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THE MECHANICAL BEHAVIOR OF THE LUNGS IN HEALTHY ELDERLY PERSONS [1,2]

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In a previous study it was found that the elastic properties of lungs appeared to be unaffected by age in healthy adults 17 to 39 years old (1). The slope of the static volume-pressure curve of lungs in the resting tidal range of breathing was used as a measure of pulmonary compliance. The present study extends observations to adults 50 years and older. To obtain a more complete description of the elastic behavior of lungs, static transpulmonary pressure has been related to the total volume of gas in the lungs, and the range of volume change has been extended from that of tidal volume to inspiratory capacity. In addition, measurement has also been made of pulmonary compliance at various rates of breathing, and of pulmonary flow resistance. Finally, these data have been compared with findings in young adults.

MATERIAL AND METHODS

Eight male and twenty female volunteers, ranging in age from 50 to 89 years, were studied. All were apparently healthy and lived at home. Most of the women did their own housework, while four of the eight men were still employed in office work. They denied any recent or chronic cardiopulmonary disease, and had no untoward shortness of breath. Photofluorograms of their chests were considered to be "normal." Part of the data on young adults was obtained from previous studies (1, 2). Additional measurements were made on a group of young adult volunteers.

All measurements were made with the subjects seated. Intraesophageal pressure was used as an index of intrapleural pressure. It was obtained from a thin latex balloon, approximately 15 cm. in length, affixed to polyethylene tubing (3). The balloon was passed to the lower portion of the esophagus. An inductance manometer was used to measure differences in pressure between the esophagus and the mouthpiece (transpulmonary pressure). Pulmonary compliance was measured statically and dynamically, that is, during interrupted and spontaneous breathing. Air flow was interrupted by means of a solenoid valve located in the mouthpiece assembly; the pressure tap on the mouthpiece lay between the mouth and valve. Volume was recorded with a nine-liter capacity Benedict-Roth spirometer. A commutator on the spirometer wheel energized the solenoid valve at steps of 250 ml. (ATPS). The duration of valve closure was controlled by a time-delay circuit (1); closure lasted approximately three seconds. All static measurements of compliance were made during inspiration starting from the resting end-expiratory level.

For dynamic measurements of pulmonary compliance, volume changes were measured with a seven-liter capacity Krogh spirometer to which was attached a rotational transducer. The spirometer was connected to a bag-box system (4), enabling the subject to breathe air for periods lasting up to several minutes. Instantaneous flow rate was obtained by electrical differentiation of the volume signal. The three electrical signals (pressure, volume, flow rate) were amplified and transcribed by means of a direct-writing oscillograph.

During spontaneous breathing, pulmonary compliance was measured as the ratio of the change in volume (tidal volume) to the change in transpulmonary pressure between instants of zero air flow at the volume extremes of inspiration and expiration. Because variations occurred due to changes in intraesophageal pressure accompanying cardiac contraction, average values for compliance (and flow-resistance) during spontaneous breathing were calculated from at least 20 to 30 measurements.

Pulmonary flow-resistance was calculated in two ways. The first method is shown in Figure 1. Points were chosen in both the inspiratory and expiratory phases of a respiratory cycle when lung volumes were identical and flow rates were about maximal. In the tidal range of volume change the elastic component of transpulmonary pressure is the same at these instants. Accordingly, the observed change in pressure between these points relates solely to flow-resistance. The ratio of this pressure change to the corresponding change in flow between these points has been calculated. This value represents an "average" flow-resistance for inspiration and expiration.

In the second method, flow-resistance was measured separately for inspiration and expiration. To do this, values for instantaneous flow-resistive pressures were calculated as the difference between observed changes in transpulmonary pressure occurring between the start of inspiration (or expiration) and some point near maximal flow rate, and the corresponding elastic component

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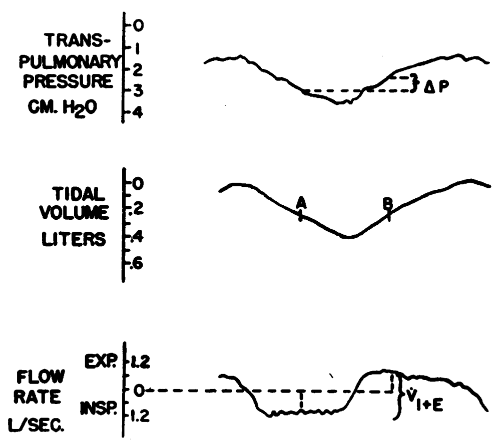

FIG. 1. AT IDENTICAL LUNG VOLUMES, A AND B, ΔP RELATES ONLY TO PULMONARY FLOW-RESISTANCE

"Average" pulmonary flow-resistance for a respiratory cycle may be expressed as:

$$R = \frac{\Delta P}{\dot{V}_I + \dot{V}_E} \text{ in } \frac{\text{cm. } H_2O}{\text{L./sec.}}$$

of transpulmonary pressure. The elastic component, in turn, was estimated from measurements of compliance and the volume change that had occurred between the two points.

Each measurement of flow-resistance has two components—airway, including upper airway and glottis in addition to tracheobronchial tree, and tissue viscous resistance. No attempt was made to measure these components separately. Finally, the assumption is implicit that in the range of air flow rates encountered during quiet breathing, flow-resistance is nearly constant.

The resting end-expiratory gas volume of the lungs (FRC) was measured by use of a helium closed-circuit technique (5). Subdivisions of the vital capacity were recorded on a spirometer, and the total lung capacity was calculated from the sum of the functional residual capacity and inspiratory capacity. All volumes were expressed at body temperature and pressure saturated (BTPS).

TABLE I

Pertinent physical characteristics of 28 healthy elderly subjects

	No.		Age	Height	Weight	B. S. A.*
			yrs.	*cm.*	*Kg.*	*M.²*
Male	8	Mean	76	173	17.0	1.79
		S.D.	8	4	8.7	0.13
		Range	66–89	167–178	61.8–86.3	1.56–1.97
Female	20	Mean	67	163	61.6	1.66
		S.D.	8	5	7.8	0.17
		Range	50–81	150–170	39.1–74.5	1.34–1.83

* Body surface area calculated from Du Bois height-weight formula (19).

TABLE II

Mean pulmonary compliance, end-expiratory and maximal static inspiratory pressures, and lung volumes in healthy subjects

	No.		Age	Height	Compl.	End-exp. trans-pulm. pressure	Max. static insp. transpulm. pressure	Corresponding vol. change	I. C.*	E. R. V.†	Vital capacity Observed	Vital capacity Predicted	F. R. C.‡	R. V.§	T. L. C.‖
			yrs.	*cm.*	*L./cm. H_2O*	*cm. H_2O*	*cm. H_2O*	*L.*	*L.*	*L.*	*L.*	*%*	*L.*	*L.*	*L.*
Younger subjects	11	Mean	28	166	0.150	4.2	30.4	2.30	2.51	1.35	3.86	125	2.93	1.58	5.44
		S.D.	7	7	0.027	1.6	7.4	0.36	0.45	0.26	0.59	18	0.54	0.42	0.79
		Range	22–47	158–178	0.08–0.18	2.5–6.5	21.5–45.0	1.70–2.80	1.95–3.49	0.93–1.75	2.88–5.24		2.45–3.81	1.18–2.39	4.38–7.39
Older subjects	21	Mean	71	166	0.131	4.8	20.7	1.78	2.06	1.06	3.13	116	3.67	2.60	5.73
		S.D.	9	7	0.038	2.0	6.4	0.46	0.61	0.46	0.71	16	0.80	0.50	1.11
		Range	50–89	150–178	0.08–0.23	1.5–8.5	12.5–37.0	1.01–2.84	0.83–3.43	0.18–2.06	1.90–4.47		2.50–5.23	1.80–3.73	3.96–7.58
		p			>0.1	>0.1	<0.01	<0.01	<0.05	<0.1	<0.01		<0.02	<0.01	<0.1

* Inspiratory capacity.
† Expiratory reserve volume.
‡ Functional residual capacity.
§ Residual volume.
‖ Total lung capacity.

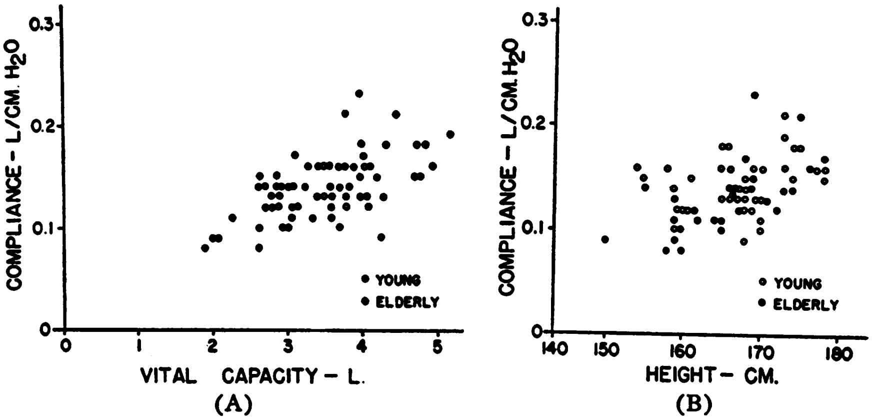

FIG. 2. COMPLIANCE IS PLOTTED AGAINST (A) VITAL CAPACITY AND (B) HEIGHT FOR 26 ELDERLY AND 41 YOUNG SUBJECTS

RESULTS

Average values for the pertinent physical characteristics of 28 elderly[3] subjects are shown in Table I.

Static measurements

In 26 of the elderly subjects, measurements of compliance were made during interrupted breathing starting from the end-expiratory relaxation volume, and compared with similar measurements in a group of 41 younger subjects of the same average height (1).[4] This measurement expresses the slope of the static volume-pressure characteristics of lungs in the range of normal tidal volume for the sitting position. Average values for compliance were 0.130 ± 0.036 L. per cm. H_2O among older subjects and 0.144 ± 0.036 L. per cm. H_2O among younger subjects; the difference was not significant. The correlation between compliance and either height or vital capacity was approximately the same in both age groups (Figures 2A and 2B).

Measurements of total lung capacity and subdivisions were made in 21 of the older and 11 of the younger subjects, each group being of the same average height. Average values are shown in Table II, along with values for compliance, static end-expiratory transpulmonary pressure, and transpulmonary pressure measured at the peak of maximal inspiration. The latter pressure was measured after gas flow had stopped and while the glottis was open. These data are plotted in Figure 3.

It will be noted that, whereas functional residual capacity was larger among elderly subjects ($p < 0.01$), static end-expiratory transpulmonary pressures were not significantly different for the two groups. These findings indicate that the average over-all static volume-pressure curve of the lungs

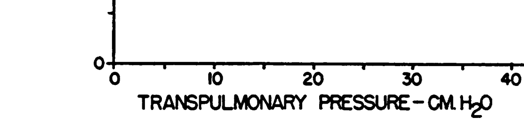

FIG. 3. AVERAGE VALUES FOR STATIC VOLUME-PRESSURE CHARACTERISTICS OF LUNGS ARE SHOWN FOR 21 OLDER AND 11 YOUNGER SUBJECTS

Points indicate measured volumes and pressures. Slopes of the solid lines indicate values for compliance computed from direct measurements. The broken lines are estimated values.

[3] "Elderly" is applied in this study to persons 50 years and older.

[4] Previously, no consistent difference was found in compliance between males and females when subjects of the same size were compared (1). For this reason the data on compliance, including those shown in Figures 2A and 2B, are not subdivided according to sex.

TABLE III

Pulmonary flow resistance in healthy subjects

	No.		Age	Height	Resistance
			yrs.	*cm.*	*cm. H_2O/L./sec.*
Younger subjects	28	Mean	28	168	1.9
		S.D.	6	9	0.6
		Range	18–47	154–189	1.2–3.4
Older subjects	28	Mean	70	165	2.8
		S.D.	9	7	0.8
		Range	50–89	150–178	1.3–4.4

was shifted to the left among elderly subjects. In addition, the young subjects were able to develop greater transpulmonary pressures during maximal inspiratory effort ($p < 0.01$). Despite this difference, total lung capacity was not significantly different for the two groups.

Flow-resistance measurements

In 28 young adults[5] the range of values for "combined" inspiratory and expiratory flow-resistance (see under Methods) was 1.2 to 3.4 cm. H_2O per L. per second, averaging 1.9 ± 0.6 cm. H_2O per L. per second (Table III); only one subject had a value for flow-resistance above 3.0 cm. H_2O per L. per second. Among the 28 elderly subjects, it varied between 1.3 and 4.4 cm. H_2O per L. per second, averaging 2.8 ± 0.8 cm. H_2O per L. per second; flow-resistance was higher than 3.0 cm. H_2O per L. per second in 10 of this group. The average value for the eight elderly males was

TABLE IV

Inspiratory and expiratory pulmonary flow resistance in healthy elderly subjects

	Inspiratory resistance	Expiratory resistance	Inspiratory resistance / Expiratory resistance
	cm. H_2O/L./sec.	*cm. H_2O/L./sec.*	
(a) Eighteen subjects having "combined" flow resistance* under 3.0 cm. H_2O/L./sec.			
Mean	2.0	3.4	0.6
S.D.	0.7	1.2	
Range	0.9–3.0	1.4–5.9	
(b) Ten subjects having "combined" flow resistance over 3.0 cm. H_2O/L./sec.			
Mean	3.1	4.9	0.6
S.D.	0.9	1.14	
Range	1.6–4.1	3.5–6.8	

* Defined in Methods.

[5] Ten of these subjects were reported before (2).

TABLE V

Mean pulmonary compliance, end-expiratory and maximal static inspiratory transpulmonary pressures and lung volumes in healthy elderly subjects having pulmonary flow-resistance below or above 3.0 cm. H_2O/L./sec.

Flow resistance	No.		Age	Height	Compl.	End-exp. trans-pulm. pressure	Max. static insp. transpulm. pressure	I. C.	E. R. V.	V. C.	F. R. C.	R. V.	T. L. C.
			yrs.	*cm.*	*L./cm. H_2O*	*cm. H_2O*	*cm. H_2O*	*L.*	*L.*	*L.*	*L.*	*L.*	*L.*
Below 3.0 cm. H_2O/L./sec.	14	Mean	72	166	0.137	5.0	19.9	1.73	1.50	3.23	3.80	2.62	5.85
		S.D.	11	7	0.042	2.2	5.9	0.44	0.49	0.70	0.75	0.49	1.07
		Range	50–89	150–178	0.09–0.23	1.5–10.0	14.0–37.0	1.01–2.35	0.74–2.46	2.09–4.47	2.51–5.23	1.97–3.73	4.69–7.58
Above 3.0 cm. H_2O/L./sec.	6	Mean	69	164	0.113	5.3	22.8	1.73	1.08	2.82	3.33	2.45	5.25
		S.D.	9	6	0.035	1.6	8.2	0.41	0.45	0.81	1.03	0.64	1.32
		Range	53–79	158–172	0.08–0.17	3.5–8.0	12.5–36.0	1.24–2.34	0.53–1.74	1.90–4.08	2.50–4.82	1.80–3.41	3.96–7.49

TABLE VI

Pulmonary compliance during interrupted, quiet and rapid breathing in healthy elderly subjects

Subject no.	Flow resistance	Interrupted breathing compl.	Quiet breathing Rate	Quiet breathing Compl.	Rapid breathing Rate	Rapid breathing Compl.
	cm. H_2O/L./sec.	*L./cm. H_2O*	*min.*	*L./cm. H_2O*	*min.*	*L./cm. H_2O*
5	2.1	0.17	14	0.17	74	0.16
13	2.2	0.11	13	0.14	33	0.12
25	2.2	0.12	16	0.13	52	0.09
26	2.7	0.13	10	0.12	48	0.08
	Mean	0.132		0.140		0.112
2	3.8	0.12	15	0.09	42	0.08
9	4.4	0.08	16	0.07	41	0.06
15	3.2	0.14	14	0.12	59	0.11
18	3.1	0.13	20	0.12	42	0.11
27	4.2	0.14	20	0.12	52	0.10
	Mean	0.122		0.104		0.092

2.5 ± 0.8 cm. H_2O per L. per second, and for the 20 elderly females, 2.9 ± 0.8 cm. H_2O per L. per second. To determine whether the higher values (over 3.0 cm. H_2O per L. per second) for flow-resistance were due to changes predominantly in one or the other phase of the respiratory cycle, flow-resistances were calculated separately for inspiration and expiration at identical lung volumes (Table IV). Inspiratory resistance measured about two thirds as much as expiratory resistance for the group whose "combined" flow-resistance was less than 3.0 cm. H_2O per L. per second, as well as for those with higher values. The ratio of inspiratory to expiratory flow-resistance was also calculated in six of the young subjects and found to be nearly 0.9. The latter value is roughly equal to that derived from the data of Fry, Ebert, Stead, and Brown (6) in healthy young adults at a flow rate of 1.0 L. per second, although higher than the value of 0.7 found by Attinger, Monroe, and Segal (7) at slow rates of breathing in the sitting position. It is felt that the number of observations in the present study is too small to draw a conclusion regarding the significance of the difference in ratios between the two age groups.

When the elderly subjects were divided into groups having flow-resistance below or above 3.0 cm. H_2O per L. per second, no significant differences were found in mean static compliance, subdivisions of total lung capacity (including F.R.C.), or static transpulmonary pressures, both at the end of normal expiration and following maximal inspiration (Table V).

Dynamic compliance measurements

Measurements of compliance were made in nine of the elderly subjects during quiet and rapid breathing, care being taken to prevent changes in end-expiratory lung volume and tidal volumes. The group was divided into those having flow-resistance either below 3.0 cm. H_2O per L. per second or above that value (Table VI). The group having lower flow-resistance showed no consistent change in compliance as the rate of breathing increased. The group having higher flow-resistance showed a progressive decline in compliance with increasing rates of breathing in all instances; the magnitude of change was small, however, when compared with that observed among patients having emphysema (2, 8–10).

Smoking habits of the elderly subjects

Twenty-one elderly subjects had not smoked; five had been regular smokers more than 10 years, three of cigarettes and two of cigars; two of the subjects were not questioned. Pulmonary flow-resistance was above 3.0 cm. H_2O per L. per second in only 6 of the 21 nonsmokers, whereas it was above this value in four of the five smokers. (One subject who smoked cigars had a value of 2.2 cm. H_2O per L. per second.) Despite this considerably greater incidence of elevated flow-resistance among smokers, it is felt that the group is too small to warrant a conclusion about the possible relation of smoking to changes in flow-resistance. With regard to other measurements, there was no apparent pattern of change in static compliance or subdivisions of lung volume among the elderly smokers.

DISCUSSION

It should be emphasized that this study does not permit a distinction between changes inherent in the aging process and those which may represent the effects of repeated disease or injury to the lungs. According to Bates and Christie, "emphysema is a gross exaggeration of what happens to the lungs with advancing years" (11). They found a reduction in vital capacity and an increase in functional residual capacity in both healthy elderly persons and patients having emphysema. The changes accompanying aging were attributed to "fixation of the thoracic cage" and to reduced elastic recoil of the lungs, though no direct measurement of elastic properties of either structure was reported. The judgment of these authors gains support from findings in the present study. In general, the static volume-pressure curve of the lungs in elderly subjects was shifted to the left so that at any volume their lungs appeared to have diminished elastic recoil compared with those of young adults. This shift of the entire volume-pressure curve could be detected only by relating measurements of compliance to absolute gas volumes in the lungs and transpulmonary pressure. The fact that there was no significant difference in mean compliance in the range of tidal breathing between the two age groups emphasizes that this measurement expresses only a part of the over-all elastic behavior of the lungs.

In addition, there is evidence of an alteration in the elastic properties of the thorax which may be described as follows: The volume of gas remaining in the lungs at the end of expiration during quiet breathing is determined by the opposing elastic recoil of the lungs and thorax. An increase in this volume can result from either reduced elastic recoil of the lungs, increased elastic recoil of the thorax, or a combination of both. The relative contribution of the two forces should be reflected in the end-expiratory transpulmonary pressure. For example, if all of an increase in functional residual capacity were due to reduced elastic recoil of the lungs, end-expiratory transpulmonary pressure would decrease as the thorax approached its own "relaxation" volume. On the other hand, if all of an increase in functional residual capacity were attributable to increased tendency of the thorax to recoil "outward," end-expiratory transpulmonary pressure would increase. It follows that an increase in functional residual capacity which is unaccompanied by significant change in transpulmonary pressure is evidence for a combination of reduced elastic recoil of the lungs and increased thoracic elastic recoil. The observation that young and elderly subjects have substantially the same end-expiratory transpulmonary pressures during quiet breathing indicates that the larger functional residual capacity of older subjects results from a combination of diminished elastic recoil of the lungs and increased elastic recoil of the thorax. For the purpose of this discussion it has been assumed that the functional residual capacity is a "relaxation" volume not influenced by muscular contraction.

The thesis of Bates and Christie may be extended to include other attributes of the mechanical behavior of lungs. For example, it has been well established that pulmonary flow-resistance is increased in emphysema (2, 6, 8–10, 12), the change being greater during expiration; to a much smaller degree pulmonary flow-resistance, chiefly during expiration, was also elevated in some elderly subjects. In emphysema, dynamic pulmonary compliance falls rapidly as the respiratory rate increases (2, 8–10); among the elderly subjects, when flow-resistance was elevated, compliance did fall slightly but significantly as the rate of breathing rose, whereas changes in compliance were not consistent when flow-resistance was within the range encountered in young adults. A possible mechanism for dependence of compliance upon respiratory rate has been described, based on the mechanical implications of nonuniformity of flow-resistance and/or elastic changes within the lungs (2, 8). The authors concluded that alterations in the distribution of ventilation must occur in association with the reduction in dynamic compliance at increased respiratory rates. This conclusion is consistent with the observation of Greifenstein, King, Latch, and Comroe (13) who found with the use of single breath and pulmonary emptying rate tests that many healthy older subjects show evidence of a greater nonuniformity of ventilation than do young subjects.

It is apparent that the changes in mechanical behavior of lungs of elderly adults compared with young adults are in every instance qualitatively similar to those observed in emphysema. On the other hand, it should be noted that the magnitude of such changes that accompany aging is generally small, and in individual instances not detectable. It would seem that additional factors must play a role in the reduced performance of elderly subjects in such tests of maximal effort as the vital capacity (8, 13–18), and maximal breathing capacity (13, 16, 18). An attempt was made in the present study to estimate respiratory muscle strength by measuring the maximal pressure each subject could develop across an obstructed mouthpiece. The attempt was discontinued after a few studies because it was felt that most of the subjects did not understand the procedure well enough to cooperate satisfactorily. But apart from the question of muscular strength, it would appear that changes in elastic properties of the thorax might well account for much of the reduction in vital capacity. Evidence has already been presented suggesting that the thorax has an increased tendency to recoil outward, and that this together with diminished elastic recoil of the lungs accounts for the increased functional residual capacity of elderly subjects. The change in elastic behavior of the thorax would also be expected to result in an increase in residual volume of the lungs and a decrease in vital capacity (largely at the expense of the expiratory reserve) due to the fact that it was more difficult to compress the thorax. Table II shows that such changes in subdivisions of the total lung capacity were typical in the present study; they have been reported by other investigators as well (12–16).

SUMMARY

Physical properties of the lungs of 28 healthy subjects 50 years and older were measured in the sitting position. Values were related to measurements of total lung capacity and its subdivisions. When compared with a group of 11 healthy adults ranging in age from 22 to 47, the older subjects showed a shift in static volume-pressure curve of the lungs to the left. Pulmonary flow-resistance was above 3.0 cm. H_2O per L. per second in 10 out of 25 elderly subjects, and in only 1 out of 28 younger subjects. Among elderly subjects, dynamic compliance decreased consistently as the respiratory rate increased in those having values for pulmonary flow-resistance above 3.0 cm. H_2O per L. per second. These changes in physical properties of the lungs were similar in kind to, though much less than those found in, emphysema. They were associated with an increase in functional residual capacity, decrease in vital capacity, and no change in total lung capacity.

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