow-volume curves were recorded via a low inertia, plastic bell type spirometer (Anima Corp.) and high-speed X-Y recorder (Watanabe Sokki). Flows were obtained by differentiating the volumes electrically.

Maximum expiratory and inspiratory flow-volume curves (MIFV and MEFV) during helium-oxygen or sulfur hexafluoride ($SF_6$)-oxygen breathing were recorded after completion of washout of the residual gas in the lungs or after at least five vital capacity maneuvers.

Each subject repeated at least three MEFV and MIFV maneuvers for each experimental condition and the mean values of MEFV and MIFV at various lung volumes were calculated from recordings with consistent reproducibility.

**Table 1.** Vital statistics of volunteer subjects. All the subjects were well-trained laboratory workers.

| SUBJECT | T.Y. | Y.K. | Y.O. | K.S. | S.T. | C.M. |
|---|---|---|---|---|---|---|
| AGE (yrs.) | 31 | 26 | 40 | 37 | 31 | 24 |
| SEX | male | female | male | male | male | female |
| HEIGHT (cm) | 170.0 | 151.0 | 175.0 | 173.0 | 175.0 | 150.0 |
| WEIGHT (kg) | 58.0 | 46.0 | 60.0 | 53.0 | 70.0 | 49.0 |
| % vc | 119.3 | 96.7 | 124.2 | 121.9 | 130.1 | 96.7 |
| $FEV_{1.0\%}$ | 86.2 | 87.6 | 80.0 | 78.8 | 86.3 | 83.3 |
| FRC (L) | 3.11 | 2.30 | 4.13 | 4.85 | 4.10 | 1.96 |
| RV/TLC (%) | 19.0 | 26.5 | 24.6 | 35.6 | 26.8 | 27.6 |
| PULM. $N_2$ CLEARANCE DELAY (%) | 25.4 | 55.0 | 38.0 | 5.1 | 22.9 | 25.8 |

**Table 2.** Physical properties of gases used in the present study. Kinematic viscosity stands for the value obtained by dividing viscosity by density.

| | $P_B$ | He + 20% $O_2$ | AIR | $SF_6$ + 20% $O_2$ |
|---|---|---|---|---|
| RELATIVE DENSITY | 0.5 ATA | 0.21 | 0.49 | 1.90 |
| | 1.0 ATA | 0.38 | 1.00 | 4.06 |
| | 2.0 ATA | 0.74 | 2.02 | 8.40 |

| | He | AIR | $SF_6$ |
|---|---|---|---|
| VISCOSITY ( $\mu$ poises) | 189 | 171 | 153 |
| KINEMATIC VISCOSITY ($cm^2/s$) | 1.05 | 0.13 | 0.02 |

## RESULTS

Fig. 1 shows typical patterns of flow-volume curves under various experimental conditions (Subject; Y.O.).

Tables 3 and 4 indicate relative values of peak flow and flows at 50% and 25% of vital capacity of MEFV and MIFV curves ($\dot{V}_{50}$ and $\dot{V}_{25}$), which are expressed as percentages of those for air-breathing.

The data shown in Table 3 and flows at 10% of vital capacity ($\dot{V}_{10}$) were treated statistically and are summarized in Tables 5 and 6.

Table 6 indicated correlation coefficients between flows and density at each lung volume, and Table 6 shows correlation coefficients between $\dot{V}_{10}$ and density, viscosity or kinematic viscosity.

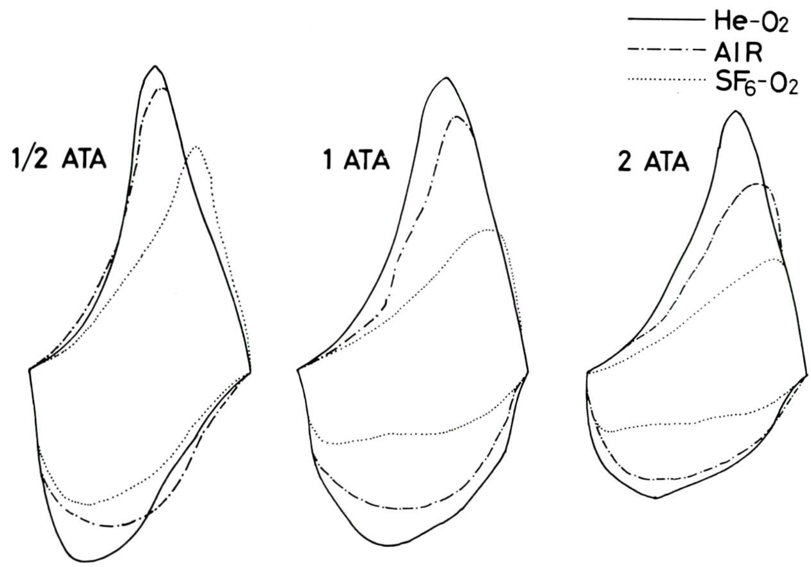


Fig. 1 Illustrative recordings of MEFV and MIFV curves of a subject while breathing He-$O_2$, air or $SF_6$-$O_2$ under 1/2, 1.0 or 2.0 atmospheres.

**Talbe 3.** Relative values of MEF at lung volumes of 25 and 50% of vital capacity ($\dot{V}_{25}$ and $\dot{V}_{50}$, respectively) and peak flow ($\dot{V}_{max}$). For details, see text.

| INSPIRED GAS | $He\text{-}O_2$ | $He\text{-}O_2$ | AIR | $He\text{-}O_2$ | AIR | $SF_6\text{-}O_2$ | AIR | $SF_6\text{-}O_2$ | $SF_6\text{-}O_2$ |
|---|---|---|---|---|---|---|---|---|---|
| $P_B$ (ATA) | 0.5 | 1.0 | 0.5 | 2.0 | 1.0 | 0.5 | 2.0 | 1.0 | 2.0 |
| No. of SUBJECTS | 4 | 6 | 4 | 5 | 6 | 4 | 5 | 6 | 5 |
| RELATIVE DENSITY | 17 | 33 | 50 | 66 | 100 | 173 | 200 | 425 | 850 |
| RELATIVE VISCOSITY | 108 | 108 | 100 | 108 | 100 | 96 | 100 | 90 | 90 |
| $\dot{V}_{max}$ | 145 | 131 | 118 | 110 | 100 | 85 | 78 | 59 | 48 |
| $\dot{V}_{50}$ | 214 | 168 | 138 | 126 | 100 | 72 | 80 | 52 | 46 |
| $\dot{V}_{25}$ | 180 | 136 | 130 | 119 | 100 | 82 | 87 | 62 | 59 |

$SF_6\text{-}O_2$ mixture breathed under 0.5 ATA contained 40% oxygen.

**Table 4.** Relative values of MIF at lung volumes of 25, 50 and 75% of vital capacity ($\dot{V}_{25}$, $\dot{V}_{50}$ and $\dot{V}_{75}$, respectively) and peak flow ($\dot{V}_{max}$).

| INSPIRED GAS | $He\text{-}P_2$ | $He\text{-}O_2$ | AIR | $He\text{-}O_2$ | AIR | $SF_6\text{-}O_2$ | AIR | $SF_6\text{-}O_2$ | $SF_6\text{-}O_2$ |
|---|---|---|---|---|---|---|---|---|---|
| $P_B$ (ATA) | 0.5 | 1.0 | 0.5 | 2.0 | 1.0 | 0.5 | 2.0 | 1.0 | 2.0 |
| No. of SUBJECTS | 4 | 6 | 4 | 5 | 6 | 4 | 5 | 6 | 5 |
| RELATIVE DENSITY | 17 | 33 | 50 | 66 | 100 | 173 | 200 | 425 | 850 |
| RELATIVE VISCOSITY | 108 | 108 | 100 | 108 | 100 | 96 | 100 | 90 | 90 |
| $\dot{V}_{max}$ | 138 | 121 | 121 | 100 | 100 | 91 | 76 | 66 | 43 |
| $\dot{V}_{75}$ | 116 | 115 | 101 | 94 | 100 | 89 | 78 | 63 | 36 |
| $\dot{V}_{50}$ | 146 | 109 | 126 | 103 | 100 | 95 | 72 | 61 | 40 |
| $\dot{V}_{25}$ | 130 | 116 | 116 | 95 | 100 | 92 | 74 | 60 | 40 |

$SF_6\text{-}O_2$ mixture under 0.5 ATA contained 40% oxygen.

**Table 5.** Correlation of gas density with MEF. Correlation coefficients were calculated from the equation: $MEF = K \cdot (Density)^X$.

| | X | K | CORRELATION COEFF. |
|---|---|---|---|
| $\dot{V}_{max}$ | −0.300 | 5.12 ~ 9.44 | −0.987 |
| $\dot{V}_{50}$ | −0.401 | 3.50 ~ 7.08 | −0.986 |
| $\dot{V}_{25}$ | −0.300 | 1.34 ~ 2.33 | −0.976 |
| $\dot{V}_{10}$ | −0.145 | 0.53 ~ 0.79 | −0.734 |

**Table 6.** Correlation coefficients of MEF at lung volumes of 10% of vital capacity ($\dot{V}_{10}$) to density, viscosity and kinematic viscosity. A, X and K form the equation $\dot{V}_{10} = K \cdot A^{X}$.

| A | X | K | CORR. COEFF. |
|---|---|---|---|
| DENSITY | −0.145 | 0.53 ~ 0.79 | −0.734 |
| VISCOSITY | +3.001 | $0.80 \times 10^{-3}$ ~ $6.76 \times 10^{-11}$ | −0.730 |
| KINEMATIC VISCOSITY | +0.14 | 0.21 ~ 0.48 | −0.739 |

## DISCUSSION

A mixture of 80% $SF_6$ and 20% $O_2$ is sometimes hard to breathe for a long time because of its narcotic action and severe sensation during inspiration. However, five vital capacity maneuvers, which were well tolerated by the subjects, were revealed to be sufficient to eliminate the residual gas under 1% in the lung. Forced vital capacities recorded at each MEFV maneuver were not significantly different from each other except for $SF_6$-$O_2$ breathing at 2 ATA (Table 7), and this indicates that thorough expiration is obtained even during breathing of $SF_6$ at 2 ATA.

Patterns of MEFV curves are affected by the mechanical or electrical properties of measuring devices. Neither pneumotachographs nor hot-wire flow meters can be used for measuring flows other than air without special calibration. Therefore, in the present study, we used a respirometer with a low inertia and a high-speed X-Y recorder, and flows were obtained by differentiation of the volumes.

**Table 7.** Relative values of forced vital capacity (FVC) as expressed in percentage of FVC obtained during breathing of ambient air. FVC were obtained from flow-volume curves observed in the present study.

| | | He | AIR | $SF_6$ |
|---|---|---|---|---|
| 1/2 ATA | n = 4 | 94 | 96 | 96 |
| 1 ATA | n = 6 | 100 | 100 | 97 |
| 2 ATA | n = 5 | 99 | 99 | 92 |

Table 3 shows an inverse relation between MEF and gas density. Marshall et al.(1956), Lord et al.(1966), and Wood et al.(1969) observed a consistent graded decrease in MEF as the gas density was raised. Wood and Bryan (1969) found that at lung volumes greater than 25% of vital capacity, MEF was proportional to gas density$^{-0.45}$ for practical purposes. If we attempt to estimate relative values of MEF for the present experimental conditions from gas density$^{-0.45}$, we obtain 222, 165, 137, 121, 100, 78, 73, 52 and 38, respectively, for the columns of Table 3 (from left to right). It will be seen that $\dot{V}_{50}$ in Table 3 shows fairly good agreement with this prediction, although the correlations were poor at extremely high or low gas densities. The reason why our data showed some discrepancies with respect to those by Wood et al.(1969) is not clear, but it may be derived from the fact that our volunteer subjects included heavy smokers and females. However, our major concern is to analyze whether MEF at low lung volumes is density-dependent.

According to the theory of Mead et al.(1967), the pressure drop upstream from the equal pressure point equals Pst (1), which has two components: frictional pressure losses and losses due to convective acceleration (Pca). The former is composed of turbulent and laminar pressure (Pca) drops.

If all the flow in the upstream segment were laminar, an empirical equation indicates that MEF would be independent of gas density, and:

$$Pla = \frac{8L\eta\dot{V}}{D^4}$$

Where L = length, D = diameter and $\eta$ = viscosity.

Observations by Wood et al. (1969), Schilder et al.(1963) and Mead et al. (1967) confirmed that viscosity of the inspired gas affected MEF at lung volumes below 25% of vital capacity.

This finding suggests that laminar flow accounts increasingly for the pressure drops along the upstream segment, and if He-$O_2$ were breathed in, Pla would increase by 12% and Pca would decrease to approximately a third of that during air breathing. This is a basic theory of volume of isoflow (1) where MEFs of air — and He — breathing cross each other.

Recent analysis of air flows in the airways (8) implies that Poiseuille flow is very unlikely to be in the tracheobronchial tree, which is quite different from a straight, smooth tube applied in the Hagen-Poiseuille Law. From their experimental data, Vorosmarti et al. (12) and Maio et al. (4) came to believe that MEF at most lung volumes responded to changes in gas density in such a manner that flow was predominantly non-laminar.

Hence, we treated data statistically in the form of Flow = K· $(\text{Density})^x$ to see if there is any correlation between MEF and density. As indicated in Table 5, MEFs at lung volumes above 25% of vital capacity have a very close relation to gas density and even at very low lung volumes (10% of VC), they still have a fair correlation.

Table 6 indicates another statistical treatment of $\dot{V}_{10}$. It shows that viscosity or kinematic viscosity has almost the same correlation coefficient as density with $\dot{V}_{10}$.

Our observations and analysis do not provide direct evidence concerning the flow regime in the peripheral airways, but we may conclude that even at very low lung volumes or even in the upstream segment of EPP, flows are not simply laminar nor merely viscosity dependent.

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