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Lung
lung elasticity
pulmonary compliance
pulmonary resistance
vital capacity

Lung Tissue Resistance in Healthy Children

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Extract

In ten healthy children, simultaneous measurements were made of the total pulmonary resistance and the airway resistance. The difference between these two measurements gave the lung tissue resistance which amounted to 1.08 ± 0.32 cm H_2O/l/s (range, 0.65 to 1.59), or 29% of the total pulmonary resistance. It was on an average three times higher in children than in healthy adults. An inverse relation was found between lung tissue resistance and the vital capacity. Moreover, the results of measurements made in one child breathing at three different breathing patterns, indicate that with increasing tidal volume, lung tissue resistance increases. These observations suggest that lung tissue resistance itself is the sum of two components; one being due to the flow-dependent frictional forces of lung tissue, and the other, independent of flow resistance, being due to the nonideal elastic properties of the lung. The results obtained can be explained reasonably well on the basis of the latter component which seems to be much more important than the former.

Speculation

Dynamic measurements of the nonflow resistive hysteresis may give information about the properties of surface-active substance in healthy and diseased lungs.

Introduction

The respiratory mechanics of healthy children have been extensively studied by several authors [3, 5, 7, 8, 10, 14, 27]. Total pulmonary resistance (R_p) was found to be considerably higher in children than in healthy adults. Furthermore, a positive correlation could be shown between compliance and size of the lung and a negative one between body height and pulmonary resistance. R_p is the sum of two components, airway resistance (R_a) and lung tissue resistance (R_{lt}). In healthy adults breathing with normal or small tidal volumes (panting), R_{lt} has been estimated to be a small fraction of R_p [1, 9, 12, 15]. As yet, however, no attempt has been made to determine whether the high values R_p found in children are due only to an increased airway resistance (owing to the small airways in the child's lung), or whether, and to what extent, the possible existence of increased lung tissue resistance may be an additional factor to explain this observation. It was our purpose, therefore, to attempt to resolve this problem by studies using a plethysmograph.

Methods

Ten children, free of lung disease and infections of the upper airways, were studied. The lung volumes were determined by spirometry, and the functional residual capacity was calculated with a helium dilution technic (one measurement). Physical data and results of lung volume measurements are given in table I. The method to determine the lung tissue resistance is described in detail elsewhere [1, 2, 12]. Airway resistance (R_a) was measured by means of a volume displacement plethysmograph of the type designed by MEAD [17] and modified by JAEGER and OTIS [12], and total pulmonary resistance (R_p) by simultaneous recordings of intraesophageal pressure and rate of air flow. By subtracting the value of R_a from that of R_p, the lung tissue resistance (R_{lt}) could be determined indirectly. Intraesophageal pressure was measured by means of a thin-walled rubber balloon (length 7 cm; perimeter 3 cm) similar to that described by SCHILDER *et al.* [23]. A spray of 1 % solution of Oxybuprocain (Novesin®, Wander) was used in the nose and nasopharynx as a topical anesthetic for insertion of the intraesophageal balloon. With the fluctuations of the intraesophageal

Table I. Physical data and lung volume (BTPS) in ten healthy children

Name	Sex	Age	Height	Weight	Vital capacity	Residual volume	Total lung capacity
		years	cm	kg	ml	ml	ml
L.M.	♂	10	126	26.5	1600	460	2060
R.D.	♂	7	127	23	1700	320	2020
R.H.	♂	7	130	26.5	2100	290	2390
B.A.	♂	10	136	30	2170	440	2610
S.R.	♀	10	136	30.5	2310	610	2910
S.H.	♀	11	136	33	2620	760	3380
H.R.	♂	10	137	32.5	2470	1210	3680
K.U.	♀	11	138	40	2160	300	2460
B.B.	♀	10	138	28	2160	860	3020
J.P.	♂	11	145	32	3150	500	3650

Table II. Dynamic compliance of the lung: total pulmonary resistance, airway resistance and lung tissue resistance in ten healthy children[1]

Name	f	$\bar{\dot{V}}$	V_T (BTPS)	FRC (BTPS)	R_p	R_a	R_{lt}	R_{lt} as % R_p	Cdyn (l)
	rpm	l/s	ml	ml		cm H_2O/l/s		%	ml/cm H_2O
L.M.	28	0.61	650	1350	4.82	3.23	1.59	33	72
R.D.	27	0.51	570	1050	4.87	3.55	1.32	27	78
R.H.	36	0.66	550	1600	3.15	2.06	1.08	34	93
B.A.	36	0.68	570	1800	3.54	2.60	0.94	27	94
S.R.	21	0.46	660	2100	3.39	2.35	1.04	31	105
S.H.	22	0.50	690	1900	2.85	2.13	0.72	25	88
H.R.	22	0.54	740	2000	3.12	2.47	0.65	21	114
K.U.	30	0.52	520	1250	3.98	2.71	1.27	32	91
B.B.	28	0.61	650	1400	4.03	2.58	1.45	36	83
J.P.	24	0.54	670	1750	3.37	2.57	0.80	24	117
Mean					3.71	2.63	1.08	29	94
SD					±0.70	±0.46	±0.32		

[1] f: respiratory rate; $\bar{\dot{V}}$: mean flow rate; V_T: tidal volume; FRC: functional residual capacity; R_p, R_a and R_{lt}: total pulmonary, airway, and lung tissue resistance; Cdyn (l): dynamic compliance of the lung.

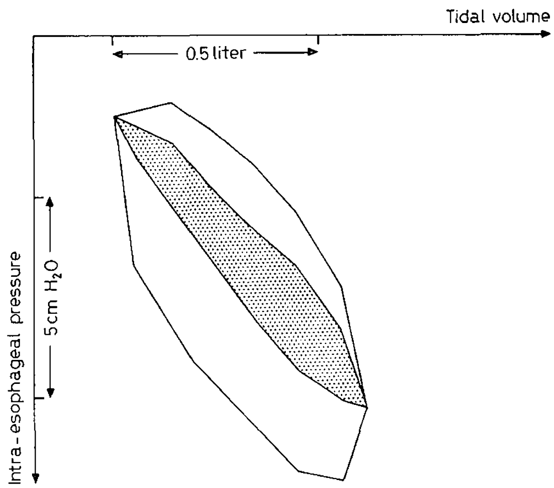

Fig. 1. Volume-pressure loop in a healthy child (K.U., table I). The stippled area corresponds with the work done against lung tissue resistance.

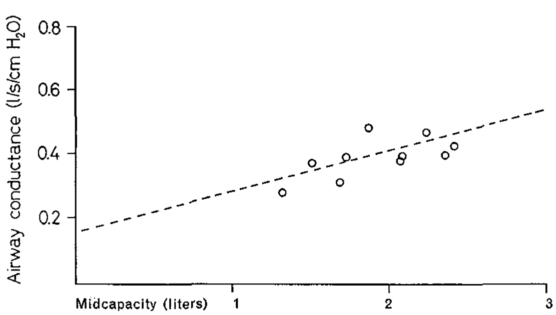

Fig. 2. Relation between airway conductance and midcapacity in 10 healthy children. The regression line is: Airway conductance = 0.12× midcapacity +0.16. The correlation coefficient is 0.65.

Table III. Lung tissue resistance measured with three different breathing patterns in a healthy child (S.H., table I). Lung tissue resistance increases with increasing tidal volume[1]

	V_T = 300 ml	V_T = 690 ml	V_T = 1360 ml
f rpm	51	22	12
$\bar{V}$ l/s	0.51	0.50	0.55
FRC ml	1800	1900	1700
Cdyn (l) ml/cm H_2O	–	83	79
R_p cm H_2O/l/s	2.20	2.85	3.70
R_a cm H_2O/l/s	1.90	2.13	2.49
R_{lt} cm H_2O/l/s	0.30	0.72	1.21

[1] See table II for symbols.

pressure or intraalveolar pressure, respectively, and the tidal volume (V_T), pressure-volume loops were plotted as shown in figure 1. The areas of the loops were measured with a planimeter and the total pulmonary (R_p), airway (R_a) and lung tissue (R_{lt}) resistances were derived using the area formula (equation 3) indicated by NISELL and EHRNER [20]. The values of R_p, R_a, R_{lt} and of the dynamic compliance (Cdyn) (l) given in table II are averages of five measurements.

The children were asked to breathe with similar breathing patterns, the tidal volume and the mean flow rate being within a comparable range in all subjects examined. In one child (S.H., table I), measurements were made with three different breathing patterns. The tidal volume was varied from small through medium to deep breaths, the functional residual capacity and the mean flow rate being constant (table III).

Results

The measurement data are given in table II. Total pulmonary resistance (R_p) averaged 3.71±0.70 cm H_2O/l/s (range, 2.85 to 4.87), thus being considerably greather than in healthy adults (1, 9, 12, 14, 15]. Compared with the results of previous authors [5, 7, 8, 10, 14, 27], these values seem to be relatively low. But considering the large individual variations found in children and the small number of measurements in our series, this difference is probably an incidental one. Airway resistance (R_a) amounted to 2.63±0.46 cm H_2O/l/s (range, 2.06 to 3.55), a value almost 100%

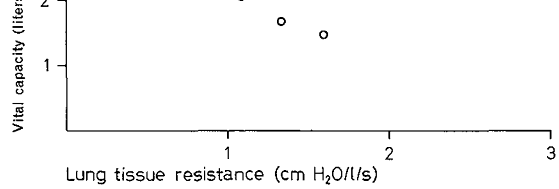

Fig. 3. Relation between the vital capacity and the lung tissue resistance in 10 healthy children. O = children; ♂ = mean value of 18 adult males; ♀ = mean value of 11 adult females. All subjects were examined during spontaneous breathing).

higher than that found in healthy adults [1, 9, 12, 15]. As expected, higher resistances were found in small children with small lung volumes. This negative correlation between R_a and the lung volume is demonstrated by a graphical analysis, wherein the airway resistance was substituted by its reciprocal value, the airway conductance, in order to obtain linearity (fig. 2); between the conductance and the midcapacity (functional residual capacity plus half the tidal volume) a linear relation was found, quite similar to that obtained by BRISCOE and DUBOIS [3]. Lung tissue resistance averaged 1.08 ± 0.32 cm $H_2O/l/s$ (range, 0.65 to 1.59), or 29 % of total pulmonary resistance. This value (expressed as an absolute amount) was about 200 % higher than that reported for healthy adults but the quotient R_{lt}/R_p (= 0.29) was found to be almost the same as in the adult groups [1]. No striking difference could be detected between male and female children. By plotting the values of R_{lt} and the vital capacity, an inverse relation was found between these two values (fig. 3), i.e., with increasing size of the lung, the lung tissue resistance decreased.

Discussion

The data given in table II indicate that the high pulmonary resistance in children (found by different authors) is associated with both its components, the airway and the lung tissue resistance. Keeping in mind the small caliber of the airway in the child's lung, the high airway resistance and the negative correlation between R_a and the lung volumes seem to be satisfactorily explained. A further attempt should be made, however, to determine the extent of airway resistance in children originating in the upper airways (larynx, pharynx and mouth). It can be noted here that FERRIS *et al.* [9] and HYATT *et al.* [11] have found that in healthy adults both upper and lower airways contribute almost equally to the total airway resistance.

The interpretation of the inverse relation between R_{lt} and the size of the lung is more puzzling. Previously, a similar relation was shown to exist in adults [1]. R_{lt} was significantly higher in females than in males. It was suggested that this result might be explained by the significant differences in lung volumes and compliances between both groups, i.e., by the size difference rather than by the sex difference. However, the mechanism involved could not be elucidated satisfactorily. Provided that R_{lt} was a 'true' flow-dependent resistance, i.e., that the lung tissue had the same physical properties as a Newtonian liquid, one would expect lung tissue resistance (expressed in cm $H_2O/l/s$) to be about the same in children as in adults. The influence of maturation of he human lung on the mechanical properties of lung tissue is hard to ascertain. Anatomical and morphometric investigations [28] have shown that only the size but not the number and structure of respiratory units is different when comparing adults with children of the same age as those examined in this study. Furthermore, the distensibility of the lung is about the same in children of this age as in adults [5]. Consequently, the findings obtained could be explained only by assuming an alteration in viscosity of lung tissue which depended upon the maturation of the lung; but this suggestion seems to be a rather improbable one.

As was pointed out in another paper [2], it is not possible to judge by the method used whether the hatched area of the volume-pressure loop (fig. 1) represents work done against the frictional forces of the lung tissue only or whether it also includes considerable nonflow resistive volume-pressure hysteresis. Indeed, the latter factor may account for the inconsistencies between the expected and observed results. Several investigators have demonstrated that neither the human lung [18, 21, 24] nor other 'elastic' organs [22] exhibit ideal elastic behavior. This nonideal elasticity of the lung as shown by static volume-pressure hysteresis [8, 21, 24] and stress relaxation [16] is probably influenced by various factors: reopening of alveoli during inspiration, surface film activity [4, 18, 19] and tissue stress relaxation. By the cyclic deformation of any elastic material which shows a considerable degree of stress relaxation, a hysteresis loop will be obtained, the width of the loop being determined by the amplitude of the stretch [25, 26]. Thus, the inverse relation between the size of the lung and the lung tissue resistance may be explained reasonably well by this mechanism. If lungs of different size are inflated by the same tidal volume, the stretch amplitude of the elastic elements is higher in the small lungs; accordingly, a larger area of the hysteresis loop on cyclic deformation is expected. Further support is given to this interpretation by the results of measurements made in one healthy child (S.H., table I) at three different breathing patterns. The data shown in table III indicate that with increasing tidal volume (increasing stretch-amplitude), R_{lt} increases, although the mean flow rate does not change. Consequently, the results obtained suggest that R_{lt} is itself the sum of at least two components: one being due to the nonideal elastic behavior of the lung, the other to flow-dependent frictional forces of lung tissue. Moreover, the conclusion seems to be justified that the high R_{lt} found in children must be accounted for by the nonideal elasticity of the lung. The 'true' flow-dependent viscous lung tissue resistance is probably very small, considering the low value of R_{lt} when measurements are made during breathing with small tidal volumes (table III). This view would be in good agreement with the results recently reported by MACKLEM and MEAD [13] which were obtained with a new method. These data indicate that the flow-dependent component of R_{lt} is negligible.

The body plethysmograph is the instrument of choice for determining airway resistance. Without doubt, the esophageal-balloon technique is a useful tool for judging the degree of bronchial obstruction as shown by several authors [7, 8, 27]. It should be kept in mind, however, that in children, lung tissue resistance contributes considerably to total pulmonary resistance, being dependent on the size of the lung and on the breathing pattern as well.

Summary

Pulmonary resistance during spontaneous breathing was measured in ten healthy children by employing a plethysmographic technique. On the average, total pulmonary resistance was 3.71 ± 0.70 cm H_2O/l/s; airway resistance was 2.63 ± 0.46 cm H_2O/l/s, and lung tissue resistance was 1.08 ± 0.32 cm H_2O/l/s. Lung tissue resistance was on an average about three times higher in children than in spontaneously breathing adults. It could be shown that lung tissue resistance is dependent on the lung size as well as on the breathing pattern.

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