The Journal of
Thoracic and
Cardiovascular Surgery

VOLUME 40
AUGUST 1960
NUMBER 2

Original Communications

PRESIDENTIAL ADDRESS

PULMONARY RESERVE AND ITS INFLUENCE ON THE DEVELOPMENT OF LUNG SURGERY

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MEMBERS of the American Association for Thoracic Surgery and Guests:
I wish to begin this discussion by expressing my deep appreciation for the high honor of being chosen to serve as President of our Association. I first attended a meeting of this distinguished Society in 1929. The meeting was held at Barnes Hospital, St. Louis, in a medium-sized classroom. During the 31 intervening years, thoracic and cardiovascular surgery has grown and matured, and our organization has continued to enjoy an enviable reputation among graduate medical educational groups.

During my 25 years of membership, I have attended all annual meetings except one, at which time I was doing graduate work under Prof. Ferdinand Sauerbruch at the University of Berlin. My experiences during these years, in listening to the presentations, in occasional participation in the programs, and in enjoying the general fellowship of this Association, are among the most treasured memories of my professional career.

I would like at this time also to express my appreciation to the other officers and councilors of the Association for their valued counsel, and especially to thank our Secretary, Dr. Langston, and our Administrative Assistant, Miss Hanvey, who have handled the many and varied affairs of our Society in a most expert and proficient manner.

From the Department of Surgery, University of Chicago, Chicago, Ill.
Presented at the Fortieth Annual Meeting of The American Association for Thoracic Surgery at Miami Beach, Fla., May 11-13, 1960.

In deciding upon a subject for this occasion, various educational, historical, and scientific problems presented themselves. Provocative questions were not lacking in any of these areas. The subject I have chosen is one that first interested me over two decades ago at the time of several deaths following total pneumonectomy. Autopsy findings in these cases were those of cardiac failure, although no primary cardiac lesion was found. At that time, total pneumonectomy was the only curative type of surgery considered for primary carcinoma of the lung.

Although much concern regarding pulmonary function and reserve was expressed in early medical history, the full significance of this matter was not appreciated until the years of development of modern thoracic surgery. The delay in an understanding of this problem was due partly to the difficulty in

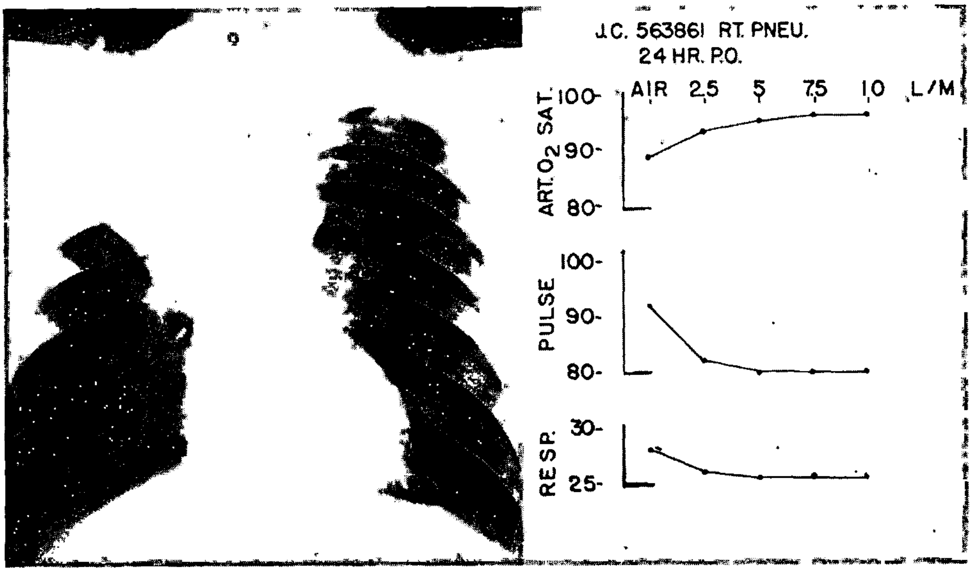


Fig. 1.—Roentgenogram of chest of a 63-year-old white man and data showing degree of desaturation of blood oxygen 24 hours following a right pneumonectomy. A satisfactory rise in arterial oxygen saturation was obtained by the administration of only 2½ L. per minute of oxygen flow via an oropharyngeal catheter. Note changes in pulse and respiration closely following the changes in arterial oxygen saturation.

evaluating pulmonary reserve, which later was forced upon us (partly by trial and error) with the evolution of modern pulmonary surgery. It is now appreciated that this problem is not confined only to pulmonary resection, but also to other intrathoracic surgery, as well as in the general field of surgery, especially in the elderly or poor-risk patient. Interference with pulmonary ventilation following a general anesthetic and major operation in the older age group, or in the obese patient, tends to encourage the retention of bronchial secretions with resultant patchy atelectasis. This in turn may lead to increased pulmonary vascular resistance, as well as to hypoxia, which results in increased strain on the right heart. Evidence that this occurs quite frequently was demonstrated repeatedly in a study of a series of 50 patients who had undergone major surgery. The average level of arterial blood oxygen on the first day after operation was 88 per cent as seen in Fig. 1, with a range of 80 to 92 per cent. This could be readily corrected by the use of small amounts of oxygen administered through an oropharyngeal catheter. As little as 1 to 2 L. of oxygen flow per minute usually led to a desirable level of blood arterial oxygen. In the series of patients studied, some degree of hypoxia of clinical significance usually persisted for several days after surgery, the amount gradually decreasing as the patient became more active.[1]

The dangers accompanying decreased pulmonary reserve were recognized by the ancient Greeks. However, they understood relatively little of the underlying principles upon which this danger was based. As early as the 16th century, some knowledge of the influence of altered intrathoracic pressures on cardiorespiratory function was gained from animal experimentation.

Fig. 2.—Andreas Vesalius (1514-1564), famous anatomist at the University of Padua, and one of the first medical scientists.

Andreas Vesalius,[2] a Belgian by birth and a noted anatomist and physician at the University of Padua, was one of the most outstanding figures in European medicine between Galen and Harvey (Fig. 2). Vesalius was an astute observer, an accurate recorder, and an inspiring teacher as indicated by his demonstration of altered respiratory function by animal experimentation, much as it is being done today, four centuries later. Allow me to refresh your memory on his erudite discussion with his students of the dangers of open pneumothorax during experiments on rabbits. After exposing the transparent parietal pleura through which the movements of the lung could be seen, he showed how the lung would fall away from the side of the chest wall on breaking the pleura and allowing the pleural cavity to communicate with the outside. If only one side of the chest was involved, the motion of the chest remained unchanged. However, if the opposite pleural cavity was opened, "the lungs are seen as the result of perforation to fall together and collapse.

The cardiac motion may not be observed for long, since suffocation of the animal will come on account of the collapse of the lungs. In order to restore the life of the animal, an opening is made in the upper part of the trachea, into which a pipe made from a reed is introduced. When it is breathed into, if the lung rises up, the animal receives air. The lung should be inflated to the degree to which it occupied the thorax in life. The heart now gathers strength and its motion will change beautifully. Therefore, by maintaining repeated inflation of the lung, you may have opportunity to examine the motion of the heart both by touch and sight as much as you desire." Thus, it is quite obvious that this great anatomist and scientist fully understood the ill effects of reduced pulmonary reserve. It is also obvious from his description of the experiment that a means of avoiding these untoward results, or of overcoming them once

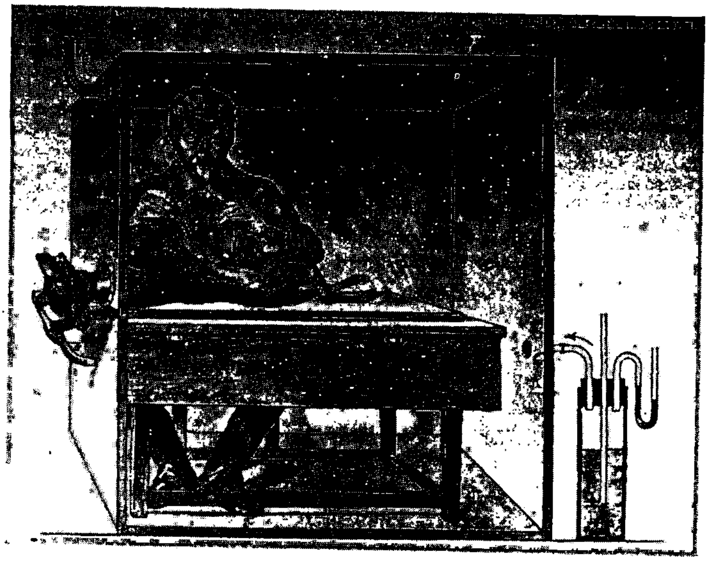


Fig. 3.—Negative pressure room developed by Sauerbruch for intrathoracic operations on animals. A similar room was constructed for clinical use (after Sauerbruch).

they were established, was possible through the use of positive pressure intratracheal insufflation. It seems incredible that the dangers associated with open pneumothorax continued to be remembered for four centuries, but that the principle involved in the method overcoming or obviating these hazards was forgotten, or at least was not associated with thoracic problems.

Methods, procedures, and even principles seem to have a way of being rediscovered again and again, and so it was with this medical problem. Three centuries later, in 1903, Johann von Mikulicz, the noted German surgeon at Breslau, visited William Worrell Mayo at Rochester and discussed problems involved in surgery of the esophagus. Following this visit, he set his young assistant, Ferdinand Sauerbruch, at that time a young doctor of 27 years of age, to investigate methods of making intrathoracic surgery a safe procedure, with relatively little hope that a solution could be found. As a result of Sauerbruch's work, a negative pressure chamber was constructed in which open-chest operations could be safely performed under reduced atmospheric pressures[3, 4] (Fig. 3). When Brauer demonstrated that positive pressure insufflation of the lungs gave satisfactory results and was a far more practical arrangement, this type of anesthesia supplanted the negative pressure chamber. The work of Meltzer and Auer soon followed and, after overcoming certain inertia, led to the establishment of anesthetic methods and procedures in common use today.[5]

Although resection of an entire lung had been accomplished in animals as early as 1492 by Rolandus,[6] it did not become an established clinical procedure until in the early 30's when reports of a total pneumonectomy were made independently by Haight,[7] Nissen,[8] and Graham.[9] Two main factors repsonsible for the long delay in this field of surgery were (1) a lack of complete understanding of altered respiratory physiology during an open pneumothorax, and (2) the delayed development of anesthetic methods and techniques presently used in this field. Thus, in spite of observations made by Vesalius in the 16th century, almost four centuries elapsed before clinical use was made of this information.

With the operative risk associated with pulmonary resection reduced to an acceptable status, this field of surgery was extended to include resections of parts of both lungs usually performed for bilateral bronchiectasis. Eloesser[10] in 1933 was the first to report such a case, followed by Overholt[11] in 1937 with a report of a tri-lobectomy. In 1940, Graham[12] posed the question, "With how little lung tissue is life compatible?" At that time he reported the results of surgery in a patient in whom both lower and middle lobes were resected, the lingula on the left being considered as a left middle lobe, with only the two upper lobes remaining. Pulmonary resection was extended even farther in this patient, in whom, in addition to the four lower lobes, a portion of the right upper lobe was also excised for emphysematous blebs and bullae which had developed in association with bilateral bronchiectasis (Fig. 4). Reimann[13] and his co-workers have demonstrated on dogs that overdistention of the remaining lung tissue following massive reduction of lung capacity, such as by total pneumonectomy, is not accompanied by any significant increase in pulmonary resistance. Even with reduction of lung capacity to one upper lobe or 15 per cent of the normal, pulmonary artery pressures were no greater in the overdistended state than in the normally expanded state of the remaining lung tissue. These results corroborate those of Charbon and Adams[14] who found that filling of a pleural space with a plastic prosthesis following pneumonectomy did not improve the survival rate following further reduction of lung capacity to 15 per cent. Instead, he obtained no survivors at all in a group of 12 dogs, whereas, when no prosthesis was used, 4 of 13 dogs survived for weeks or months following operation. Graham's posed question was a very pertinent one and required further investigation in the laboratory. In experiments on dogs, reported by Phillips[15] and Rasmussen[16] and their associates, pulmonary capacity was reduced successfully to the right upper lobe or approximately 15 per cent of the original lung capacity. To accomplish this, it was necessary to reduce lung capacity in stages extended over a period of several weeks. This was accomplished by a combination of resection of the lower lobes as the first stage, and later occlusion of the bronchi to the remainder of the lung with the exception of an upper lobe, and subsequent

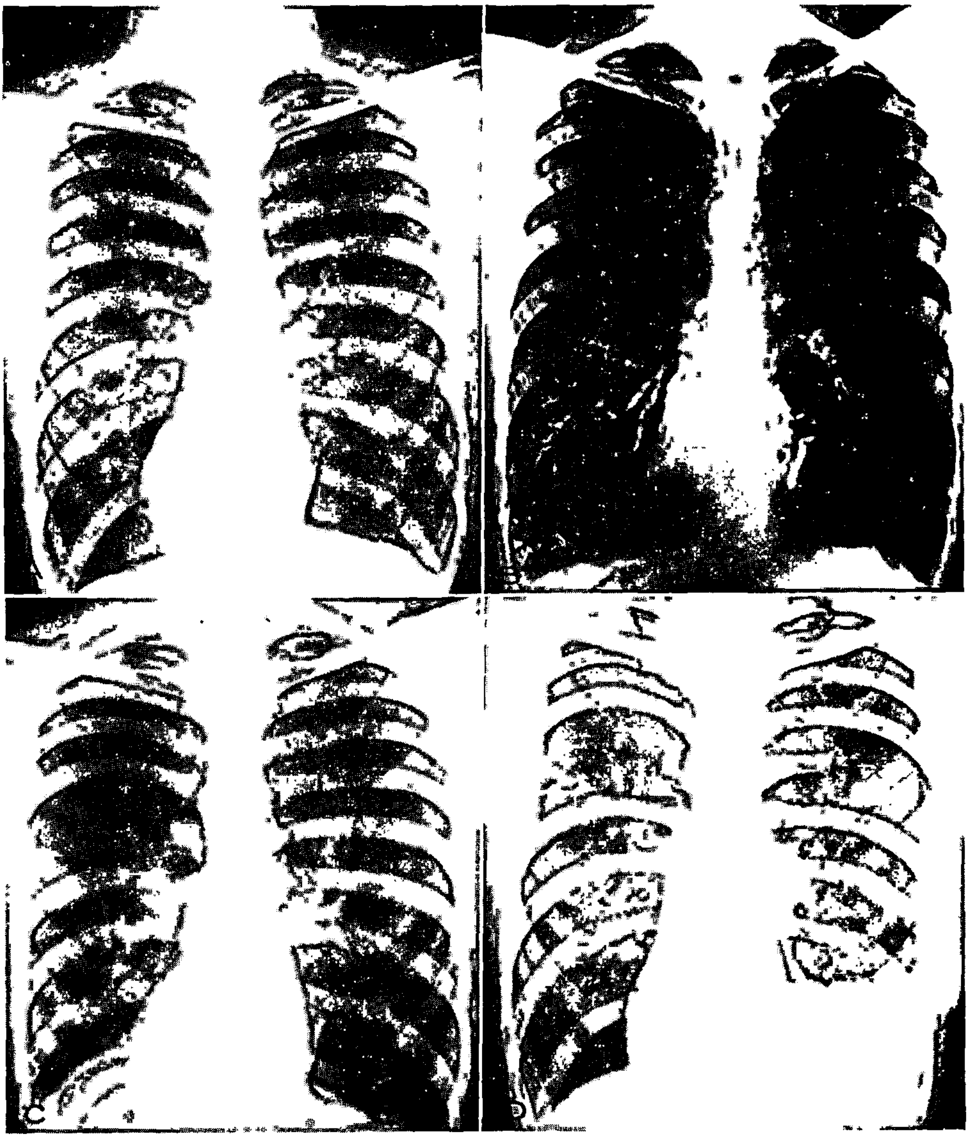


Fig. 4.—Roentgenograms of chest of a 33-year-old white man which show *(A)* normal posteroanterior view of chest exhibiting bilateral emphysema in the lower lung fields; *(B)* bronchogram showing bronchiectasis with complete collapse of both lower lobes and the right middle lobe, as well as involvement of the left upper lobe; and *(C)* and *(D)* x-ray appearance after resection of both lower lobes, the right middle lobe, as well as the lower portion of the right upper lobe for bullous emphysema, and resection of the lingula of the left upper lobe (patient's pulmonary reserve reduction was due to infection gradually over a period of years; compensation was adequate to obviate serious cardiopulmonary symptoms following bilateral resection).

collapse of those lobes by absorption of the entrapped air. Carlson and his co-workers,[17] at a later date, were able to accomplish this marked reduction in capacity to 15 per cent by a staged resection of the remaining portion of the lung. However, only 4 of 13 animals survived this method; the remainder died of excessive (right) heart strain (pulmonary artery pressures were increased by 100+ per cent). Thus, the dog's ability to tolerate marked reduction of lung capacity was governed, at least in part, by the rate at which the diminution was made. Furthermore, when a small physiologic shunt remained, such as that represented by the remaining atelectatic lobes, the risk of reducing the capacity to this small amount was lessened (Fig. 5, *A*).

Fig. 5*A*.—Two bronchograms of a dog made after a staged reduction in lung capacity by a combination of surgery and bronchial stenosis. On the left, the capacity has been reduced to both upper lobes and the right middle lobe or approximately 38.7 per cent of normal through bilateral excision of both lower and the right accessory lobes. On the right, the capacity has been further reduced to only the right upper lung lobe or approximately 15 per cent of normal through bronchial stenosis of the right middle and the left upper lobes. By staging the reduction of lung capacity slowly, this animal was able to tolerate reduction to only this small per cent. (From Rasmussen et al.[16])

Following this marked reduction in capacity, these animals appeared to be healthy, remained well nourished, and were able to tolerate moderate exercise. They were usually active in the kennel and, although somewhat dyspneic on exercise, did not show evidence of cyanosis. Upon sacrificing such an animal having only 15 per cent of his original lung capacity, the remaining lobe was found greatly overdistended and, on microscopic examination, revealed some fragmentation of the peripheral respiratory units (Fig. 5, *B*). This, however, did not represent a true emphysema since no increase in fibrous tissue in the alveolar walls was observed. In spite of this marked alteration of microscopic appearance, these animals tolerated a rarefied atmosphere remarkably well. A test of their tolerance to such a situation was made by placing them in an evacuation chamber and reducing the pressure therein until consciousness was lost. When normal dogs were subjected to this procedure they were able to tolerate a reduction in pressure to approximately 221.6 mm. Hg (comparable to an altitude of 30,400 feet and 6.25 per cent O_2), or a pressure similar to that tolerated by man before losing consciousness. Dogs with only three functioning lung lobes, or approximately 38 per cent of normal, had the same tolerance. When the one-lobe dogs (15 per cent of normal) were

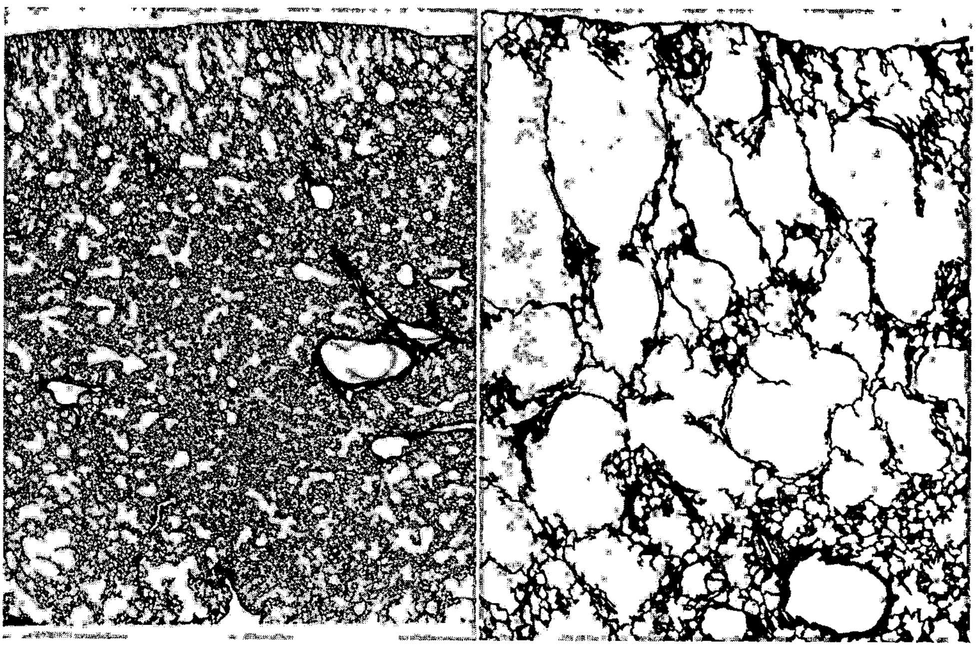


Fig. 5*B*.—Microscopic appearance of a dog's lung following reduction in pulmonary capacity to one upper lobe or 15 per cent of normal. Note marked tendency to overdistention of terminal respiratory units, especially at the peripheral portion of the lung, with marked dilatation of terminal respiratory units. Definite compensatory emphysematous changes are seen in the alveolar ducts and sacs; however, no increased fibrous tissue production is present. (*Left*, ×7—*Right*, ×20; both reduced ⅔.) (From Rasmussen.[16])

subjected to this test, consciousness was lost at 270 mm. Hg (altitude of 25,833 feet and only 7.75 per cent O_2), thus demonstrating a remarkable ability to oxygenate the blood with but a small amount of functioning lung tissue (Table I). Although these animals appeared well for a few weeks or months following these experiments, most of them died much earlier than would have been otherwise expected. At the time these experiments were made, the mechanism of death was not well understood.

The ability of human beings to tolerate marked reduction in pulmonary capacity has been repeatedly demonstrated by the use of bilateral pneumothorax in the treatment of pulmonary tuberculosis. Here again it was necessary gradually to produce collapse in order to avoid cardiopulmonary distress. An example of this marked reduction in capacity tolerance is illustrated by a

TABLE I. RESPIRATORY RESERVE AT REST AS DETERMINED BY REDUCTION OF ATMOSPHERIC PRESSURE

STANDARD ATMOSPHERIC PRESSURE		CONDITION OF ANIMAL AND % OF FUNCTIONING LUNG	NO. OF DOG	ALTITUDE TOLERATED	TIME OF ASCENT MINUTES	AVERAGES	
ALTITUDE FEET	PRESSURE MM. Hg					ALTITUDE FEET	PRESSURE MM. Hg
0	760		1	30,500	10		
1,000	733		2	30,500	10		
		Normal (6 lobes) 100%	3	29,500	10	30,400	221.6
5,000	632.4		4	32,000	8		
10,000	522.6		4	29,500	11		
15,000	428.8		917	32,000	6		
			993	32,000	7		
20,000	349.2	3 lobes 38%	3	25,000	7	30,000	225.6
25,000	282		637	31,000	9		
30,000	225.6		871	30,000	9		
35,000	178.7	2 lobes 23%	636	27,500	4	26,000	269.8
40,000	140.7		869	24,500	6		
			635	26,500*	5		
		1 lobe 15%	621	25,000†	6	25,833	272
			695	26,000	10		

Table shows respiratory reserve at rest during the lowering of pressure in an evacuation chamber in dogs with normal lung capacity as well as with reduced lung capacity to 38, 23, and 15 per cent of normal. Note marked degree of tolerance to rarefied atmosphere with lower oxygen available to animals with only 15 per cent of original capacity. The percentage of oxygen available at 30,000 feet altitude or 230 mm. Hg pressure is approximately 6.4 per cent, whereas that available at 26,000 feet altitude or a pressure of 270 mm. Hg is approximately 7.7 per cent. (From Rasmussen et al.[16])

*Failed to recover.

†Did not become unconscious.

patient treated by Dr. Victor S. Randolph. A roentgenogram of this patient taken at the end of deep expiration showed scarcely any inflated lung tissue. The second view taken at the end of deep inspiration revealed relatively little functioning lung on either side (Fig. 6). During this phase of the patient's treatment, he was at bed rest and therefore the requirements for oxygen were considerably reduced. (This was a young adult male patient and therefore the lung tissue might be expected to tolerate a greater degree of collapse than in an older individual.)

From the evidence these patients revealed and the results of animal experimentation, it appeared that total pneumonectomy was a procedure that should be well tolerated with little risk to the patient. In normal, healthy animals, this has been proved beyond a doubt. Likewise, in the younger individuals, cardiopulmonary function has been repeatedly demonstrated to be quite adequate, not only while at rest, but also sufficient to insure a relatively normal way of life.

However, as more experience in this problem was obtained, the mortality rate of this operation in older people (above 60 years of age) was found to be definitely increased. Furthermore, the cause of death in some patients was inadequately explained by the results of pulmonary function studies prior to surgery. This led to further investigation of the problem on dogs, in which pulmonary resistance and pulmonary flow rates were correlated with pulmonary function values before and after varying degrees of reduction in lung capacity.[18]

It was fully appreciated that in animals only relatively normal lung tissue was involved, whereas in clinical cases, dealing with inflammatory, neoplastic, or degenerative disease, a combination of changes in lung tissue structure, as well as function, might very well play an important role. These experiments revealed that when a dog's lung capacity was rapidly reduced to 15 or 20 per cent of normal, pulmonary vascular resistance was more than doubled, and that an intolerable level of pulmonary hypertension occurred in a high percentage of animals. Furthermore, it was found that a demand for increased cardiac output during exercise further increased the degree of cardiac strain.

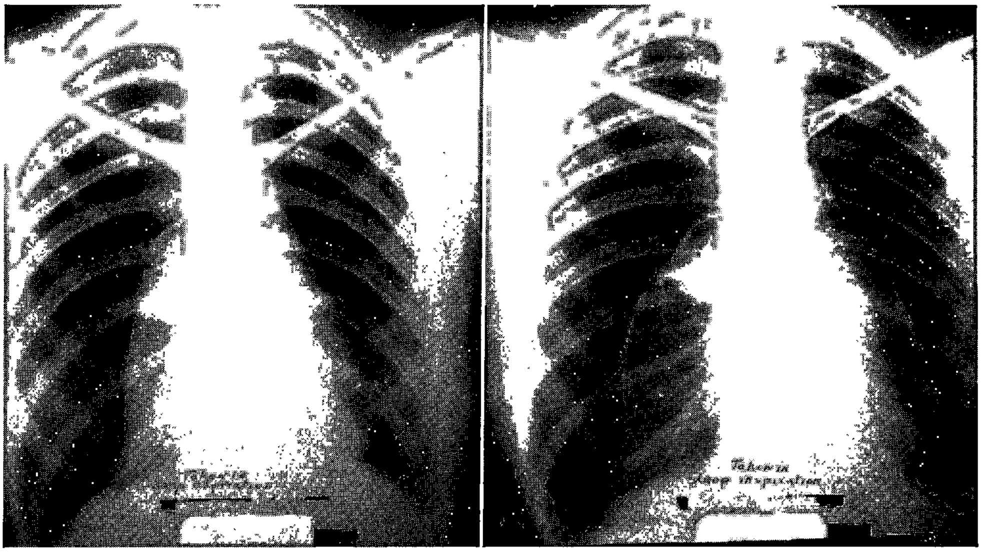


Fig. 6.—Two roentgenograms of the chest of a young, white man taken during deep expiration on left and on deep inspiration on right. This patient was being treated for bilateral pulmonary tuberculosis by bilateral pneumothorax. Note marked degree of collapse of both lungs by therapy. Since the requirements for oxygen at rest were quite low and since this was a relatively young individual, this marked degree of reduction in lung capacity was tolerated.

On the other hand, blood oxygen saturation suffered relatively little (5 per cent) while the animal was at rest, even with reduction of lung capacity from 50 to 15 per cent. During exercise, the saturation level dropped precipitously but could be restored to normal immediately by the administration of oxygen (Fig. 7).

In patients with bilateral alteration of the lung which is due to inflammatory, degenerative or other conditions, the pulmonary vascular resistance may be increased by as much as 100 per cent. This is especially true in the so-called older age group. Thus, removal of an entire lung may carry considerable risk. In nonmalignant disease it is frequently possible to limit pulmonary resection, thus preserving maximum lung capacity. However, in the case of malignant lesions, it has been generally believed that removal of the entire lung along with adjacent tumor-bearing tissue is the operation of choice, when it can be tolerated by the patient. In patients of this older age group with an already reduced pulmonary reserve, a sudden additional reduction in lung capacity by pneumonectomy may lead to an intolerable degree of increased cardiac strain due to increased pulmonary vascular resistance without lowering blood oxygenation to a dangerous level. Postoperative alteration in pulmonary tissue and chest wall function may well augment the serious degree of increased pulmonary vascular resistance produced by pulmonary resection. Since the risk of pneumonectomy is increased in the older age group having poor pulmonary reserve, repeated attempts have been made to determine the "resection tolerance" of such patients prior to surgery. Studies made by a number of investigators[19] have increased our knowledge of factors concerned with this problem. In the past several years, special attention has been given to the problem of changes in pulmonary vascular resistance attending the resection of lung tissue both in animals and in man.[20]

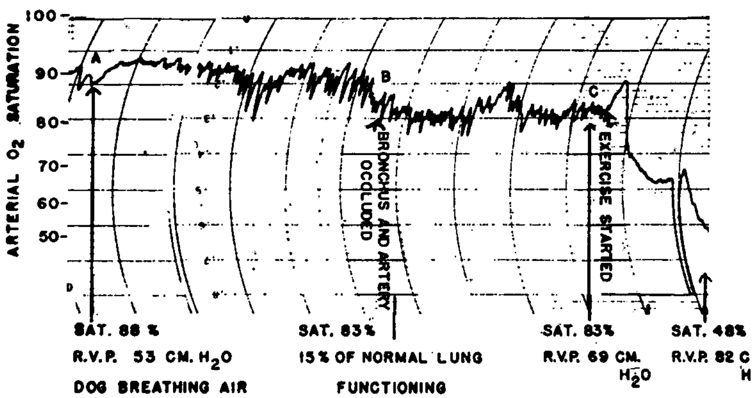


Fig. 7.—Dog 737—March 25, 1952. Continuous recording oximeter tracing of oxygen saturation in the dog during reduction in pulmonary capacity from 50 per cent on the left to 15 per cent by suddenly obstructing the bronchus and vessels to all except one upper lobe at point *B*. Saturation levels, right ventricular pressures and other data are indicated below the tracing. The record reveals a marked elevation in right ventricular pressure from 53 to 69 cm. of water with reduction in lung capacity from 50 per cent at *A* to 15 per cent at *B* and *C*. Oxygen saturation during this period was reduced by only 5 per cent. The effect of exercise begun at *C* on oxygen saturation as well as right ventricular pressure is demonstrated. When oxygen was given by nasal catheter, the saturation level became suddenly elevated to normal; however, right ventricular pressures remained high. (From Adams et al.[18])

In young, healthy people, both pulmonary function studies as well as pulmonary vascular data show a considerable range of safety in the majority of cases following total pneumonectomy. Blood oxygen saturation is usually normal during the resting state and shows only mild elevation during exercise. The cardiac output is likewise normal at rest, and increases in a normal manner with exercise. The following patients will serve as examples of fairly characteristic responses following pneumonectomy in older people. The fatalities which occurred in Cases 1 and 2 were due to intolerable pulmonary hypertension and cardiac failure, occurring 19 and 11 days, respectively, following pneumonectomy for malignant disease.

Case 1.—The first patient (O. C., Case 1) was a 66-year-old white man whose pulmonary function studies made before operation showed a moderate reduction of ventilatory capacity. At the time of surgery, preocclusion pressure of the pumonary artery showed a mean of 39 cm. of water. This pressure rose to 53 cm. of water after occlusion of this artery. The surgical procedure was tolerated quite well and his immediate postoperative course was quite satisfactory. Oximetric studies revealed decreased saturation of blood oxygen; however, this was easily corrected with a very low flow of oxygen via oropharyngeal catheter. Although the patient was digitalized, his condition did not improve and he died on the nineteenth postoperative day of cardiorespiratory failure (Fig. 8).

CASE 2.—The second patient (R. R., Case 2) was a 59-year-old white man who underwent a total pneumonectomy for primary carcinoma of the left lung involving the left chest wall. The general physical examination of this patient showed him to be in relatively good condition prior to surgery. Likewise, pulmonary function studies revealed only mild to moderate reduction in functional values. During operation, preocclusion pressures were

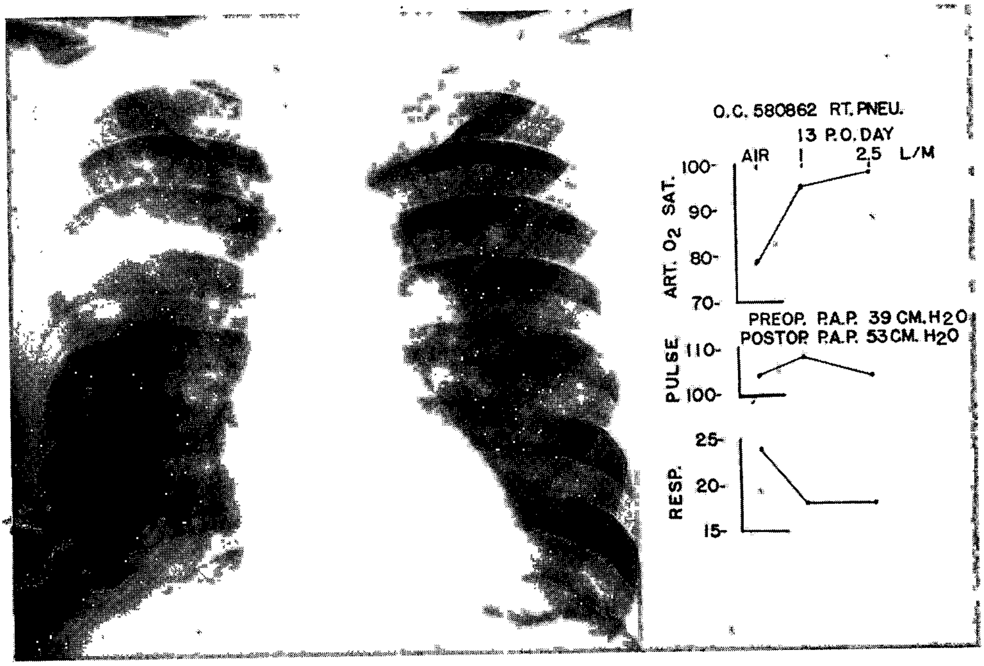


Fig. 8.—Case 1 (O. C.). Roentgenogram of the chest which reveals a bronchogenic carcinoma of the right lung. Data on *right* were obtained 13 days following surgery, except for preocclusion and postocclusion pressures of pulmonary artery at the time of surgery. Note lower oxygen saturation to 80 per cent which was elevated to a satisfactory level with only 1 L. per minute of oxygen flow via an oropharyngeal catheter. Death occurred on the ninteenth day after operation of cardiac failure.

48/12 mm. Hg. Following occlusion, the pressures rose to 60/12 mm. Hg. Because of this high pulmonary resistance, he was started on prophylactic digitalis. He appeared to be progressing satisfactorily, although the electrocardiogram revealed some premature auricular beats. His convalescence on the fifth postoperative day was quite satisfactory, the blood oxygen saturation being 93 per cent on air with an elevation to 98 per cent on oxygen. X-ray studies showed a satisfactory postoperative appearance of the chest. By the ninth postoperative day, he became rather lethargic and again showed evidence of auricular fibrillation. The oxygen saturation studies still remained good, being 95 per cent on air and 100 per cent on oxygen on the tenth day. On the following day, he suddenly became quite dyspneic and died (Fig. 9).

CASE 3.—This next case is presented to indicate how data from pulmonary function studies appeared unsatisfactory, whereas those obtained from investigation of pulmonary circulation proved to be quite adequate, and where the results of surgery were satisfactory. This patient was a 63-year-old white man (H. M., Case 3) who had had a pneumonectomy for a primary carcinoma of the left lung. Pulmonary function studies showed relatively normal ventilatory values, but an increased residual volume and a markedly decreased maximum mid-expiratory flow, and timed vital capacity was definitely below normal. Circulatory studies on this patient showed a normal pulmonary artery pressure both at rest and during exercise before operation. Likewise, arterial oxygen saturation was within satisfactory limits. Pulmonary vascular resistance decreased during exercise while cardiac output increased. This patient underwent a left pneumonectomy without difficulty. The mean pulmonary artery pressures have remained about the same during the 4-month period of study since operation. The pulmonary vascular resistance has continued low and has permitted an adequate increase in cardiac output without the necessity of increased pulmonary artery tension.

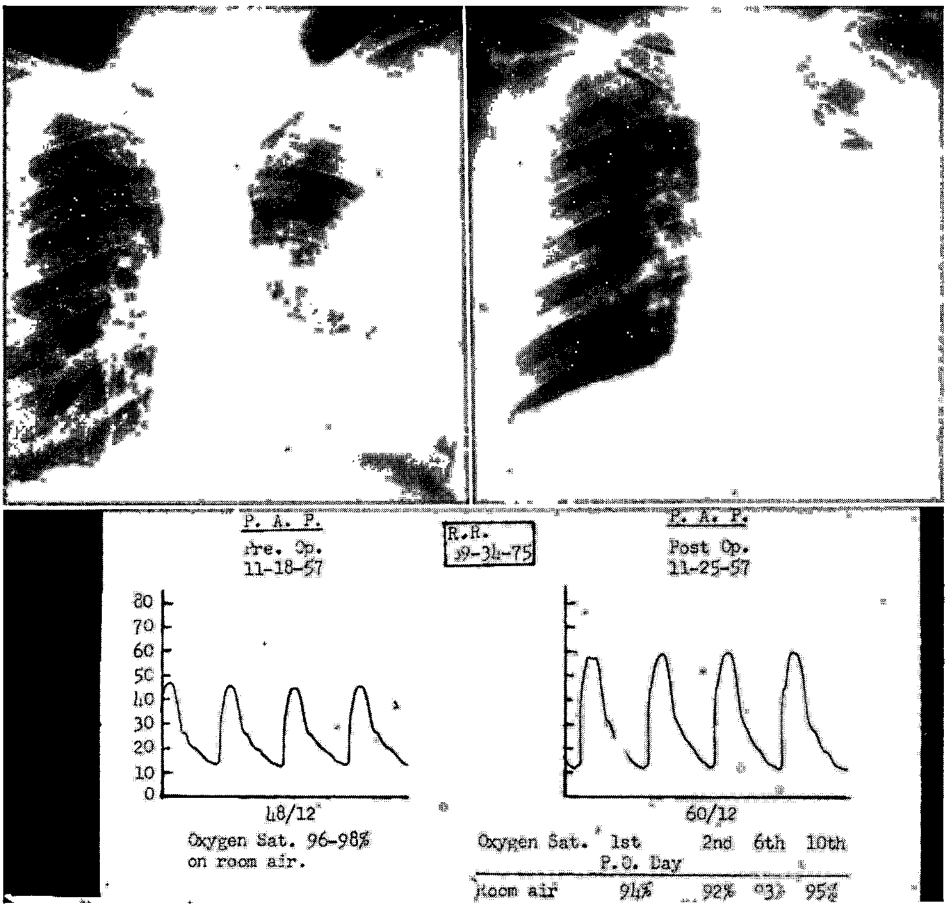


Fig. 9.—Case 2 (R. R.). Roentgenograms of the chest made before and following a left pneumonectomy. Preocclusion pressures were 48/12 and postocclusion 60/12 mm. Hg. Oxygen saturation levels were quite satisfactory both before and following surgery. The patient died on the eleventh day after operation of cardiac failure.

Case 4.—This next patient demonstrated opposite results during study before operation, that is, the results of pulmonary function studies were excellent in all respects and tended to indicate that the operation would carry little risk. He was a 61-year-old white man (J. D., Case 4) in whom a pneumonectomy for primary carcinoma of the right lung was done. At surgery, the preocclusion pressure in the pulmonary artery was found to be double the normal value. After occluding the artery to the side to be removed, this pressure increased 10 to 15 per cent. Because of the location of the tumor, it was necessary to do a total pneumonectomy. In view of this patient's marked pulmonary resistance and pulmonary hypertension, all precautions were taken to bring him through the postoperative period. This included a tracheostomy, oxygen therapy, absolute bed rest, and digitalization of the heart. He responded in a satisfactory manner and was kept on this routine for 4 weeks. At this time, a study of his lesser circulatory values revealed approximately the same findings as at the time of operation. Mild exercise increased these pressures materially. Repeated tests made at 2 and 4 months after surgery showed a gradually decreasing level of pulmonary artery pressures with relatively normal blood oxygen saturation. However, as the pulmonary artery pressures were reduced in amount, the cardiac output was likewise reduced, indicating a remaining high pulmonary resistance. This patient was allowed to go home 6 weeks after operation and was readmitted for these studies. Shortly after returning home on the last occasion, he suddenly died. He had been receiving x-ray therapy for metastases and it was felt that spread of the tumor may have played a role in the gradually diminishing cardiac function.

CHRONIC PULMONARY HYPERTENSION

After patients have survived the ablation of an entire lung, the question might be raised, "How well will this reduced pulmonary capacity be tolerated during later life?" Should the patient change his occupation if it requires strenuous exercise or work and lead a more sedentary type of life? What may be anticipated in the way of life expectancy? It is well known that some patients may continue their normal occupation for many years without difficulty. On the other hand, either shortly after operation or at some period of years later, so-called "pulmonary cripples" have developed with complete incapacitation and reduction of the normal life span.

In order to answer some of these questions, a study was begun some 10 years ago and accelerated during the past 3 years with financial aid from the American Cancer Society. This has enabled the collection of considerable data on 55 patients whose operation had been performed up to 16 years before the study. These patients were admitted to the hospital for a period of 2 or 3 days during which time a detailed investigation included (1) securing data for clincial evaluation, (2) measurements of various aspects of pulmonary function, and (3) obtaining pressure flow values of the lesser circulation. A correlation of the results from each evaluation was made. These detailed studies extended from a few weeks to several years following surgery, in addition to studies made prior to operation and at the time of operation. The results of this study to date would indicate that in general the younger age group of patients, namely, under 50 years of age, revealed little or no difficulty in either pulmonary or vascular reserve during the several years after operation. Functional studies showed some decrease in ventilatory capacity; however, diffusion ability remained normal and adequate, permitting reasonable degrees of exercise or work. Likewise, pulmonary-circulatory studies showed normal resting pressure flow values with only moderate elevation of pressure on exercise (Fig. 10—J. K., Case 5). Some of these patients have been followed over a period of 4 or 5 years, and the pulmonary and circulatory determinations have remained approximately constant. On the other hand, some patients under the age of 50 remained healthy and active for a period of 5 to 10 years at which time they began to develop symptoms of cardiopulmonary insufficiency when active, and subsequently became decompensated, as indicated by the following example.

CASE 6.—This patient was a 56-year-old white man (O. L., Case 6), who, 11 years previously at the age of 45, had had a right pneumonectomy for bronchogenic carcinoma of the lung. After operation, he had an uneventful convalescence and was followed in the Out-patient Department. Eight years following pneumonectomy he began showing signs of increasing pulmonary insufficiency with marked dyspnea, orthopnea, and chronic

FUNCTIONAL CLASS I.

T.L.C.	3.85 L.	
V.C.	2.05 L. (68%)	
R.V.	1.5 L.	
M.B.C.	57.0 L./min. (60%)	
1 sec V.C.	74%	
	Rest	Exer.
Pulm.Art.Press.	25/8 (14)	41/17 (25)
Art. O_2 Sat.	95%	97%
Pulse Rate	110.0	146.0
O_2 Consumption	235.0	579.0
Cardiac Output (L./min.)	5.5	9.3

J.K. 37 F.
3 yrs. post-left pneumonectomy

Fig. 10.—Case 5 (J. K.). Roentgenogram of chest and data collected from cardiopulmonary evaluation on a 37-year-old white woman 3 years after a left pneumonectomy. Note relatively good pulmonary function values, satisfactory arterial oxygen saturation levels at rest and during exercise, normal cardiac output response to exercise with only moderate increase in pulmonary artery pressure as compared to that of the resting state which is at a normal level. *T.C.L.* = total lung capacity; *V.C.* = vital capacity—per cent of normal predicted for subject with two lungs; *R.V.* = residual volume; *M.B.C.* = maximum breathing capacity—per cent of predicted value for a normal chest with both lungs; 1 sec. V.C. = per cent of the vital capacity expired in the first second; *Pulm. Art. Press.* = pulmonary artery pressures (mm. Hg) (mean pulmonary artery pressure in parentheses); *Art. O_2 Sat.* = arterial oxygen saturation; *O_2 Consumption* = oxygen consumption (ml./min.). (From Harrison et al.[20])

nonproductive cough. On the early morning of admission, he awakened and coughed up two or three tablespoons of bright red blood. General physical examination showed nothing remarkably abnormal. However, cardiopulmonary function evaluation revealed lowered ventilatory values, blood-oxygen saturation of 90 per cent, and a right ventricular pressure of 56/0 mm. Hg. A moderate degree of exercise for one minute lowered the saturation to 86 per cent and elevated the right ventricular pressure to 85/0 mm. Hg. This patient's condition has continued to worsen and he is at the present time a pulmonary cripple, being unable to tolerate more than walking across the room.

In still other patients, cardiopulmonary insufficiency appeared and was markedly accentuated during mild upper respiratory infections. The following case illustrates this point.

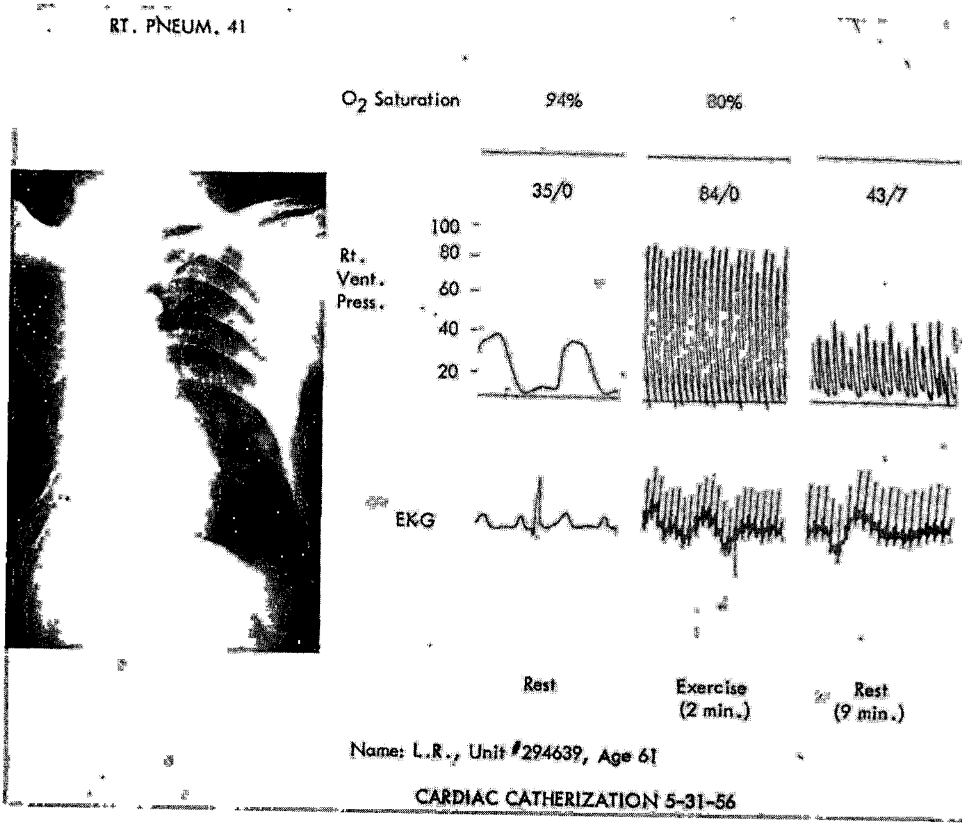
CASE 7.—This patient was a 61-year-old white man (L. R., Case 7) who had had a right pneumonectomy for bronchogenic carcinoma 13½ years previously at the age of 47.

Two years later, an empyema developed in the right chest for which a Schede thoracoplasty was made. For 10 years following pneumonectomy he was able to do full-time office work without any evidence of a cardiopulmonary problem. At the end of that time, there developed one-flight exertional dyspnea and a mild nonproductive cough. Physical examination showed signs of mild decompensation. He had had a mild upper respiratory infection prior to admission which had accentuated his dyspnea. Pulmonary function studies showed relatively normal values, except for a low maximum breathing capacity. His oxygen saturation at rest was 94 per cent. Cardiac catheterization showed a pressure of 35/0 mm. Hg. With only moderate exercise, his pressures elevated to 84/0 mm. Hg and the saturation was lowered to 80 per cent of normal. With the subsidence of his upper respiratory infection, his symptoms became much relieved and he continued his routine work. When the cardiopulmonary studies were repeated 2 years later, 15½ years following pneumonectomy, the pulmonary function values were somewhat diminished and arterial oxygen saturation was 94 per cent. Pulmonary artery pressure at this time was only mildly elevated but became almost doubled in amount on moderate exercise. The oxygen saturation, however, was not lowered by exercise. This patient has subsequently become gradually less able to carry on his work without difficulty. Although not a pulmonary cripple at the present time, he has had to reduce his activities and lead a very sedentary type of life (Fig. 11, *A* and *B*).

In older patients who underwent surgery after the age of 60, acute or chronic pulmonary hypertension was more likely to develop than in patients under 50 years of age. Although our clinical data are as yet insufficient percentagewise for prognostication, patients over 60 years of age are more likely to develop pulmonary hypertension sooner than are those patients whose surgery was performed before 50 years of age. This would suggest that if surgery is performed in the younger age group, a degree of compensation may occur over a period of years following surgery which will offset the development of chronic pulmonary hypertension. The following case is an illustration of this point.

CASE 8.—This patient was a white man, 66 years of age at the time of pneumonectomy (J. S., Case 8), whose convalescence after operation was quite satisfactory. Within 5 years following operation, he began showing an increasing amount of dyspnea on mild exertion. Eight years later, he was having much more difficulty and was admitted for study. Pulmonary function data indicated a moderate to severe degree of reduction in maximum breathing capacity and timed vital capacity. In spite of this, the oxygen saturation was 96 per cent. Pulmonary artery pressures at rest were markedly elevated to 75/35 with a mean of 48 mm. Hg. On moderate exercise, this rose to 112/45 with a mean of 67, at which time the oxygen saturation had dropped to 90 per cent. He was put on digitalis and reduced activity with considerable relief of symptoms. However, in spite of this regimen, his degree of incapacitation continued to increase. He died suddenly of cardiac decompensations, having been a pulmonary cripple during the preceding 4 or 5 years (Fig. 12).

This study has led us to believe that a number of things may be considered when accurate determinations of the pulmonary and circulatory status are made prior to, or at the time of, surgery for pulmonary abnormalities. In the case of nonmalignant pulmonary lesions, added precautions may be taken to insure adequate cardiopulmonary reserve following surgery. In some conditions, a preoperative period of medical management may alter the pulmonary lesion to such an extent that cardiopulmonary reserve may be enhanced and



A.

FUNCTIONAL CLASS III.

T.L.C.	2.8 L.
V.C.	1.2 L. (34%)
R.V.	1.6 L.
M.B.C.	31.0 L./min. (34%)
1 sec V.C.	71%

	Rest	Exer.
Pulm. Art. Press.	38/13 (21)	56/30 (39)
Art. O_2 Sat.	94%	95%
Pulse Rate	88.0	116.0
O_2 Consumption	206.0	591.0
Cardiac Output (L./min.)	3.2	6.3

L.R. 63 M,
15 1/2 yrs. post-right pneumonectomy & thoracoplasty

B.

Fig. 11.—Case 7 (L. R.). *A*, Roentgenogram of chest and data obtained on cardiopulmonary evaluation 13½° years after a right pneumonectomy; *B*, the same information obtained 2 years later, namely, 15½ years postpneumonectomy. The data obtained in *A* were shortly after an upper respiratory infection which had led to some degree of cardiac decompensation. Note a lowering of pulmonary function values as well as an increased amount of lesser circulatory pressure at the time of this patient's infection as compared to that obtained after the infection had subsided. (Same key as in Fig. 10.) (*B*, From Harrison et al.[20])

surgery made less hazardous. In a case of neoplastic disease in which the lesion is peripherally located and reserve appears to be limited, removal of less than an entire lung may well be adequate for ablation of all tumor-bearing tissue. Although total pneumonectomy may be the procedure of choice in most of these patients, many long-term survivals have been reported following ablation of one or two lung lobes. When it is essential to remove an entire lung in patients with low cardiopulmonary reserve, the employment of various measures for supporting the individual through surgery may insure a more satisfactory result. Since increased pulmonary resistance requires a greater right heart load with increased pulmonary pressures for the maintenance of adequate cardiac output, reduction of activity through sedentary types of employment, restriction of other physical activities, and the prevention of pulmonary infections may go far in preventing the development of a "pulmonary cripple."

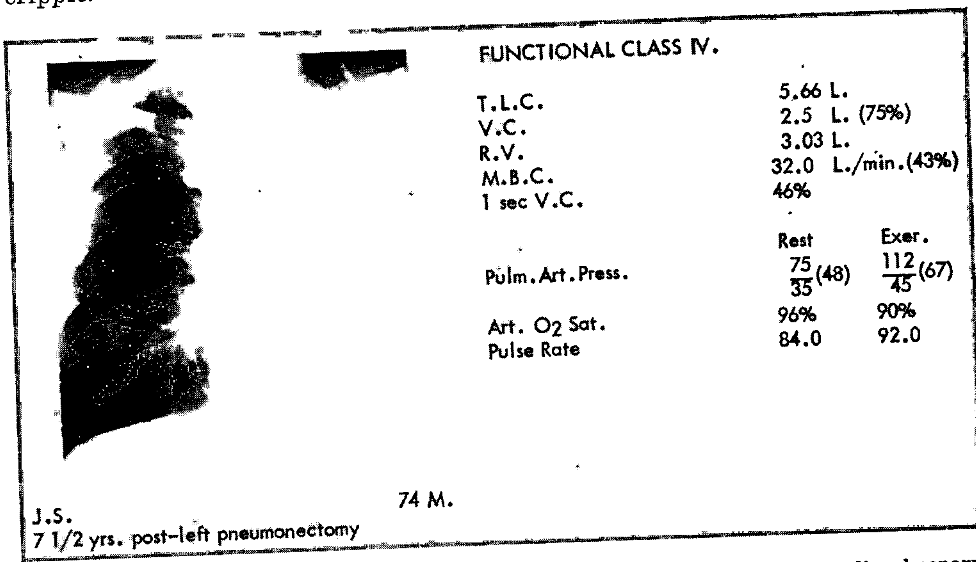


Fig. 12.—Case 8 (J. S.). Roentgenogram of chest and data collected at cardiopulmonary evaluation on a 74-year-old white man 7½ years after a left pneumonectomy. Note some lowering of pulmonary function values with, however, a normal arterial oxygen saturation during rest. The pulmonary artery pressures in this patient were extremely high and became markedly elevated with moderate exercise. (Same key as in Fig. 10.) (From Harrison et al.[20])

The modern trend in pulmonary surgery is to conserve on the amount of lung resected. Furthermore, attempts are made to re-establish functioning lung tissue when it has been disabled by disease or trauma. An example of this is seen in the use of bronchoplasty following bronchial stenosis due to pulmonary tuberculosis. Another example is the re-aeration of an atelectatic lung following traumatic stenosis of a primary bronchus. The report given this morning by Dr. Long and his co-workers was another step forward in this direction. Progress has been made in this field by several workers[21-24] who have reported a number of instances of successful re-aeration of an atelectatic lung. Studies have at times not been available by which to determine the physiologic status of these re-aerated lungs. It is hoped that in the future, surgeons who have this opportunity may make physiologic studies which will determine if the human lung reacts in a manner similar to that of the dog's lung in a state of chronic atelectasis. Although the studies reported by Dr. Long show that a re-inflated atelectatic lung in dogs has only 25 to 30 per cent of its original functional value, nonetheless this small amount of function may mean considerable to the individual as cardiopulmonary reserve diminishes during later years. Furthermore, the functioning lung tissue would then be distributed to both sides of the tracheobronchial tree.

Time has not permitted giving credit to the many workers who have made valuable contributions in this field. This will appear in the published article. In addition, I wish to give a full measure of credit to Drs. Harrison, Long, Reimann, Benfield, Nigro, Attalla, Borquez Vial, Mikouchi, and Shankarappa, who have contributed materially in the investigative work referred to in this discussion. With the continuing increase in life expectancy, this problem in connection with lung surgery assumes an increasing importance. Much more work needs to be done and a step in this direction is replacement of a diseased lung by transplantation of a healthy one. Transplantation of liver, spleen, kidney, lung[25] and other organs has proved to be technically assured. Inroads on the problem of the tissue "rejection phenomenon" are gradually being made. With continued united effort, scientific endeavor, and imagination, what is impossible today may be an accepted procedure in the not-too-distant future.

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