INTRABRONCHIAL PRESSURE MEASUREMENT BY CATHETER

G. A. Lyubimov

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Measurement of pressure in the air passages is used in clinical practice to estimate resistance of the trachea and main bronchi [2]. The results of measurement of intrabronchial pressure in the more distal bronchi also have been used [4-8] to study the nature and to identify the sites of increased resistance, restricting the flow during forced expiration. In all these investigations a catheter with side sampling hole was used. Naturally with the introduction of methods of recording intrabronchial pressure for assessing the distribution of resistances in the lung on a wide scale it has become necessary to measure pressure in the distal bronchi. However, in this case (just as, indeed, when measurements are made in the large bronchi) a number of technical problems connected with the estimation of error of such measurements arise. These include purely mechanical questions, such as the effect of the position of the catheter in the bronchus on the parameter to be measured, the ratio of the diameter of the bronchus to the diameter of the catheter, the conditions upstream and downstream from the point of measurement, and so on, as well as physiological questions connected with the nonhomogeneity of the lung and the possible effect of the catheter on the conditions of ventilation and behavior of the bronchi during respiration (for example, the effect of an indwelling catheter on collapse of the respiratory passages).

In order to answer these questions and also to estimate changes in resistance of the bronchi during the introduction of a catheter into them, special experiments were carried out on a mechanical model.

EXPERIMENTAL METHOD

A description of the apparatus was given in [1]. Experiments were carried out in air within the range of Reynolds' numbers characteristic of flow in the large bronchi, and conditions of expiration were simulated. The bronchi in these experiments were simulated by metal tubes of different diameters (d) — from 6 to 12 mm, and the catheter by a metal tube (probe) with a diameter (d_c) of 5 mm, with holes for sampling the static pressure. The catheter was introduced along the axis of the tube in which the pressure was measured, for different distances. Errors of measurement of pressure due to a nonaxial position of the catheter in the bronchus were analyzed in [7]. The distribution of pressure along the tube, in the absence of the catheter and during its introduction for different distances, was measured by means of drainage holes in the wall of the tube. The experiments were carried out with an assigned total pressure drop on the apparatus (Δh), determined by the air flow rate in the absence of the catheter. During introduction of the catheter and a change in its position the conditions at the entrance to the apparatus were such that the over-all pressure drop was maintained.

EXPERIMENTAL RESULTS

The experiments showed that introduction of the catheter into a tube of relatively small diameter ($0.42 \leqslant d_c/d \leqslant 0.83$) substantially changes the pattern of distribution of pressure along the tube. Curves of distribution of pressure obtained with different depths of introduction of the catheter are given in Fig. 1 (curves 1-7). Curve 0 corresponds to the distribution of pressure in the absence of the catheter. As Fig. 1 shows, on introduction of the catheter the pressure upstream from the catheter is considerably increased and there is a sharp pressure drop along the annular gap formed by the tube and catheter. Curve 7, represented by a broken line in Fig. 1, connects the points of measurement of pressure by the cath-

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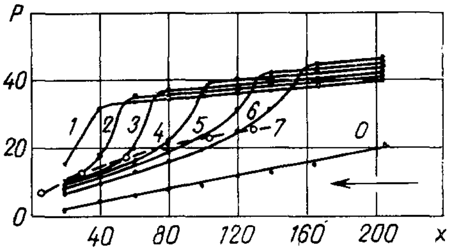

Fig. 1. Distribution of static pressure along a tube of diameter (d) 8 mm during insertion of a measuring catheter of diameter (d_c) 5 mm into it (d_c/d = 0.63). Abscissa, distance (x) along measuring tube (in mm); ordinate, static pressure p (in mm Hg). Arrow shows direction of flow. Curve 0 corresponds to distribution of pressure in absence of catheter (corresponding air flow rate Q_0 = 0.96 liter/sec). Curves 1–6 correspond to depth of insertion of catheter into tube of x_1 = 10 mm (air flow in this position of the catheter is Q_1 = 0.60 liter/sec); x_2 = 35 mm (Q_2 = 5.7 liters/sec); x_3 = 60 mm (Q_3 = 0.54 liter/sec); x_4 = 85 mm (Q_4 = 0.51 liter/sec); x_5 = 110 mm (Q_5 = 0.49 liter/sec); x_6 = 135 mm (Q_6 = 0.47 liter/sec). Broken curve 7 shows static pressure measured by catheter.

eter. The pressure measured by the catheter was shown to differ appreciably from the true pressure in the tube in the absence of the catheter (curves 0 and 7).

The principal parameter determining the resistance of the encumbered part of the tube is the value $\alpha = \dot{V}/\dot{V}_0$ (where $\dot{V}_0$ is the volume air flow in the free tube and $\dot{V}$ the volume air flow in the tube containing the catheter). It was shown that within the range of parameters used the value of α is determined mainly by the geometric parameters of the tube–catheter system (Fig. 2). The resistance of the encumbered part practically coincides with the resistance of the annular gap formed by the catheter and tube, and it can be calculated by the equations:

$$R = \frac{P_2 - P_1}{G} = 1{,}07\cdot 10^5 \; \frac{\alpha \dot{V}_0 L}{(d-d_3)\left(d^2-d_3^2\right)^2}\zeta, \tag{1}$$

$$\zeta = \begin{cases} \dfrac{64}{R_e} & \text{when} R_e<2000 \\ \dfrac{0{,}36}{R_e^{0,25}} & \text{when} \quad R>2000 \end{cases} \qquad R_e = 0{,}92\cdot 10^6 \frac{\alpha \dot{V}_0}{d+d_3},$$

where R is the resistance (in mm water•sec•liters^{-1}), $\dot{V}_0$ the air flow rate in the tube without catheter (in liters•sec^{-1}), d and d_c the diameters of the tube and catheter, respectively (in mm), L the length of insertion of the catheter into the tube (in mm), and α is determined through d_c/d and L/d by the curves in Fig. 2.

Let us now examine the conditions realized in the lung during measurement of pressure in the bronchi. The main aim of such measurements is to determine the sites of increased resistance (the locations of regions with obstruction to the air passages) and regions subject to collapse of the respiratory passages as a result of changes in the elastic properties of the bronchi [4-8]. In these experiments the measuring catheter is introduced into bronchi of different generations, and the resistance of the segment of the respiratory passages between the points of measurement is determined from values of the pressures measured at those points.

Calculation of resistance assumes that the lung is homogeneous with respect to levels of generations (laminar heterogeneity of the lung) and, consequently, the values of the pressure and air flow in all bronchi of the chosen generation are equal. (To estimate the distribution of resistances in the presence of regional heterogeneity of the lung, besides pressure, it is essential also to measure the air flow through the corresponding air passages at the appropriate points in different parts of the lung. Measurement of distribution of air flow

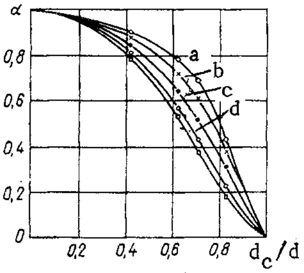

Fig. 2

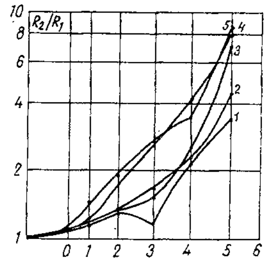

Fig. 3

Fig. 2. Relative change in air flow rate in tube depending on d_c of catheter and depth of its insertion L_1 into the tube. Abscissa, ratio d_c/d; ordinate, ratio $\alpha = \dot{V}/\dot{V}_0$, where $\dot{V}_0$ is the flow rate in the tube without catheter; $\dot{V}$ the flow rate in the tube with catheter, with the same pressure drop in the system. Curves *a*–e correspond to different depths of insertion of the catheter L_1 (the relative depth of insertion L_1/d increases from curve *a* to curve e, and its values are 2, 3, 5, 10, and 15 mm, respectively).

Fig. 3. Change in resistance of different generations of bronchi on introduction of a measuring catheter 2 mm in diameter into them. Abscissa, No. of generation of bronchus; ordinate, ratio of resistance of "encumbered" bronchus (R_2) to its resistance in absence of catheter (R_1). Curve 1 corresponds to air flow of 10 liters/sec, curve 2) 5 liters/sec, curve 3) 3 liters/sec, curve 4) 1 liter/sec, and curve 5) 0.5 liter/sec.

in the regionally heterogeneous lung requires the development of special techniques.) In this case there are two different technical problems: the effect of introduction of the measuring catheter on conditions of ventilation of that part of the lung which is connected with the bronchus in which the measurement is made, and the difference between the measured pressure and that which would have existed at the point of measurement in the absence of the catheter.

The experiments described above show that introduction of a catheter leads to increased resistance in the segment of the respiratory tract located downstream from the point of measurement, which is equivalent to the appearance of regional heterogeneity of the lung. Under these circumstances ventilation of an isolated volume of the lung may be changed (for example, on account of different time constants the alveolar pressure in the isolated portion will differ from the alveolar pressure in the remaining parts of the lung), and, consequently, the distribution of pressure along the isolated segment of the air passages and, in particular, the pressure at the point of measurement, also may change.

To estimate the heteorgeneity thus produced, let us assume that the bronchus—catheter system possesses the resistance of the annular gap between cylinders of corresponding radii. It will further be assumed that the change in air flow in the encumbered bronchus will be the same as in experiments on the model (Fig. 2). In the real lung the outflow segment consists of a tube with variable flow (inflow of air through the bifurcation below the measuring point). In that case the change in air flow in the chosen bronchus will depend not only on the geometric parameters of the encumbered bronchus, but also on the distribution of resistances along the other bronchi. Determination of α from the data in Fig. 2, therefore, is generally speaking inadmissible, and can be used only for obtaining rough estimates. The ratio $\chi = R_2/R_1$ for resistances of the encumbered (R_2) and free (R_1) bronchi calculated in this way, depending on the generation number and the total air flow through the lung for a catheter 2 mm in diameter, is illustrated in Fig. 3. Geometrical parameters corresponding to the human lung were used in the calculations.

Investigation of the mechanics of the heterogeneous lung [3, 9] shows that when $\chi \triangleright 5$ the alveolar pressure in components of the lung during quiet breathing may already differ significantly. In this connection, it follows from Fig. 3 that from the standpoint of the current problem (the effect of the measuring catheter on the mechanics of respiration of an isolated part of the lung) during quiet breathing a catheter 2 mm in diameter can be used to measure pressure in bronchi as far as the fourth generation, and during forced breathing as far as the fifth generation. Similar estimates for a catheter 3 mm in diameter show that it can be used during quiet breathing to measure pressure in bronchi as far as the second generation, and during forced breathing as far as the third generation.

On introduction of a measuring catheter into a bronchus of relatively small diameter the pattern of distribution of pressure along the bronchus changes substantially (Fig. 1). This change, with an assigned pressure drop in the system, is linked with a decrease in the air flow as a result of a local increase of pressure in the tract.

Moreover, the absolute value of pressure measured depends on the position of the sampling hole (by changing the position of the pressure sampling point, it is possible to measure any value of pressure belonging to the curve corresponding to the assigned position of the catheter — curves 2-7 in Fig. 1). It will be noted that depending on the outflow resistance and the position of the pressure sampling point, the measured value may be both higher and lower than the true value. The difference between the true and measured values of pressure decreases with a fall in the ratio d_c/d.

By using the simplest model ideas, the data shown in Fig. 3, and corresponding data for catheters of other diameters, it is possible to estimate roughly the error of measurement of pressure (and resistances) by the method we have examined. It was concluded from these estimates that the catheter introduced has only a little effect on the distribution of pressure along the respiratory passages if the minimal diameter of the bronchus into which the catheter is introduced is more than twice the diameter of the catheter ($d_c/d \leqslant 0.5$). The maximal change of air flow during introduction of the catheter into individual bronchi under these circumstances is about 10-15%, and the corresponding values of pressure and resistance vary by not more than 50%.

Let us now consider another important matter. In all previous estimates it was assumed that the bronchi are rigid tubes whose diameter is independent of the pressure in the tube. However, we know that during forced expiration the pressure in a certain region of the tracheobronchial tree may fall to such an extent that the transmural pressure becomes negative. Under these conditions dynamic contraction of the bronchi, leading to a sharp increase in resistance, is possible. Estimates show that on introduction of the catheter the pressure in the tract may either increase or decrease. In the first case the point of equal pressure is shifted toward bronchi of greater diameter, whereas in the second case, on the contrary, it is shifted toward bronchi of smaller diameter. The distribution of pressure along the respiratory tract in this case may vary significantly.

Estimation of the effect of dynamic constriction of the bronchi on the pressure as measured by the catheter, and also of the possibility of determining the position of the point of equal pressure by measuring pressures with a catheter at different points of the tracheobronchial tree is not really possible by means of simple methods, and this places additional restrictions on the method of measurement. Evidently it must be used with caution in cases when dynamic contraction may become considerable — in diseases associated with increased elasticity of the bronchi, during forced breathing, and so on. Moreover, in the course of further investigations into the basic principles of the method, the resistance must be measured in a regionally heterogeneous lung.

LITERATURE CITED

1. Yu. A. Vinogradov, G. A. Lyubimov, and V. I. Rozhdestvenskii, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 1 (1983).
2. L. Ts. Ioffe and Zh. A. Svetysheva, Mechanics of Respiration [in Russian], Alma-Ata (1975).
3. G. A. Lyubimov, Fiziol. Cheloveka, No. 1, 105 (1980).
4. E. Dekker, J. G. Defares, and H. Heemstra, J. Appl. Physiol., 13, 35 (1958).
5. H. Herzog, R. Keller, and A. Perruchoud, Mechanics of Airways: Obstruction, Disease, Cape Town (1979).
6. P. T. Macklem, R. G. Fraser, and D. V. Bates, J. Appl. Physiol., 18, 699 (1963).
7. P. T. Macklem and N. Y. Wilson, J. Appl. Physiol., 20, 653 (1965).
8. P. T. Macklem, R. G. Fraser, and W. G. Brown, J. Clin. Invest., 44, 897 (1965).
9. R. Peslin, J. Appl. Physiol., 24, 761 (1968).