THE EFFECT OF PNEUMONECTOMY UPON CARDIOPULMONARY FUNCTION IN ADULT PATIENTS* †

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In recent years pneumonectomy has become an accepted method of treatment of malignant and benign tumors of the bronchus, and of various types of chronic pulmonary suppuration. Clinical experience has repeatedly demonstrated that the surgical ablation of one of a pair of as vitally important organs as the lungs is compatible with survival and maintenance of a fairly high degree of physical activity. Studies on the physiologic effect of pneumonectomy, until recently,[1, 2] have been almost exclusively experimental. The observations of Bremer[3] on cats, and of Longacre, Carter, *et al.*,[4, 5] on dogs are best known. It was shown by Longacre, Carter, *et al.*, in a series of experiments covering several years, that age at the time of the lung resection influences (1) the subsequent behavior of the dogs under conditions of physical stress; and (2) the later development of hyperplasia and/or emphysema in the remaining lung. However important these experiments may be, to extend their conclusions to human subjects would fail to recognize fundamental differences encountered in experimental and clinical conditions. For example, the highly mobile mediastinum of the dog has not its counterpart in man, and, in the latter, the remaining lung is quite frequently already the site of pathologic changes. Aside from information of theoretic interest regarding the immediate and remote effects of pneumonectomy upon pulmonary function, physiologic studies in man may be of practical value in individual cases, chiefly in helping to decide which are the most favorable conditions for the maintenance of a high degree of functional efficiency in the remaining lung. They may be especially contributory to the problems of optimum position of the mediastinum and of supplemental thoracoplasty. During the past several years, on the Tuberculosis Service at Bellevue Hospital, under a grant of the Commonwealth Fund, a method for the study of pulmonary function and of cardiocirculatory function, insofar as it is related to the former, has been developed,[6] and the tests devised were used in various chronic pulmonary diseases and in surgical chest conditions.[7, 8] Already, reports have been made upon the late effect of pneumonectomy in children,[1] and the immediate postoperative influence of pneumonectomy upon the state of respiratory gases in the arterial blood of adult subjects.[2] The present report, based upon a

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study of 12 subjects, is concerned with various physiologic problems arising as a result of pneumonectomy performed in adults.

Material for Study—Physical characteristics and clinical data concerning the 12 subjects studied have been tabulated in Table I. There were one

TABLE I

PHYSICAL CHARACTERISTICS AND CLINICAL DATA ON THE 12 PATIENTS STUDIED

Pt.	Sex	Age Yrs.	Ht. Cm.	Wt.* Kg.	Body Surface* Sq. M.	Diagnosis	Time of Study† ā pn.	p̄ pn.	p̄ Suppl. Thoraco.	Mediastinal Mobility‡	Follow-Up after Pneumonectomy
W. J.	M.	53	160	54 47	1.48 1.56	Ca. rt. M. L. bronchus	+	+	+	+	Survival 2 years, active
W. W.	M.	64	175	64 67	1.78 1.81	Ca. lt. U. L. bronchus	+	+	0	0	Survival 18 mos., active
D. M.	M.	62	178	57 65	1.72 1.80	Ca. lt. U. L. bronchus	+	+	0	++	Survival 15 mos., active
T. G.	M.	43	169	62 57	1.71 1.64	Ca. rt. main bronchus	+	+	0		Death—metastasis, 7 mos.
E. B.	M.	31	190	98 103	2.18 2.32	Ca. lt. main bronchus	+	+	0	+	Death—metastasis, 20 mos.
R. B.	M.	60	175	55 62.5	1.65 1.76	Ca. lt. L. L. bronchus	+	+	0	0	Survival 1 year. Metastasis chest wall.
W. H.	M.	47	168	72.5	1.82	Ca. lt. main bronchus	0	+	0	0	Death—metastasis, 21 months
E. R.	M.	32	174	54.5 53	1.66 1.64	Bronchiectasis left upper and lower lobe	+	+	+	0	Survival 9 mos. Recent thoracoplasty
A. M.	F.	23	148	44.5 37.5	1.35 1.25	Bronchiectasis	+	0	+	0	Survival 12 mos., active
F. I.	M.	46	178.5	70 65	1.88 1.82	Endobronchial Tbc. Obstruction rt. main bronchus	+	0	+	0	Survival 9 mos., active
M. K.	M.	37	169	66	1.76	Chronic lung abscess, rt.	0	+	0	0	Survival 31 mos., active
K. G.	M.	33	175	83	1.99	Traumatic fracture rt. main bronchus with complete obstruction	0	+	0	0	Survival 2 yrs., active

*The two figures correspond to pre- and postoperative weight and body-surface area.
†Time of study—ā pn. = before pneumonectomy.
p̄ pn. = after pneumonectomy.
p̄ Suppl. Thoraco. = after supplemental thoracoplasty.
‡Mediastinal mobility after pneumonectomy.

female and 11 males, with ages from 23 to 64 years. Pneumonectomy was undertaken in seven instances after a diagnosis of carcinoma of the bronchus had been established; in three, for chronic suppuration of the lung; in one, after traumatic fracture of a main bronchus and resulting stenosis; and in one case, for almost complete obstruction of a main bronchus secondary to an endobronchial tuberculosis.

In six subjects the studies were carried out before pneumonectomy and at various intervals afterwards, when the patients had resumed normal activity; in two of these, studies were again repeated after a supplemental thoracoplasty had been completed. In two patients, studies were made before ablation of the lung and again after the pneumonectomy had been supplemented by a thoracoplasty, without measurements in the interval. In the four remaining cases measurements were made singly or repeatedly after pneumonectomy.

Method of Study—In Table II, information concerning the functions studied, and the measurements made, along with references regarding technics, normal control values, etc., have been summarized.

Briefly stated, the measurements were as follows: (A) Lung volumes and subdivisions; (B) maximum breathing capacity; (C) ventilation, breathing reserve, and respiratory gas exchange under basal conditions, during moderate exercise, and during a five-minute period of recovery following exercise;

TABLE II

SUMMARY OF MEASUREMENTS OF CARDIOPULMONARY FUNCTION

A. VENTILATORY FUNCTION

Measurement	Definition	Significance	References
Lung Volume in liters		Description of available air space for ventilation	Technics — formula for prediction of normal values according to body size, age, sex[9, 10, 11]
Vital Capacity (V. C.)	Volume of maximally deep breath		
Residual Air (R. A.)	Volume in lung after extreme expiration		
Total Capacity (T. C.) (T. C. = V. C. + R. A.)	Total volume in deepest inspiration		
Ratio $\frac{R.A.}{T.C.} \times 100$	Residual air expressed as per cent of total capacity	Expression of degree of pulmonary distention, physiologic or pathologic (emphysema)	
Maximum Breathing Capacity—lit./min. (M. B. C.)	Maximum volume of air that can be displaced per minute	Estimation of the efficiency of the chest bellows in displacing air per unit of time	Technics[6, 12]—formula for prediction M. B. C. lit./min. = 80.9 × B. S. in sq. m. = 29.3
Ventilation in liters per min. per sq. m. body surface (V): (1) Basal (2) Moderate exercise (3) During 5 minutes of recovery from moderate exercise	Actual volume of air per minute displaced in a given physical state		Technic[6]. Normal control values—according to age, sex (unpublished data)
Breathing Reserve (B. R. = M. B. C. − V)	Excess breathing capacity beyond actual ventilation in a given state		
Ratio $\frac{B.R.}{M.B.C.} \times 100$	Breathing reserve expressed as per cent of maximum breathing capacity	Provides a numerical estimation of dyspnea in pulmonary insufficiency	Relation with dyspnea.[6] Normal control values according to age, sex (unpublished data)

B. ALVEOLORESPIRATORY FUNCTION

Measurement	Definition	Significance	References
Pulmonary Emptying Rate	Nitrogen concentration of alveolar air after 7 minutes' pure oxygen breathing	A numerical estimate of adequacy of inspired air distribution in alveoli	Technic and range of variation[11]
Respiratory Gas Exchange: (1) Basal (2) Moderate exercise (3) During 5 minutes of recovery	Carbon dioxide output and oxygen intake in a given physical state expressed (a) in cc./sq. m./min. (b) in cc./liter vent.	(a) Measures amount of gas exchange used in a given physical state (b) Gives efficiency of ventilation in providing O_2 absorption (utilization)	Technic.[6] Normal range according to age and sex (unpublished data)
State of Respiratory Gases in Arterial Blood: (1) Basal (2) During early recovery from moderate exercise	(a) Oxyhemoglobin saturation—% (b) Carbon dioxide pressure—mm. Hg.	Measures effectiveness of lungs in aerating blood and state of respiratory gases reaching tissues	Technic — Normal range[6]

C. CARDIOPULMONARY FUNCTION

Measurement	Definition	Significance	References
Includes: (a) *Routine:* Arterial blood pressure Electrocardiogram Ballistocardiogram			
(b) *Cardiovascular response* to rapid intravenous saline infusion	(a) Variation of venous pressure (b) Circulation time (c) Vital capacity following infusion of 1500 cc. isotonic solution in 30 min.	Brings out latent congestive state due to back pressure from failure of left heart, of pulmonary vascular bed, or of right heart	Technic[6, 13, 14]

(D) state of respiratory gases in the arterial blood at rest and immediately after completion of the moderate exercise; and (E) variations in venous pressure, circulation time, and vital capacity following an increase in blood volume produced by a rapid intravenous infusion of 1500 cc. of a saline solution. Data available from the literature[9] and a separate study of 60 normal subjects, age 20 to 69, supplied the desired control values.

Results—Four separate headings may better describe the data obtained in this study:

(1) State of pulmonary and cardiocirculatory function after pneumonectomy in comparison with normal subjects.

(2) State of ventilatory function before and after pneumonectomy in same subjects.

(3) Influence of thoracoplasty supplementing a pneumonectomy upon the state of ventilatory function.

(4) Influence of mediastinal adjustment and preexisting pulmonary emphysema upon pulmonary function.

(1) State of Pulmonary and Cardiocirculatory Function after Pneumonectomy: Comparison with Normal Subjects—Data on ten patients are available, two subjects studied only after supplemental thoracoplasty was completed have been excluded. The ten patients have been separated into two groups according to age: Group I consists of six patients, ages ranging from 32 to 47. Group II consists of four patients, ages ranging from 53 to 66.

The predicted normal figures and the control normal figures were calculated according to data available in subjects in the same age-groups. Mean values, observed, predicted, or calculated for controls, are tabulated in Tables III to IX.

A—VENTILATORY FUNCTION

1. Lung volumes and subdivisions (Table III, Chart 1).

In both groups I and II, the mean size of the remaining lung in deepest inspiration is somewhat larger than the predicted size of one of a pair of normal lungs. This increase is due to the persistence of a large residual air volume; the remaining lung after pneumonectomy is slightly smaller at the end of a complete expiration than two normal lungs in Group I, and as large as two normal lungs in Group II. There is then evidence of lung distention after pneumonectomy, especially in the older age-group, although the mean residual air of 37 per cent of the total capacity does indicate that if pulmonary emphysema is present, it is of mild degree, or present only in a small proportion of the group. Studies of individual data prove the latter to be the case.

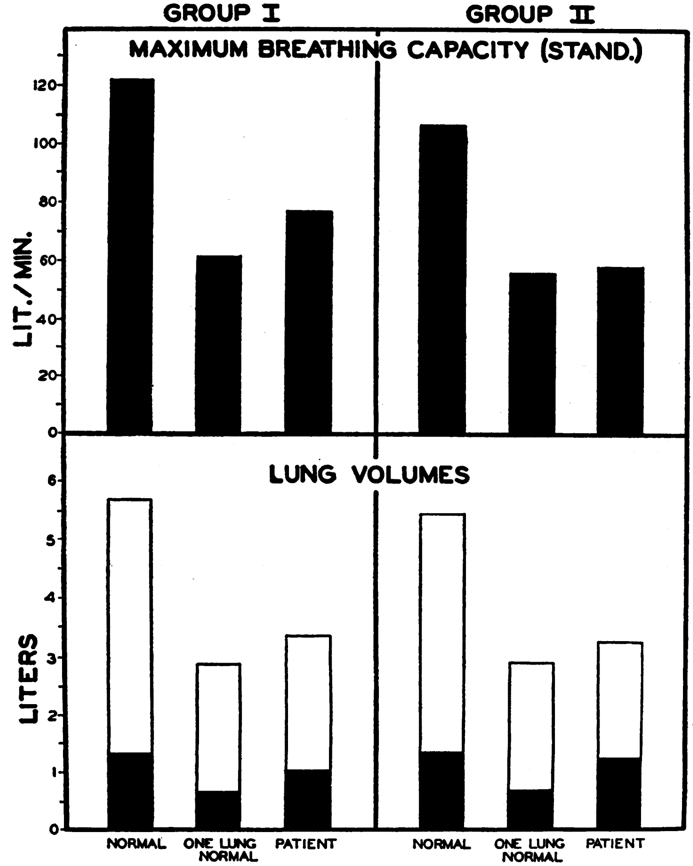

CHART 1.—Lung volumes and subdivisions in liters, and maximum breathing capacity in liters per minute. In each of the two groups, the blocks to the left = average predicted values for normal subjects of same size, sex, and age distribution; the blocks in the center = the average assumed value for one lung of the normal subjects; the blocks to the right = average observed values in patients studied after pneumonectomy. Under lung volumes, solid blocks = residual air volume; white blocks = vital capacity (complemental air + reserve air).

2. Maximum breathing capacity in liters per minute (Table III, Chart 1). The maximal efficiency of the chest bellows in displacing air after pneumonectomy is reduced in both groups: In Group I the maximum breathing capacity is 63 per cent of the predicted value for two normal lungs, and in Group II 50 per cent. In the younger age-group, coincident with less distention, the remaining lung is more effective in circulating air than the remaining lung in the older age-group, and in addition is more effective than one of a pair of normal lungs, (maximum breathing capacity 26 per cent greater than predicted value for one lung).

TABLE III

LUNG VOLUMES* AND MAXIMUM BREATHING CAPACITY AFTER PNEUMONECTOMY

Group	Total Capacity (liters) Mean	Vital Capacity (liters) Mean	Residual Air (liters) Mean	R. A. / T. C. × 100 Mean	Maximum Breathing Capacity—Standing (liters/minute) Mean
Group I†					
Predicted					
Both lungs.......	5.68	4.44	1.28	22.5	121.4
One lung.........	2.84	2.22	0.64		60.8
Observed...........	3.35	2.32	1.03	30.8	76.6
Group II†:					
Predicted					
Both lungs.......	5.45	4.12	1.33	24.4	106.0
One lung.........	2.86	2.16	0.70		55.8
Observed...........	3.25	2.03	1.33	37.5	57.8

*Saturated dry gas at 37° C. and prevailing barometric pressure.

†Group I consists of 6 patients, age 32 to 47, and Group II of 4 patients, age 53 to 65.

Average predicted and observed values in two groups of adults after pneumonectomy.

3. Ventilation at rest, during moderate exercise, during each of five minutes of recovery (Table IV, Chart 2).

There are significant differences between the two groups: In the younger age-group the average figures of ventilation under varying states of activity are almost identical with the average control normal figures; in the older age-group, ventilation is somewhat larger than normal at rest, much more so during exercise and during recovery.

TABLE IV

VENTILATION AT REST*, DURING MODERATE EXERCISE, AND DURING EACH OF FIVE MINUTES OF RECOVERY FROM MODERATE EXERCISE, AFTER PNEUMONECTOMY

Group	Ventilation, liters/min./sq. m. B. S.* Basal Mean	Exercise Mean	Rec. 1 Mean	Rec. 2 Mean	Rec. 3 Mean	Rec. 4 Mean	Rec. 5 Mean
Group I†:							
Normal controls.................	3.42	9.72	12.80	8.30	7.50	6.13	5.40
Patients after pneumonectomy....	3.28	9.88	12.84	8.32	7.52	5.60	5.26
Group II†:							
Normal controls.................	3.92	11.13	14.83	10.83	8.37	7.08	6.20
Patients after pneumonectomy....	4.17	15.11	15.35	13.02	10.25	8.65	7.62

*Saturated gas at 37° C. and prevailing barometric pressure.

†See Table III.

Average observed values in two groups of adults after pneumonectomy, and average values in two corresponding groups of normal subjects.

TABLE V

RATIO $\frac{\text{BREATHING RESERVE}}{\text{MAXIMUM BREATHING CAPACITY}} \times 100$ AT REST, DURING MODERATE EXERCISE, AND DURING EACH OF FIVE MINUTES OF RECOVERY, AFTER PNEUMONECTOMY

Group	Ratio $\frac{\text{Breathing Reserve}}{\text{Maximum Breathing Capacity}} \times 100$ Basal Mean	Exercise Mean	Rec. 1 Mean	Rec. 2 Mean	Rec. 3 Mean	Rec. 4 Mean	Rec. 5 Mean
Group I*:							
Normal controls....................	94.0	83.7	76.0	83.4	86.9	88.9	90.2
Patients after pneumonectomy.......	89.3	76.0	59.4	75.4	80.2	83.5	84.1
Group II*:							
Normal controls....................	91.2	79.6	67.4	76.4	81.4	84.4	86.2
Patients after pneumonectomy.......	86.5	51.7	49.3	57.4	66.8	71.2	74.9

*See Table III.

Average observed values in two groups of adults after pneumonectomy, and average values in two corresponding groups of normal subjects.

4. Ratio $\frac{B.R.}{M.B.C.}$ x 100, at rest, during exercise, during each of five minutes of recovery (Table V, Chart 2).

This ratio being dependent upon the values of maximum breathing capacity and of ventilation, it is not surprising to find it lower in the older age-group

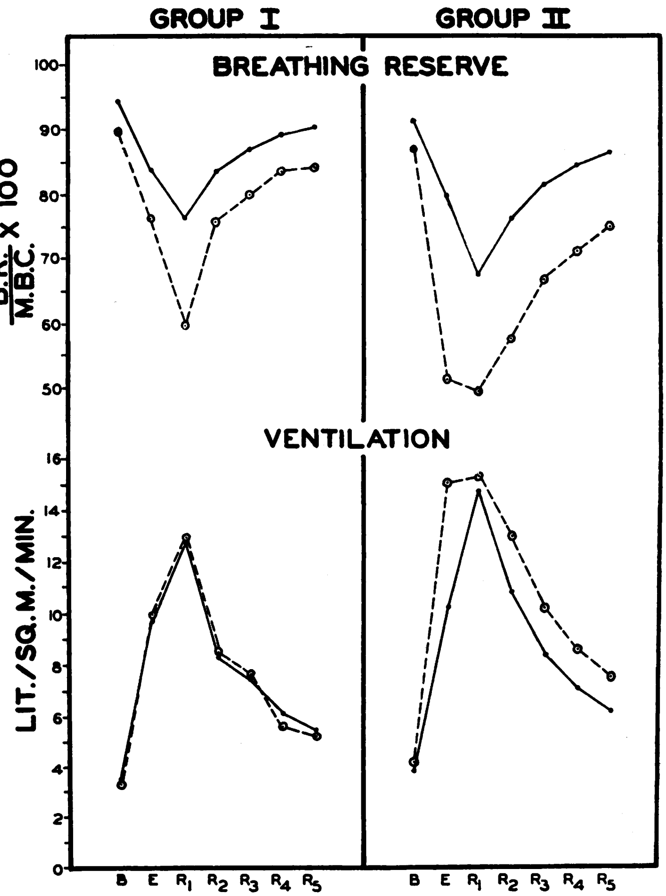

CHART 2.—Ventilation and ratio $\frac{\text{breathing reserve}}{\text{maximum breathing capacity}}$ x 100 under standard basal conditions (B), during moderate exercise (E), and each of the five minutes of recovery following moderate exercise (R_1 = 1st minute of recovery, R_2 = second minute, etc.) Solid lines = average values for normal subjects, age 30 to 50 (Group I), and 51 to 69 (Group II). Broken lines = average values in 10 patients after pneumonectomy in same age-groups.

than in the younger, especially during exercise and during the recovery period from exercise. As dyspnea usually occurs when the value of this ratio is below 60 to 70 per cent, it should be more marked and more persistent for the same degree of activity in Group II than in Group I. This is supported by observations concerning dyspnea made in both groups during the recovery period—in Group I the average duration of dyspnea following completion of the standard exercise was 33 seconds; in Group II it was 142 seconds.

Summarizing the main findings concerning the anatomic status of the remaining lung, and its ventilatory function, in ten patients after pneumonectomy: (a) The lung was somewhat distended, more so in the older group; (b) maximal efficiency of the chest bellows in displacing air with only one lung was better than predicted in the younger subjects, but just exactly as predicted in the older age-group; and (c) relative hyperventilation was present during exercise and persisted during the recovery period in the older subjects, and it further encroached upon the breathing reserve and resulted in a greater tendency to dyspnea.

B—ALVEOLORESPIRATORY FUNCTION

1. Pulmonary emptying rate: Following pneumonectomy, the average figures of nitrogen concentration in alveolar samples taken after seven minutes of pure oxygen breathing in Groups I and II, as well as individual figures, were well within normal range. Tidal air, in spite of a definite increase in residual air volume, was thus efficiently distributed during quiet breathing to the functioning alveoli of the remaining lung.

2. Respiratory gas exchange—carbon dioxide output and oxygen intake (Table VI and VII).

TABLE VI

RESPIRATORY GAS EXCHANGE. CARBON DIOXIDE OUTPUT AT REST*, DURING MODERATE EXERCISE, AND DURING FIVE MINUTES OF RECOVERY FROM MODERATE EXERCISE, AFTER PNEUMONECTOMY

	CO_2 Output, cc./min./sq. m. B. S.†			CO_2 Output, cc./liter vent.		
Group	Basal	Exercise	Recovery	Basal	Exercise	Recovery
Group I‡:						
Normal controls	104	329	1516	35.4	36.8	42.5
Patients after pneumonectomy	107	336	1449	36.7	37.6	40.4
Group II‡:						
Normal controls	104	329	1523	30.5	34.0	37.5
Patients after pneumonectomy	101	374	1601	27.9	28.5	33.2

*Under basal conditions.
†Dry gas at 0° C. and 760 mm. Hg. barometric pressure.
‡See Table III.
Average observed values in two groups of adults after pneumonectomy, and average values in two corresponding groups of normal subjects.

TABLE VII

RESPIRATORY GAS EXCHANGE. OXYGEN INTAKE AT REST*, DURING MODERATE EXERCISE, AND DURING FIVE MINUTES OF RECOVERY FROM MODERATE EXERCISE, AFTER PNEUMONECTOMY

	O_2 Intake, cc./min./sq. m. B. S.†			O_2 Intake, cc./liter vent.		
	Basal	Exercise	Recovery	Basal	Exercise	Recovery
Group	Mean	Mean	Mean	Mean	Mean	Mean
Group I‡:						
Normal controls	134	489	1523	45.8	57.3	43.4
Patients after pneumonectomy	143	520	1524	49.1	57.5	42.9
Group II‡:						
Normal controls	130	491	1509	38.1	52.5	36.9
Patients after pneumonectomy	126	475	1438	34.9	36.7	31.0

*Under basal conditions.
†Dry gas at 0° C. and 760 mm. Hg. barometric pressure.
‡See Table III.
Average observed values in two groups of adults after pneumonectomy, and average values in two corresponding groups of normal subjects.

There are significant differences between the two groups. The average figures in Group I are but little different from the normal control values—

the direction in changes being, if anything, toward greater rather than lesser efficiency during periods of physical activity. In Group II, however, the carbon dioxide output, per minute, was larger than in the control group during exercise and recovery, and the oxygen intake per minute less during corresponding periods; hence there is evidence that efficiency in gas exchange is impaired. Particularly significant are the low rate of oxygen removal per liter of ventilation at rest and during recovery from exercise, and its total lack of increase during exercise. Two causes may be invoked to explain these changes: (a) Inefficient alveolar ventilation due to hyperventilation; and (b) inadequate increase in circulation during exertion and the following recovery period.

3. State of respiratory gases in arterial blood (Table VIII): In both groups the proportion of hemoglobin in the oxyhemoglobin state, and the tension of carbon dioxide in the blood leaving the lung, were well within normal range both at rest and after moderate exercise. This indicates that during moderate exertion the correlation between alveolar ventilation and pulmonary circulation and/or the diffusion across alveolocapillary membranes remained normal.

TABLE VIII

ARTERIAL BLOOD: STATE OF RESPIRATORY GASES AT REST AND DURING EARLY RECOVERY FROM MODERATE EXERCISE, AFTER PNEUMONECTOMY

	Oxyhemoglobin Saturation, %				CO_2 Tension in Mm. Hg.			
	Rest		Recovery		Rest		Recovery	
Group	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Normal	96.2	±1.2	95.8	±1.3	43.7	±3.5	43.0	±2.4
Group I*:								
Patients after pneumonectomy	95.5		94.8		39.8		37.4	
Group II*:								
Patients after pneumonectomy	95.9		94.6		39.8		40.9	

*See Table III.

Average oxyhemoglobin saturation % and CO_2 pressure in Mm. Hg. in two groups of adults after pneumonectomy, and normal range.

Summarizing the data on gas exchange after pneumonectomy, the only abnormality noted among the ten patients after they had resumed some activity was, in the older patients, lowered efficiency in supplying oxygen to the tissues, especially during exertion and the early recovery period. The repayment of the oxygen debt, contracted during exercise, takes longer than in the younger patients in spite of the tendency to hyperventilation noted during the short period of observation. Whether this is due to poorer alveolar ventilation occurring under stress in a lung somewhat distended, or inadequate increase in cardiac output cannot be decided on the basis of data obtained; the aeration of the blood leaving the lung remained, however, well within normal range.

C—CARDIOCIRCULATORY FUNCTION

Routine measurements of cardiocirculatory function including arterial blood pressure, electrocardiogram, and ballistocardiogram, failed to reveal any abnormality that might be connected directly to the surgical removal of the lung. One of the older subjects with auricular fibrillation, present prior to the pneumonectomy, rallied remarkably after operation; and there was no evidence that "minimal myocardial damage," as revealed by the electrocardiogram in a few patients, was increased to any significant degree. Insofar as the infusion test was concerned (Table IX), it failed to bring out any latent congestive state due to back pressure from failure of the left heart, pulmonary vascular bed or right heart. In addition, the initial venous pressure level and the circulation time were well within normal figures; the slightly lower figures for venous pressure in Group II are of no significance, being probably due to inaccurate prediction of the exact position of the right auricle in subjects with chest inflation greater than normal.

TABLE IX

STATE OF CIRCULATION: VENOUS PRESSURE, CIRCULATION TIME, AND VITAL CAPACITY BEFORE AND AT END OF INFUSION TEST (1500 CC. SALINE IN 30 MINUTES) AFTER PNEUMONECTOMY

Group	Venous Pressure Mm. H_2O Before Infusion Mean	Venous Pressure Mm. H_2O At End of Infusion Mean	Circulation Time sec. Before Infusion Mean	Circulation Time sec. At End of Infusion Mean	Vital Capacity % Decrease At End of Infusion Mean
Normal range	Below 90	Increase less than 60 Mm. H_2O or final level less than 125 Mm.	Below 18 sec.	Below 20 sec.	Less than 8%
Group I:					
Patients after pneumonectomy	64	78	15.7	17.1	5.0
Group II:					
Patients after pneumonectomy	32	46	14.3	15.9	4.6

Average observed values in two groups of subjects after pneumonectomy and normal range.

In the results so far presented, the most significant findings in patients after pneumonectomy, besides an obvious decrease in size of the lungs, were: (a) A greater tendency to dyspnea in a group of subjects age 53 to 65, due to a greater decrease in the chest bellows' capacity for circulating air and a greater demand upon ventilating requirements during and following moderate exercise; and (b) a lesser efficiency in the same group to supply oxygen to the tissues during and following exercise. There was some evidence that lung distention is more a liability than an asset, both from the point of view of mechanics of the chest bellows and of gas interchange between alveoli and circulating blood.

(2) State of Ventilatory Function Before and After Pneumonectomy in the Same Subjects—To decide whether some of the findings described in the previous section may be, to some degree, unrelated to the surgical ablation of the lung itself and the intrathoracic adjustments which followed, it is important to compare data obtained before and after pneumonectomy. Such observations were made in six patients, two of them with pathology throughout an entire lung before pneumonectomy (E. B. and E. R.), and the remaining four with pathology limited to one lobe or less (W. J., V. W., D. M., and T. G.). Changes in vital capacity and residual air in the first two patients were insignificant (within 180 cc.). The maximum breathing capacity in E. B. increased by 14 liters per minute after pneumonectomy. For the other four subjects absolute decrease in vital capacity and in residual air volumes was large, as one expected, averaging 1.2 liters for vital capacity and 0.7 liters for the residual air. But, significantly enough, the percentage of the residual air in

the total capacity remained practically unchanged—38 per cent before and 40 per cent after. As three out of four of these patients belonged to Group II of the preceding section it seems, therefore, that the somewhat larger degree of lung distention noted in older subjects after pneumonectomy antedates the surgical procedure. Another interesting observation is that as the average vital capacity in these four patients decreased by 34 per cent after pneumonectomy, the average maximum breathing capacity decreased by only 21 per cent.

(3) Influence of Thoracoplasty Supplementing a Pneumonectomy upon the State of Ventilatory Function—In four patients pneumonectomy was supplemented by a thoracoplasty. In two (W. G. and E. R.), measurements were made before and after pneumonectomy and again after thoracoplasty; in the other two (F. I. and A. M.), the lung removed being functionless, measurements made before pneumonectomy were repeated only after thoracoplasty and resumption of activity.

Data summarizing many observations on W. J. (Tables X, XI and Plate I), cover prepneumonectomy, postpneumonectomy, and postthoracoplasty periods. Following pneumonectomy the maximum breathing capacity was reduced to about 50 per cent of the preoperative value, a rather considerable decrease, and, in addition, alveolar ventilation was apparently less efficient in

TABLE X

INFLUENCE OF THORACOPLASTY UPON LUNG VOLUMES AND MAXIMUM BREATHING CAPACITY IN FOUR PATIENTS AFTER COMPLETION OF PNEUMONECTOMY

Patients	State	Total Capacity (liters)	Vital Capacity (liters)	Residual Air (liters)	R. A. / T. C. × 100	Maximum Breathing Capacity—Standing (liters/minute)
W. J., male, age 53	Before pneumonectomy...	6.22	4.07	2.15	34.5	90.9
	After pneumonectomy....	3.63	2.14	1.49	41.1	45.8
	After thoracoplasty					
	1 month...............	2.86	1.92	0.94	33.0	65.6
	6 months..............	3.23	2.00	1.23	38.2	58.2
F. I., male, age 46	Before pneumonectomy...	4.13	2.98	1.15	27.9	59.8
	After thoracoplasty.......	2.88	1.92	0.96	33.4	77.7
A. M., female, age 23	Before pneumonectomy...	2.59	1.74	0.85	32.8	34.8
	After thoracoplasty.......	1.96	1.24	0.72	36.7	37.0
E. R., male, age 32	Before pneumonectomy...	3.51	2.66	0.85	24.2	72.9
	After pneumonectomy....	3.38	2.36	1.02	30.2	67.4
	After thoracoplasty.......	3.13	2.25	0.88	28.0	64.0

TABLE XI

INFLUENCE OF THORACOPLASTY UPON BREATHING RESERVE AND RATE OF O_2 INTAKE AT REST, DURING MODERATE EXERCISE AND DURING RECOVERY FROM MODERATE EXERCISE, IN ONE PATIENT AFTER PNEUMONECTOMY

		Ratio Breathing Reserve / Maximum Breathing Capacity × 100							Rate of O_2 Intake cc./lit. vent.		
				Recovery							Average of 5 min.
Patient	State	Rest	Exercise	1 min.	2 min.	3 min.	4 min.	5 min.	Rest	Exercise	Recovery
W. J.	Before pneumonectomy	91.0	79.6	59.1	69.8	75.6	83.0	85.0	39.2	49.1	30.7
	After pneumonectomy	86.4	53.7	53.9	61.6	71.0	75.6	79.5	36.4	37.1	32.8
	After thoracoplasty, 6 months.....	89.8	69.6	59.3	69.2	71.8	79.9	81.2	41.4	43.1	36.2

supplying oxygen for tissue needs. It was thought that a plausible explanation for the unfavorable functional result was moderate relative overdistention of the remaining lung as successive measurements had shown a steady increase of the percentage of residual air in the total capacity. To control this distention thoracoplasty was decided upon. One month after its completion the percentage of residual air in the total capacity had returned to the prepneumonectomy level and the maximum breathing capacity was nearly 20 liters larger than before thoracoplasty. In subsequent months some of these gains were partly reduced as scoliosis tended to develop, but as some beneficial effects still remained, dyspnea was less marked after exercise than it was during the prethoracoplasty studies and the efficiency in providing oxygen absorption was considerably improved.

In patients F. I. and A. M. the influence of thorcoplasty is more difficult to evaluate because no data are available of the state of the pulmonary function after pneumonectomy. It is, however, suggestive that thoracoplasty little impaired the ventilating function as in both cases, especially F. I., the maximum breathing capacity after thoracoplasty was larger than before pneumonectomy.

In patient E. R., lung volume measurements and maximum breathing capacity were practically unchanged after pneumonectomy and after thoracoplasty.

It appears, therefore, that thoracoplasty after pneumonectomy does not impair further the mechanics of the chest bellows, and if scoliosis is successfully controlled, it may well improve pulmonary function by preventing lung overdistention.

(4) Influence upon Pulmonary Function of Mediastinal Adjustments and Preexisting Pulmonary Emphysema—Among the 12 patients studied there was only one who exhibited any significant clinical evidence of pulmonary emphysema before pneumonectomy. This man also presented a very difficult problem of mediastinal adjustment, and management of the remaining lung. D. M., age 62, was first studied, November 16, 1940 (Plate II, No. 1), after a carcinoma of the left upper lobe bronchus had been diagnosed and verified by biopsy. Lung volume measurements confirmed the clinical impression of pulmonary emphysema and the high ratio of residual air ($\frac{\text{R.A.}}{\text{T.C.}}$ x 100) indicated a marked degree of emphysema. Other measurements revealed that there was a considerable limitation in maximum breathing capacity, that oxygen absorption was not efficiently managed at rest or during increased physical activity, and that the arterial oxyhemoglobin saturation was somewhat below normal.

After pneumonectomy was performed the patient had to be kept in an oxygen tent for a period of three weeks, and suffered from obvious symptoms of anoxia as soon as he breathed atmospheric air. On December 14, 1940, (Plate II, No. 2) the residual air of the remaining right lung was almost exactly equal to that of both lungs prior to pneumonectomy. It constituted 71 per cent of the total capacity, indicating an extreme degree of emphysema.

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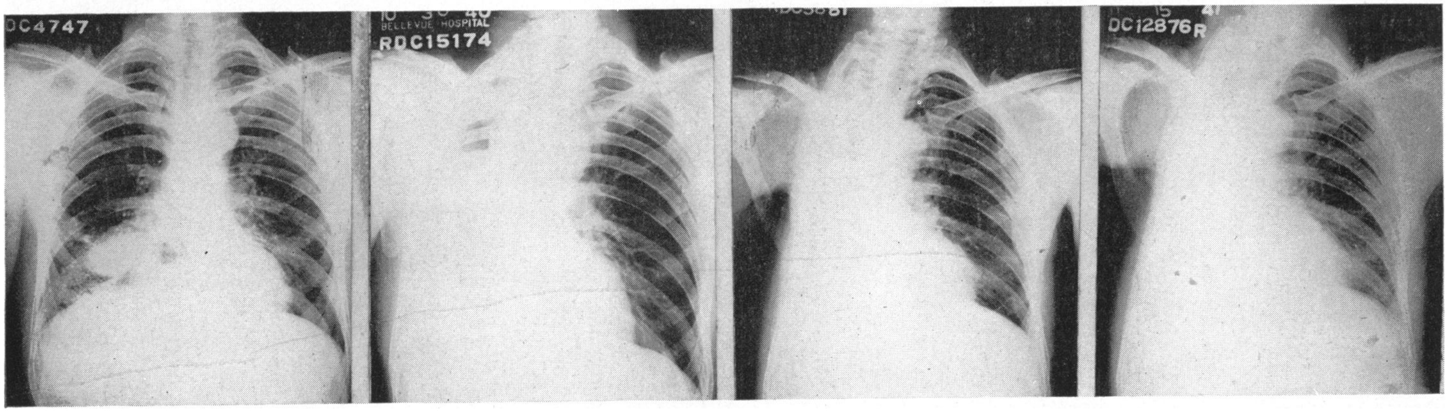
PLATE I

Patient W. J.

I 4/25/40	II 11/4/40		III 6/17/41	IV 12/15/41



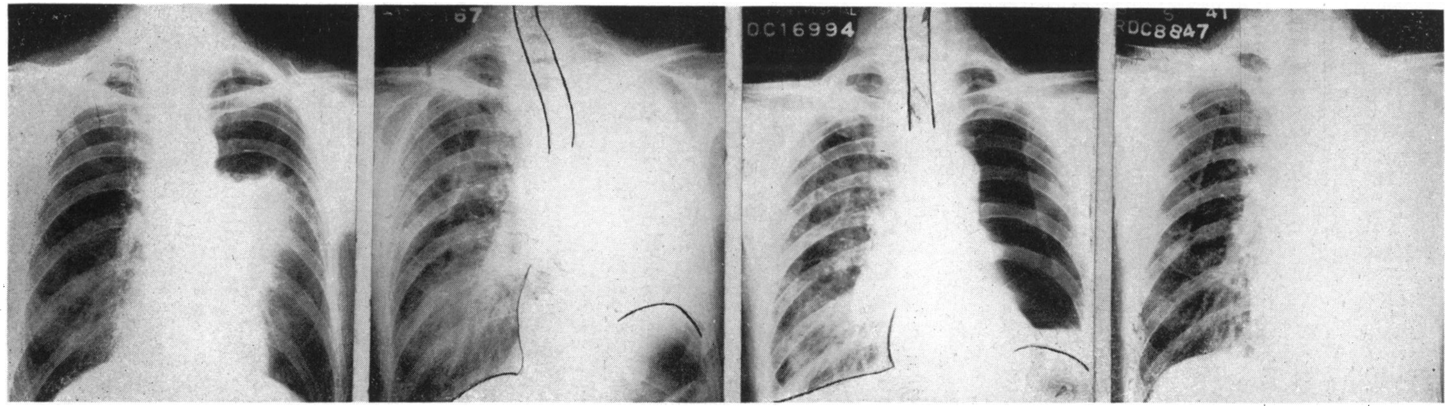
I	II		III	IV
6.22	3.63	Total Capacity/(liters)	2.86	3.23
4.07	2.14	Vital Capacity/(liters)	1.92	2.00
2.15	1.49	Residual Air/(liters)	0.94	1.23
34.5	41.1	$\frac{\text{R. A.}}{\text{T. C.}} \times 100$	33.0	38.2
90.9	45.8	Maximum Breathing Capacity (lit./min.)	65.6	58.2

Influence of thoracoplasty performed after pneumonectomy upon lung volumes and maximum breathing capacity: I. Before pneumonectomy. II. After pneumonectomy. III. One month after thoracoplasty. IV. Six months after thoracoplasty.

PLATE II

Patient D. M.

	I 11/16/40	II 12/14/40	III 12/28/40	IV 11/13/41



	I	II	III	IV
Total Capacity/(liters)	5.01	3.59	2.83	3.47
Vital Capacity/(liters)	2.36	1.04	1.33	1.99
Residual Air/(liters)	2.65	2.55	1.50	1.48
$\frac{R. A.}{T. C.} \times 100$	53.0	71.0	52.8	42.6
Maximum Breathing Capacity (lit./min.)	37.8			40.7
Arterial Oxyhemoglobin Saturation at Rest (%)	90.7	84.1	91.4	95.6

Influence of the state of lung distention upon various measurements of pulmonary function:
I. Before pneumonectomy. II. After pneumonectomy, note low right diaphragm, and displacement of trachea into left chest. III. Few days later, after air replacement in left chest. IV. One year later, after oleothorax.

Defective alveolar ventilation at that time resulted in low oxygen saturation in the arterial blood. Obviously the distention of the remaining emphysematous lung, clinically characterized by a deviation of the trachea to the left and a very low right diaphragm, was not of a compensatory nature. Physiologically, it was undesirable, and, anatomically, it was probably related to low total pressure of gases in solution in the fluid filling the deserted left hemithorax and subsequent distention of the contralateral lung.

With the mediastinum back in midline following air replacement (Plate II, No. 3) the residual air decreased to 52.8 per cent, and the arterial oxyhemoglobin saturation returned to preoperative value.

In order to maintain the mediastinum in the midline, oil was introduced and substituted for air and fluid. Frequent check-ups have prevented recurring overdistention of the right lung. One year later (Plate II, No. 4) with slight evidence of shift of the mediastinum *towards the right side,* and probably because of better muscular tone the maximum breathing capacity with one lung was almost identical to values obtained with two lungs, the percentage of residual air was lower than before pneumonectomy, and the arterial oxyhemoglobin saturation was normal. Concomitantly, the performance of the moderate exercise did not cause any more dyspnea than when the patient had two lungs.

The findings in this case suggest that the presence of emphysema is not an obstacle to satisfactory functional results if proper care is taken after pneumonectomy to avoid distention of the remaining lung.

Discussion—In discussing the effect of pneumonectomy upon pulmonary and cardiocirculatory function in animals, and in man, early and late physiologic adjustments should be considered separately.

There is little data concerning the hemodynamic adjustments associated with the rapid rerouting of the entire stroke-volume of the right heart through the vascular bed of a single lung; in particular, no information regarding blood pressure changes in the lesser circulation, velocity of blood flow in the pulmonary circuit, *etc.* Yet the failure of proper adjustment in man is probably the most important cause of early postoperative death. It is announced by a syndrome resembling acute pulmonary edema oftentimes described as "drowned lung." The exact mechanism of this syndrome is unknown, its true nature even doubtful, some ascribing it to acute cardiac failure, others to acute pulmonary failure. The tests of cardiocirculatory function, described in this report, are of no avail in predicting, before operation, the chances that such a complication may develop. In one patient who died from "drowned lung," within 24 hours after pneumonectomy, the response to the infusion test performed prior to pneumonectomy had been absolutely normal.

In very rare instances a classical picture of cardiac failure developed after pneumonectomy in individuals entirely free of myocardial damage, arteriosclerotic heart disease, valvular disease, or without clinical manifestations of acute anoxia. The precipitating causes are altogether obscure and the development of cardiac failure is unpredictable.

The return of hemorespiratory gas exchange to a normal state following pneumonectomy was studied experimentally by Heuer and Andrus.[15] On the basis of technics available at the time their studies were made, these authors concluded that proper adjustments in respiratory gas exchange, under resting conditions, in dogs may be delayed one month or more. In man, a study of the carbon dioxide content and the oxyhemoglobin saturation made in our clinic[2] revealed that in the absence of complications the state of respiratory gases in the arterial blood was normal within a few days after pneumonectomy. In addition, this study showed that following lobectomy some degree of anoxia persisted for longer periods of time, possibly as a result of inadequate correlation between alveolar ventilation and pulmonary circulation in the remaining lobe on the operated side, as it reexpanded slowly. A persistent arterial oxyhemoglobin unsaturation after pneumonectomy may be due to three causes: (1) The presence of a large bronchopleural fistula; (2) a state of distention or compression of the remaining lung brought about by mediastinal shift; and (3) development of pneumonia in the remaining lung. The additional risk of anoxia during a period, so fraught with other hazards, requires that the variation of oxyhemoglobin saturation in the arterial blood should be carefully followed.

The late effects of pneumonectomy upon pulmonary and cardiocirculatory functions have been studied in great detail in dogs, operated upon as puppies or adult animals.[4, 5] Recently these studies have to some extent been duplicated in children[1], and extended to adult man in the present report. In puppies and young children the surprising finding was that the capacity to perform exhausting exercise after pneumonectomy was comparable to that of the normal controls. In puppies, after pneumonectomy, there was enlargement of the remaining lung and histologic evidence of pulmonary hyperplasia. In young children hyperplasia was not demonstrated and the best performances were observed in those cases where the size of the remaining lung in forced expiration was not larger than predicted for one of a pair of normal lungs. The physiologic paradox of as good a performance with one lung as with two, under conditions of extreme physical demands, may be explained partly by the following considerations:

(1) Theoretically, it may be shown that the higher the ratio of tidal air to functional residual air, the more efficient is the mixing of gases in the alveoli. Such a situation arises after pneumonectomy: the dead space in the bronchial tree is reduced—the tidal air in one lung is larger, both combining to increase the efficient tidal air, and finally the functional residual air is smaller providing the remaining lung is not distended. (2) The tidal air is probably better distributed to ordinarily poorly ventilated lung areas, particularly around the hilum and at the apex, as the lung expands toward the opposite hemithorax in inspiration. (3) More blood circulates through the remaining lung as the functional diffusing surface for respiratory gas exchange is either increased in area by increase in the number of functioning capillaries or increased in efficiency by passage of more blood per unit of ventilated

alveoli. These considerations applying also to adults may well explain why respiratory gas exchange under conditions of moderate strain was efficiently managed in the younger group reported in the present paper.

In contrast to respiratory gas exchange ventilatory function is impaired in children and in adults after pneumonectomy. The breathing reserve under varying conditions of activity is lower than in normal subjects, and the tendency to dyspnea is greater. The reduction of ventilatory efficiency, however, is not proportional to the loss in lung volumes and to a considerable extent depends upon the degree of pulmonary distention.

The question of late development of pulmonary emphysema following pneumonectomy, performed during adult life, has not yet been settled because of lack of long follow-up. So far, our experience has been that when the mediastinum was maintained in its normal position, lung volume measurements failed to reveal evidence of developing emphysema. This situation, in humans, is entirely different from that encountered in dogs, where the distention of the remaining lung cannot be prevented. The shift of the mediastinum after pneumonectomy may be controlled by organization of the fluid in the empty hemithorax, by oleothorax, or by thoracoplasty. Our data tend to show that thoracoplasty does not reduce further the ventilatory function if measures are taken to keep the spine straight, and thus preserve the maximum expansion of the chest-bellows on the unoperated side. Postthoracoplasty scoliosis is highly detrimental to the efficiency of the chest-bellows mechanics, as has been demonstrated by previous work in tuberculous patients[7].

No mention has been made, so far, in this report of bronchospirometry, which permits separate estimation of ventilation and gas exchange in each lung. In two cases, with suppurative disease of the lung, this method was found to be of practical value in helping decide between limited and extensive lung resection.

SUMMARY

1. The effect of pneumonectomy upon pulmonary and cardiocirculatory function has been studied in 12 adult patients.

2. The following measurements have been made:
   (a) Lung volumes and subdivisions.
   (b) Maximum breathing capacity.
   (c) Ventilation, breathing reserve, respiratory gas exchange, and state of the respiratory gases in the arterial blood, under basal conditions, during moderate exercise, and during the recovery period from moderate exercise.
   (d) Venous pressure, circulation time, and vital capacity before, during, and following an infusion of 1500 cc. of a saline solution in 30 minutes.

3. Ten patients, studied after pneumonectomy, were divided into two groups according to age, and compared to normal controls. Two of these ten patients were again studied after a thoracoplasty had been completed, and

two additional patients, not studied after pneumonectomy, were studied only after thoracoplasty. Six of the ten patients, studied after pneumonectomy, had already been studied before operation.

4. The chief difference between patients after pneumonectomy and normal subjects was the reduction in their breathing reserve in various states of activity. This reduction caused by a decrease in maximum breathing capacity was greater in the older patients because of the cumulative effect of abnormal hyperventilation.

5. The decrease in maximum breathing capacity was not proportional to the loss of lung volume, and was greatly influenced by the state of distention of the remaining lung.

6. The late effects of pneumonectomy upon gas exchange in the lungs, the state of respiratory gases in the arterial blood, and the cardiocirculatory function were insignificant.

7. In two patients, age 53 and 63, respectively, distention of the remaining lung due to mediastinal shift was detrimental to hemorespiratory gas exchange, especially in the older patient who had pulmonary emphysema.

8. A supplemental thoracoplasty in four patients did not impair, further, the ventilatory function; and in some patients was of distinct benefit.

9. Overdistention of the remaining lung following pneumonectomy, insofar as it impairs the mechanics of the chest bellows, and reduces the efficiency of gas exchange, is physiologically undesirable.

We wish to thank, particularly, Drs. Herbert C. Maier and Richard L. Riley for their assistance and many helpful suggestions.

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DISCUSSION.—DR. ANDRÉ COURNAND (New York): Physiologic studies after pneumonectomy in children show remarkable resemblance to the findings just reported by Dr. Berry in adults. I have studied, so far, with Drs. Charles W. Lester and R. L. Riley the cases of five children after successful completion of pneumonectomy and return to normal life. Two of the five children had a marked displacement of the mediastinum toward the operated side persisting after complete expiration. Lung volume measurements show that the residual air volume of the single remaining lung of those two children was about the same as the residual air volume of two lungs of normal control. This was in contrast to the other three children, with mediastinum maintained in normal position, where the residual air volume was about half that of the normal control. Permanent overdistention of the remaining lung in the former group was associated with a much greater decrease in efficiency of the chest bellows for air displacement as in the latter. This was conclusively shown by measurements of maximum breathing capacity. As we have previously shown, this measurement is the best means of estimating the breathing reserve which, in turn, is closely related to intensity and development of dyspnea. It was thus not surprising to find that the intensity and duration of dyspnea for varying degree of exertion were greater in the two children with permanent overdistention than in the three others. These five children, during the performance of an exhausting type of exercise, showed remarkable efficiency in supplying oxygen to the tissues and displacing carbon dioxide from the circulating blood. As a matter of fact, with one lung these children were able to perform as much exercise as normal controls of same size and age; their breathing reserve was still large enough to afford the required ventilation although at the expense of comfort, as shown by greater degree of dyspnea; and finally, their oxygen intake and carbon dioxide output were as large. These observations confirmed the following concepts: 1. That the breathing reserve in normal is well over and above any physiologic demand; 2. That the limit to exhausting exercise is not ventilation but circulation.

With Dr. H. C. Maier we have studied the state of respiratory gas in the arterial blood during the immediate postoperative period following pneumonectomy. This study revealed that the carbon dioxide content and the oxygen saturation in the arterial blood, in the absence of complication, returns to normal within a few days after pneumonectomy. This is in contrast with what is observed after lobectomy, where some degree of anoxia persists for a longer period of time, supposedly as a result of inadequate correlation between the ventilation and pulmonary circulation in the remaining lobe or lobes on the operative side.

Persistent arterial oxygen unsaturation after pneumonectomy recognizes three possible causes: First, the presence of a large bronchopleural fistula; second, a state of distention or compression of the remaining lung brought about by mediastinal shift; and third, the development of pneumonia in the remaining lung. The additional risk of anoxia during a period so fraught with other hazards requires that the variation of oxygen saturation in the arterial blood should be carefully followed.

As to the late development of pulmonary emphysema after pneumonectomy in children or adults, we have not yet settled the question, because of lack of long-following, but, so far, our experience has been that when the mediastinum is maintained in its normal position we failed to see any evidence of developing emphysema.

In summary, we might state that overdistention of the remaining lung after pneumonectomy is not physiologically desirable, either in children, in adults, or in the older age-group. The teleologic concept, that the increase in size of the remaining lung to make up for the loss of the other lung, will bring about functional compensation, is not borne out by physiologic studies.

DR. EVARTS A. GRAHAM (St. Louis, Mo.): Those who have not been primarily interested in chest surgery perhaps do not realize that there has been a very great deal of discussion and uncertainty in the minds of those of us who have been confronted by these problems, as to whether or not measures should be taken permanently to obliterate the empty space which is left after the removal of a lung.

In my first case, which is just past the ninth anniversary—I know because my patient always calls me up on the fifth of April, and he called me up again this year to remind me—when I completed the operation I was alarmed at the huge empty space which remained, and I thought that the only thing to do was a thoracoplasty to obliterate it. Consequently, I at the same time removed seven ribs. The patient made an uneventful recovery, although I removed the remaining three ribs at a subsequent date, about three weeks after the operation. I was greatly impressed with the ease of the convalescence of the patient. In fact, I demonstrated him at a meeting of the Clinical Surgical Society, which met at St. Louis only about two weeks after his operation. He apparently had no dyspnea, and everything was going along very well.

Of course, this is a very radical procedure to add to the operation of pneumonectomy, and when Dr. Rienhoff announced that apparently it was not necessary to obliterate this space by thoracoplasty, my own ideas wavered considerably, and after doing several total pneumonectomies without the performance of thoracoplasty, I decided that probably Dr. Rienhoff was right. Since that time, however, my own mind has wavered a good deal back and forth.

I think that we thoracic surgeons ought to be very grateful to Dr. Cournand and Dr. Berry for these very fine studies which have been reported here this morning. These, in a sense, also tend to confirm observations that were reported before the Association of Thoracic Surgery by Longacre two years ago, in which, also, evidence was brought out that probably in the long run the patient who has had a pneumonectomy would fare better if he had the space completely obliterated by thoracoplasty.

Now, if however one attempted to add a thoracoplasty as an initial procedure to the operation of total pneumonectomy, in all probability the mortality of the operation would rise. In the early days, I undertook to compromise this measure somewhat by performing a thoracoplasty first, in some cases, followed by total pneumonectomy. That procedure I abandoned because for various reasons I do not think it is a wise one.

In the patients whom Dr. Berry recorded as carrying a permanent pneumothorax substituted by an oleothorax, that perhaps is an effective measure which might be satisfactory in patients who might otherwise be a poor risk for subsequent thoracoplasty. But after all, of course carrying a lot of oil around in the chest is carrying a foreign body, and oleothorax for tuberculosis has had a rather high proportion of unsatisfactory results, largely because it is a foreign body that is carried around.

Dr. Rienhoff, however, suggested some years ago, that it is not necessary, that a thoracoplasty be performed at the time of the operation. If it should seem necessary it can be done some time later, and I think that that is sound advice.

DR. FRANK B. BERRY (closing): I should like to thank Dr. Graham very much for his kindly discussion, and say that I agree completely with him about the dangers of oleothorax, and it was merely given to D.M. as a makeshift, as we still hesitate to undertake a thoracoplasty on him.

We have had two other patients lately in whom this question has arisen. One was the man for whom we did a pneumonectomy for intrabronchial tuberculosis. He has been hospitalized since 1924. That is a great handicap to overcome. Following his pneumonectomy, he still had many aches and pains. His chief complaint was difficulty in swallowing, though we could not demonstrate anything by esophagograms. We finally suggested that perhaps it was due to distention of his other lung and some push or pull which we could not demonstrate. Following thoracoplasty, he has been completely relieved, notwithstanding relatively good functional studies all along. He is now inquiring about the chances of getting a job; so apparently from the purely subjective standpoint it was completely worth while.

Another is a man of sixty. Following his pneumonectomy, he decided the best way to put himself in shape was to forget all about hospitals and promptly built himself up to the ability to walk ten miles a day. Two years later, this winter, he came back to us with pneumonia, from which he recovered, and again he left the hospital. He came back a few weeks later with acute dyspnea, and was markedly cyanotic from a diffuse bronchitis. Since then, during his convalescence, he has had similar attacks—paroxysms with acute dyspnea. I became very much worried about the possibility of his overdistention and within the last week we put him through complete studies, only to find that at the end of two years his lung still is about in the midline, there is a very good diaphragmatic excursion, oxygen saturation of 95 per cent, and exceedingly good maximum breathing capacity. So we have decided that his trouble is due probably to a true bacterial asthma, coming on in paroxysms, and has nothing to do with overdistention of the remaining lung.

Now we have never undertaken a thoracoplasty on him, nor do we intend to as long as he maintains this position, which it seems likely he will, and he has filled the operated side of his chest, just as Dr. Rienhoff has suggested, with some sort of plug of fibrin and coagulated serum sufficient to hold his mediastinum in place. In view of these recent difficulties, we were very much astonished to find such very good functional response in the midst of these series of paroxysms.