JOURNAL OF APPLIED PHYSIOLOGY
Vol. 26, No. 5, May 1969. *Printed in U.S.A.*

# Contribution of compliance of airways to frequency-dependent behavior of lungs

JERE MEAD
*Department of Physiology, Harvard School of Public Health, Boston, Massachusetts 02115*

airway distensibility; elastic behavior of lungs; peripheral airway resistance

AT FIRST GLANCE, one would not expect that airway distensibility could have a measurable influence on overall elastic behavior of lungs. The following analysis shows that in particular circumstances it would. This is of more than theoretical interest because the circumstances obtain in chronic obstructive lung disease. Indeed most, if not all, of the marked changes in dynamic compliance seen in these patients can be accounted for by the mechanism to be described.

Airways are more than simply conduits; they are also compliant structures. As conduits, they are mechanically in series with the air spaces which they supply. As expanding structures, however, they are mechanically in parallel with the air spaces; their expansion makes an entirely separate contribution to the total expansion of lungs from that of the air spaces. Under static conditions this contribution to overall expansion is very small, perhaps 2–3% of the total. But under dynamic conditions this contribution can become appreciable. This is the case when air-space filling is slowed by increases in airway resistance. If the resistance increase is in the smaller, more peripheral, airways a marked discrepancy between the speed of filling of the airways and air spaces can develop. In such an event the contribution of air-space expansion to total lung expansion will increase during rapid, shallow breathing.

The implications of discrepancies in the speed of filling to elastic behavior of lungs have been developed by Otis et al. (3). Their ideas can be conveniently applied here. They developed expressions that predict the dynamic compliance and resistance of systems which consist of two volume elastic elements operating in parallel. To use these expressions it is necessary to know, as well as the compliances of the separate pathways, their separate flow resistances.

Airway compliance can be estimated from changes in the volume of the anatomic dead space together with simultaneous changes in airway transmural pressures. In adult humans the dead-space volume changes by approximately 100 ml over the vital-capacity range (4). The associated change in transpulmonary pressure is approximately 30 cm $H_2O$. If static transpulmonary pressure equals static transmural pressure, the overall compliance for airways in this instance would be 3.3 ml/cm $H_2O$. The corresponding value for the lung would, for a vital capacity of 5,000 ml, be about 170 ml/cm $H_2O$. The compliance of such a lung during tidal breathing is approximately 200 ml/cm $H_2O$. With the same degree of curvilinearity for the volume-pressure behavior of airways assumed, the corresponding compliance of the airways during tidal breathing would be about 4 ml/cm $H_2O$. For convenience I have assumed airway compliance to be 5 ml/cm $H_2O$ or about 1/40 that of the lung parenchyma.

Assigning resistances to the two pathways is more difficult. All resistances in series with the two pathways, i.e., all resistances shared by them, may be disqualified. This includes the resistance of all extrathoracic airways. How is intrathoracic airway resistance to be apportioned? Clearly all airway resistance mouthward from a given point is shared by all airways and air spaces peripheral to such a point. Thus, none of the airway resistance belongs solely to the pathway for airway expansion. On the other hand, none of the airway resistance between a given point within the airways and the air spaces peripheral to such a point is shared by expanding airways mouthward from the point. The nonshared airway resistance is then the resistance between a given point in the airways and the air spaces, and all of this resistance belongs to the air-space pathway. The amount of this unshared resistance depends on the relative distribution of air-space expansion and airway resistance. This is best seen with examples.

If most of air-space expansion took place mouthward from airways contributing most of the airway resistance, the unshared resistance to air-space expansion would include nearly the total intrathoracic airway resistance. On the other hand, if most of air-space expansion took place peripheral to airways contributing most of the airway resistance, the unshared resistance to airway expansion would include almost none of the intrathoracic airway resistance. To summarize the apportionment of resistance, that of the separate pathways of airway and air-space expansion include none of the airway resistance per se in the case of airway expansion, and a fraction varying from nearly all to nearly none of the airway resistance in the case of air-space expansion.

What then is the magnitude of the unshared resistance to airway expansion? The flow resistance for the gas displaced into the dead space as it changes volume must be extremely small. (This displacement is through a total cross section which approximates the surface area of the airways.) The tissue and surface flow resistance would appear to be the only possible sources. Because of the thickness of the walls and the presence of smooth muscle, this might be appreciable; but then again the movement is shared by a very extensive wall and the linear velocities of tissue elements must be extremely small. Here I assume that this resistance is negligible, and that the total unshared flow resistance for airway expansion is very small.

The unshared resistance of the air-space pathway also includes that of gas flowing within the air spaces themselves,

which must be vanishingly small, and any resistance to flow offered by the tissues of the pulmonary parenchyma.

The expressions of Otis et al. include the time constants of the separate pathways. These are the products of the pathway compliance and resistance. (Time constants are convenient expressions for the speed of response of systems. Systems with low time constants, that is with low compliance and resistance, respond more quickly to external forcing than more compliant systems with higher resistances and hence higher time constants. The compliance dictates, in a sense, how far the system has to go in response to a given change in pressure, and the resistance, how fast it can move while getting there. The proportionality of the time constant to compliance and resistance is therefore a reasonable one. The product of resistance and compliance has the units of time, and the time is that required for about 63% of the total change to take place following a step change in driving pressure.) Since both the compliance and resistance of the airways are smaller than that for the air spaces, the time constant for the airways must be very much smaller than that for the air spaces. Furthermore the static compliance of the airways will always be very small as compared to that of the air spaces. I have reexpressed equations 13 and 14 from the article by Otis et al. for the case where the time constant of one pathway is negligible compared to that of the other, and where the contribution of the compliance of this pathway to the overall static compliance is also negligible. The original and derived expressions are as follows. ($\omega = 2\pi f$, where $f$ is the breathing frequency. C, R, and $T$ are the compliance, resistance, and time constant of the pathway.)

Equation 13, Otis et al:

$$Ce = \frac{\omega^2(T_2C_1 + T_1C_2)^2 + (C_1 + C_2)^2}{\omega^2(T_1^2C_2 + T_2^2C_1) + (C_1 + C_2)}$$

Equation 13, reexpressed for $T_1 \approx 0$ and $C_1 + C_2 \approx C_2$

$$Ce = \frac{\omega^2(T_2C_1)^2 + (C_2)^2}{\omega^2(T_2^2C_1) + C_2}$$

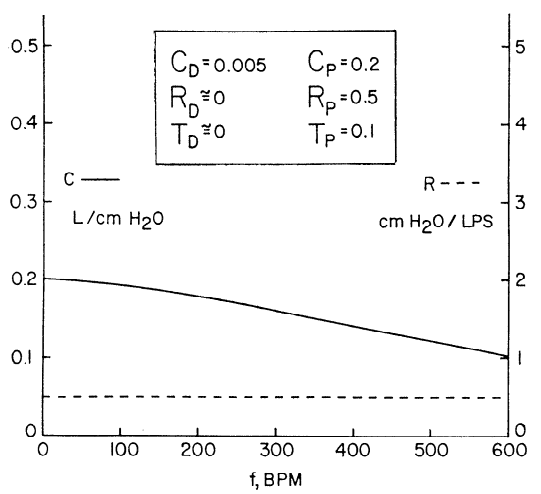


FIG. 1. Compliance and resistance for a normal lung at different breathing frequencies as predicted from the equations given in the text and based on the values for the compliance, C, and resistance, R, and time constants, $T$, of the dead space, D, and of the pulmonary parenchyma, P, given at the top of the figure.

Equation 14, Otis et al:

$$Re = \frac{\omega^2T_1T_2(T_2C_1 + T_1C_2) + (T_1C_1 + T_2C_2)}{\omega^2(T_2C_1 + T_1C_2)^2 + (C_1 + C_2)^2}$$

Equation 14, reexpressed for $T_1 \approx 0$ and $C_1 + C_2 \approx C_2$

$$Re = \frac{T_2C_2}{\omega^2(T_2C_1)^2 + (C_2)^2}$$

Figures 1–4 are based on these expressions. The airway pathway is denoted with a subscript D, which stands for dead space. The air-space pathway is denoted with a subscript P, which stands for pulmonary parenchyma. The example in Fig. 1 approximates the normal lung. The resistance of the parenchymal pathway of 0.5 amounts to approximately one-half of the total intrathoracic airway resistance. The frequency range for practical measurements of dynamic compliance for human lungs is from 0 to about 90 breaths/min. (Above this frequency

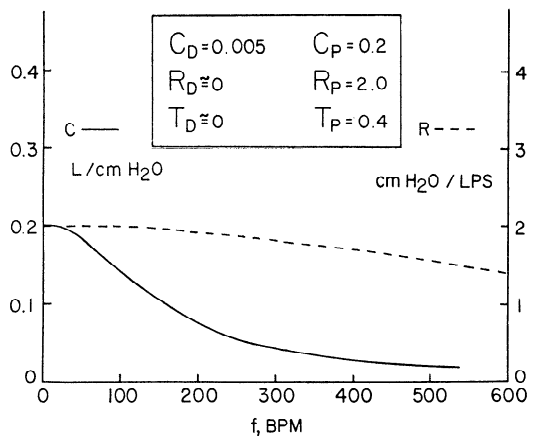


FIG. 2. Predicted compliance and resistance at different breathing frequencies for a lung with increased peripheral airway resistance.

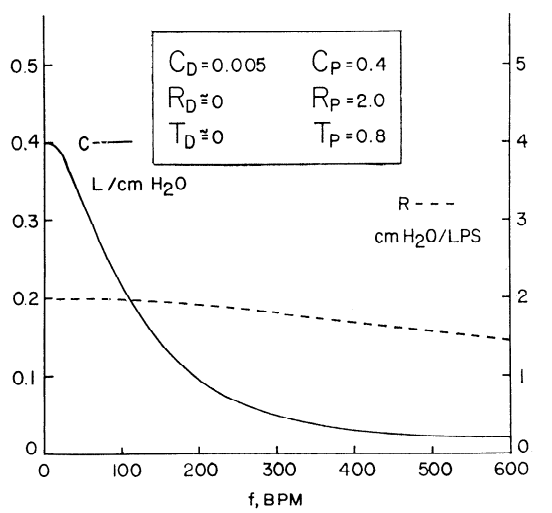


FIG. 3. Predicted compliance and resistance at different breathing frequencies for a lung with increased peripheral resistance and increased compliance.

pressure drops relating to pulmonary inertance become appreciable.) In this range, in the example shown, no change in compliance would be detectable. The approximate frequency range for practical measurement of flow resistance is between 10

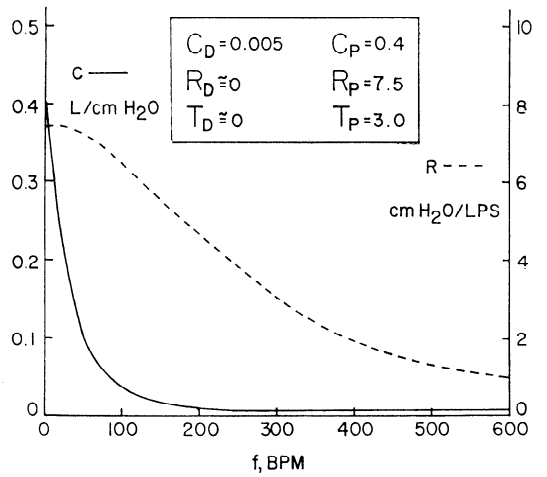


FIG. 4. Predicted compliance and resistance at different breathing frequencies for a lung with values for compliance and resistance corresponding to ones in chronic obstructive lung disease.

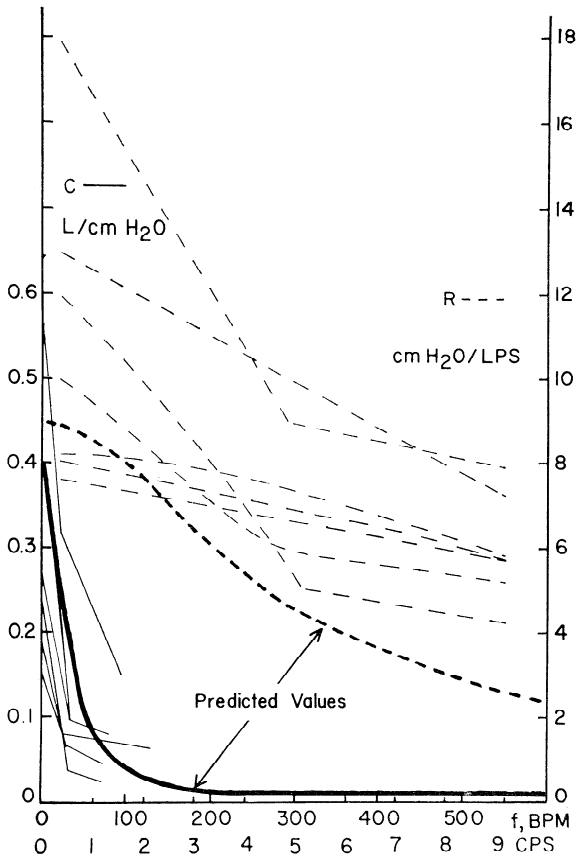


FIG. 5. Predicted values for compliance and resistance at different breathing frequencies are shown in the heavy lines along with observed values in 7 patients with chronic obstructive lung disease. Predicted values are the same as those in Fig. 4 except that 1.5 cm $H_2O$/liter per sec have been added to predicted values for resistance to approximate the resistance of the upper airways and major intrathoracic airways which are shared by the two pathways and, hence, not included in the prediction.

TABLE 1. *Effect of varying $C_D$ on frequency dependence of C and R*

| Frequency, breaths/min | Ce, liters/cm $H_2O$ | | | Re, cm $H_2O$/liter per sec | | |
|---|---|---|---|---|---|---|
| | $C_D$ | | | $C_D$ | | |
| | 0.002 | 0.005 | 0.01 | 0.002 | 0.005 | 0.01 |
| *Normal lung: Cp = 0.2, Rp = 0.5, Tp = 0.1* | | | | | | |
| 60 | 0.2 | 0.198 | 0.196 | 0.50 | 0.50 | 0.50 |
| 300 | 0.18 | 0.16 | 0.14 | 0.50 | 0.50 | 0.49 |
| 600 | 0.14 | 0.10 | 0.07 | 0.50 | 0.50 | 0.45 |
| *Chronic obstructive lung disease: Cp = 0.4, Rp = 7.5, Tp = 3.0* | | | | | | |
| 60 | 0.144 | 0.080 | 0.049 | 7.4 | 7.1 | 6.0 |
| 300 | 0.011 | 0.011 | 0.012 | 6.0 | 3.0 | 1.1 |
| 600 | 0.004 | 0.008 | 0.010 | 4.0 | 1.0 | 0.32 |

breaths/min and 10 cycles/sec (or 600 breaths/min). No detectable changes occur in this range. It should be borne in mind that total airway resistance would be some five times the value shown. (The common airway resistance would be about 2 cm $H_2O$/liter per sec and independent of frequency.)

The second example (Fig. 2) is the same as the first, but with a resistance of the parenchymal pathway increased from 0.5 to 2 cm $H_2O$/liter per sec. The third example (Fig. 3) is the same as the second, but with parenchymal compliance increased from 0.2 to 0.4. In these examples the dynamic compliance would be detectably altered, and flow resistance possibly detectably altered over practical frequencies.

The fourth example (Fig. 4) corresponds to the values that might be expected for lungs of patients with chronic obstructive lung disease. In this example, parenchymal compliance is doubled from normal and the resistance of the parenchymal pathway is increased to 7.5 cm $H_2O$/liter per sec, so that the time constant of the parenchymal pathway is 3 sec. These values are consistent with measurements made on excised lungs (P. T. Macklem, personal communication). I have assumed a normal dead space, and I have assumed that the peripheral airway resistance measured is also peripheral to the dead space and thus totally assignable to the parenchymal pathway. The calculated change in compliance and resistance with frequency is shown alone in Fig. 4 and also along with observed relationships for patients with chronic obstructive lung disease in Fig. 5. These values have been published and the reader is referred to the original publication for details of the methods used (1, 5).

I conclude from the similarity of these curves that, in considerable part, the frequency-dependent behavior of diseased lungs could reflect differences in distribution of tidal volume between the airways and the pulmonary parenchyma. The patients generally show a greater fall in compliance at very low frequencies than that predicted. It seems likely that parenchymal time constants in excess of 3 sec must be present, and that, in part, the frequency dependence reflects discrepancies between different parts of the lungs, as previously held (3). The general conclusion may be made, however, that parenchymal time-constant discrepancies need not exist for there to be a substantial frequency dependence of compliance and resistance. The essential feature in the latter instance is increased airway resistance in the peripheral airways, effectively between the air spaces and the major part of the airway's distensible volume.

I have also examined the influence of changes in the com-

pliance of the airways on the frequency dependence of compliance and resistance. In Table 1 I show values for overall compliance and resistance at three frequencies for "normal lungs," that is, ones with values of parenchymal compliance and resistance the same as those in Fig. 1, and in diseased lungs, that is, ones similar to those represented in Fig. 4. An approximate halving or doubling of airway compliance would not have a detectable influence on practical measurements of either compliance or resistance in normal lungs. The effect would be appreciable in abnormal lungs, however. The correspondence with the observed changes in compliance with frequency would be equally good over the full fivefold range of airway compliances tested. The same can be said with regard to the similarity of predicted values with observed changes in resistance with frequency, although the fit would be somewhat better for the airway compliance of 0.002 than for that of 0.01.

Dr. Peter Macklem read and reacted to an earlier version of this manuscript, and I would like to acknowledge his very helpful criticism.

This investigation was wholly supported by Public Health Service Research Grant GM-12564.

Received for publication 13 May 1968.

## REFERENCES

1. GRIMBY, G., T. TAKISHIMA, W. GRAHAM, P. T. MACKLEM, AND J. MEAD. Frequency dependence of flow-resistance in patients with obstructive lung disease. *J. Clin. Invest.* 47: 1455–1465, 1968.
2. MACKLEM, P. T., AND J. MEAD. Resistance of central and peripheral airways measured by a retrograde catheter. *J. Appl. Physiol.* 22: 395–401, 1967.
3. OTIS, A. B., C. B. MCKERROW, R. A. BARTLETT, J. MEAD, M. B. MCILROY, N. J. SELVERSTONE, AND E. P. RADFORD, JR. Mechanical factors in distribution of pulmonary ventilation. *J. Appl. Physiol.* 8: 427–443, 1956.
4. SHEPARD, R. H., E. J. M. CAMPBELL, H. B. MARTIN, AND T. ENNS. Factors affecting the pulmonary dead space as determined by single breath analysis. *J. Appl. Physiol.* 11: 241–244, 1957.
5. TAKISHIMA, T., G. GRIMBY, W. GRAHAM, R. KNUDSON, P. T. MACKLEM, AND J. MEAD. Flow-volume curves during quiet breathing, maximum voluntary ventilation, and forced vital capacities in patients with obstructive lung disease. *Scand. J. Respirat. Diseases* 48: 384–393, 1967.