STUDIES OF TOTAL PULMONARY CAPACITY AND ITS SUBDIVISIONS

IX. RELATIONSHIP TO THE OXYGEN SATURATION AND CARBON DIOXIDE CONTENT OF THE ARTERIAL BLOOD [1]

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An index of the efficiency of the exchange of carbon dioxide and oxygen between the circulating blood and the alveolar air may be derived from the analysis of the arterial blood. However, it must be born in mind that changes in the gaseous content of the blood leaving the lungs may be brought about by a multiplicity of respiratory and circulatory factors, so that the proper interpretation of the results presents considerable difficulties. Although numerous analyses of arterial blood have been made in various pulmonary conditions, a review of the literature reveals very few attempts to correlate these studies with simultaneous studies of the external respiration. This is particularly true in the case of chronic pulmonary diseases, the fibroses and emphysema of the lungs. We have presented in previous communications (1) (2), evidence showing that the changes observed in the total pulmonary capacity and its subdivisions in cases of pulmonary emphysema and fibrosis are closely related to the anatomical alterations and tend to be correlated with the degree of clinical respiratory disability. The purpose of this communication is to correlate the alterations in the gaseous content of the arterial blood with the pulmonary capacities in 37 cases of pulmonary fibrosis and in 24 cases of pulmonary emphysema.

REVIEW OF THE LITERATURE

The feasibility of obtaining arterial blood by puncture was first demonstrated by Hürter (3) in 1912, and several years later Stadie (4) in 1919, introduced the technique into this country.

Normal values. A summary of the investigations made on the carbon dioxide content and oxygen saturation of the arterial blood of normal individuals is presented in Table I. A total of 37 observations on the oxygen saturation of healthy adult male subjects have been collected from the works of Harrop (5) in 1919, Meakins (6) in 1920, Himwich and Barr (7) and Barcroft and others (8) in 1923 and Hurtado, Kaltreider and McCann (9) recently. With the exception of three cases, two reported by Himwich and Barr and one by Meakins the arterial oxygen saturation has been found to be always above 94 per cent, so that this may be adopted as the lowest normal value. In Meakin's observation the subject was in poor physical condition at the time of the investigation.

There is less agreement in regard to the normal carbon dioxide content of the arterial (whole) blood than in the case of oxygen content. We have been able to collect 35 observations made on adult male subjects reported by Harrop (5) in 1919, Meakins (6) in 1920, Barr, Himwich and Green (10) in 1923, Burwell and Robinson (11) in 1924 and Hurtado, Kaltreider and McCann (9) in a recent publication. The results varied between 40.8 and 54.69 volumes per cent, and in consequence it appears difficult to establish the limits of normal variation. It is possible that technical errors may account for some of the abnormally high and low levels reported and it must also be remembered that the amount of this gas in the arterial blood is susceptible to variations depending on abnormalities in the breathing at the time when the blood is drawn. The limits of normal variation may be placed, somewhat arbitrarily, at 42.0 and 52.0 volumes per cent.

Observations in pulmonary diseases. Numerous analyses of arterial blood have been made

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TABLE I

Normal values for CO_2 content and O_2 saturation of the arterial blood (collected from the literature)

Investigators	Number of cases	CO_2 content		O_2 saturation	
		Average	Variations	Average	Variations
		volumes per cent	*volumes per cent*	*per cent*	*per cent*
Harrop (1919)	10	49.69	44.58 to 54.69		
	15			96.4	94.3 to 100
Meakins (1920)	7	52.7	52.1 to 54.2		
	11			95.3	93.8 to 96.3
Barr, Himwich, Green (1923)	8	47.85	40.8 to 50.9		
Himwich, Barr (1923)	5			94.4	93.2 to 96.1
Barcroft and others (1923)	4			95.5	95 to 97
Burwell and Robinson (1924)	8	46.68	44.75 to 50.30		
Authors (1934)	2	46.82	43.71 to 49.97	97.5	95.3 to 99.7

in cases of pneumonia. A decrease in the oxygen saturation has been found to occur in most cases at some stage of the disease, and evidence of this change has been presented by Stadie (4) (12) in 1919 and 1922, Barach and Woodell (13) and Meakins (14) in 1921, Hastings, Neill, Morgan and Binger (15) in 1924, Binger, Hastings and Sendroy (16) in 1927, Binger and Davis (17), Davis (18) and Binger (19) in 1928. That no significant change occurs in the carbon dioxide content of the arterial blood of patients with pneumonia has been reported by some of these investigators (15) (16). That a decrease in the oxygen saturation of the arterial blood is a frequent finding in cases of pulmonary emphysema has been demonstrated by several observers: Meakins (14) in 1921, Campbell, Hunt and Poulton (20) in 1923, Himwich and Loebel (21) in 1928, Kountz, Alexander and Dowell (22) in 1929 and very recently by Christie (23). An increase in the carbon dioxide content of the arterial blood in this disease has been found by Scott (24) and Meakins and Davies (25).

Few investigations of the gas content of the arterial blood have been made in pulmonary tuberculosis. Dautrebande (25) in 1925 observed no alteration in incipient cases, while in those patients with advanced and extensive lesions the oxygen saturation was reduced and the carbon dioxide content increased. Identical results were obtained by Pomplun (26) in 1928, while Hilton (27) failed to find any significant abnormality of these values in nine cases.

Still fewer observations have been made in cases of pulmonary fibrosis. Of the three cases studied by Cossio and Berconsky (28) in 1932 only one appears to be uncomplicated by emphysema, and in this case the saturation of the arterial blood was reduced to 75.2 per cent. In five cases of pneumonokoniosis studied in the copper mines of the Peruvian Andes, at 15,000 feet, one of us (A. H.) observed an average arterial saturation of 77.8 per cent, in contrast with the corresponding normal value of 83.4 per cent for such an altitude, while the carbon dioxide content was not significantly altered, taking into consideration the normal value found at that altitude (unpublished observations).

It has been assumed (29) (30), that edema of the alveolar walls causes marked alterations in the diffusion of the respiratory gases, and this assumption seems to be corroborated by experimental work on animals (31) (32).

MATERIAL AND METHODS

Analyses of the carbon dioxide content and of the oxygen saturation of the arterial blood have been made in 37 cases of pulmonary fibrosis and in 24 cases of pulmonary emphysema. All of the subjects were adult males. A complete presentation of the clinical and roentgenographic studies, and of the different measurements in chest ex-

TABLE II

Carbon dioxide content and oxygen saturation of arterial blood in cases of pulmonary emphysema

Case number	Arterial Blood				Pulmonary Capacity							
					Vital capacity		Mid capacity		Residual air		Ratio	Ratio
	CO_2 content	O_2 content	O_2 capacity	O_2 saturation	Observed value	Difference from normal	Observed value	Difference from normal	Observed value	Difference from normal	Residual air / Total capacity	Mid capacity / Total capacity
	volumes per cent	*volumes per cent*	*volumes per cent*	*per cent*	*liters*	*per cent*	*liters*	*per cent*	*liters*	*per cent*	*per cent*	*per cent*
1	50.19	19.08	19.94	95.6	4.95	− 7.9	3.72	+41.9	2.64	+74.8	34.8	49.1
2	49.30	17.30	23.70	72.9	1.72	−60.9	5.36	+150.4	4.54	+267.7	72.5	85.6
3	48.81	19.16	21.63	88.6	2.34	−54.0	4.67	+88.3	3.87	+170.6	62.4	75.2
4	41.00	21.37	21.84	97.7	3.52	−26.5	3.09	+38.5	2.25	+66.6	39.0	53.5
5	43.01	20.60	21.40	96.4	3.76	−26.9	3.36	+36.8	2.33	+60.7	38.2	48.1
6	43.51	20.56	22.09	93.1	3.50	−30.2	2.67	+ 9.4	2.05	+45.4	36.9	48.1
7	51.32	17.88	19.94	89.7	2.78	−39.3	3.48	+55.1	2.50	+93.9	47.3	65.9
8	46.67	20.40	25.50	80.0	2.70	−52.3	6.56	+137.6	5.82	+266.6	68.3	77.0
9	47.06	20.46	22.57	90.6	3.18	−38.2	3.10	+23.5	2.28	+57.2	42.2	57.4
10	47.59	20.52	25.76	79.6	3.05	−54.2	4.67	+43.7	3.59	+90.9	54.1	70.4
11	49.00	18.60	19.90	93.4	1.94	−60.6	3.81	+58.7	2.83	+103.6	59.3	79.8
12	45.99	17.66	20.61	85.7	2.34	−55.4	3.51	+37.1	3.15	+112.8	57.3	63.9
13	43.76	20.91	23.91	87.4	3.06	−38.3	3.18	+31.4	2.66	+90.0	46.5	55.5
14	48.96	16.07	19.08	84.2	2.68	−46.0	4.30	+77.5	3.68	+162.8	57.8	67.6
15	40.73	22.80	23.93	95.3	3.54	−22.3	2.65	+19.3	1.63	+27.3	31.5	51.2
16*	55.33	17.52	23.58	74.3	0.86	−85.4	3.87	+34.8	3.61	+117.4	80.7	86.5
17*	48.19	17.37	21.16	82.1	1.20	−81.5	3.14	−0.9	2.96	+61.7	71.1	75.4
18†	55.59	15.69	19.26	81.5	2.09	−64.1	6.25	+120.0	5.77	+251.8	73.4	79.5
19†	44.04	14.34	15.58	92.0	1.68	−59.1	3.12	+56.0	2.80	+141.4	62.5	69.6
20†	45.71	20.01	21.73	92.0	3.45	−37.5	4.93	+83.2	4.23	+172.9	55.0	64.2
21†	48.66	19.91	21.62	92.1	2.08	−45.9	3.16	+68.9	2.86	+164.8	57.9	63.9
22†	42.34	17.69	19.65	89.9	2.92	−33.5	2.17	+ 1.4	1.71	+39.0	36.9	46.8
23†	45.11	16.34	18.18	89.9	2.12	−54.0	2.75	+22.8	1.91	+46.9	47.4	68.2
24†	58.16	17.57	20.31	86.5	1.66	−68.0	3.46	+36.7	2.58	+76.7	60.9	81.5

* Diagnosis of emphysematous cysts also made.
† Diagnosis of pulmonary fibrosis also made.

pansion and pulmonary capacity of these patients has been made in previous publications (1) (2), and need no repetition here. Most of the cases of pulmonary fibrosis belonged to the group of pneumonokoniosis. The blood was obtained by puncture of the radial artery after the patients had had a preliminary rest of at least 15 minutes, and just prior to the determination of pulmonary capacity. Most of the patients were in the recumbent position. The usual precautions were observed to prevent exposure of the blood to the air. The analyses were carried out according to the method of Van Slyke and Neill (33) in their manometric apparatus, within two or three hours after the blood had been drawn.

OBSERVED VALUES OF THE OXYGEN SATURATION AND CARBON DIOXIDE CONTENT OF THE ARTERIAL BLOOD

The results of the determinations of the blood gases, together with the most important findings in regard to the pulmonary capacities of all cases studied are presented in Tables II, and III, and summarized for both pulmonary fibrosis and emphysema in Table IV. A comparison of the findings in both diseases is made in Figure 1.

Oxygen saturation. Twenty-four cases of pulmonary emphysema varied between 72.9 and 97.7 per cent saturation of the arterial blood with oxygen with a mean value of 88.2 per cent, a value which is very definitely less than normal. In twenty cases (83.3 per cent) it was below the lower normal limit, 94 per cent, and in fourteen of these (58.8 per cent) the saturation was less than 90 per cent. The mean value for the oxygen combining capacities was well within the normal limits in this group of patients with emphysema but the oxygen content was significantly decreased.

In the thirty-seven cases of pulmonary fibrosis the mean value for the oxygen saturation of the arterial blood was 92.0 per cent. It varied between 80.6 and 98.5 per cent, and in twenty-six

TABLE III

Carbon dioxide content and oxygen saturation of arterial blood in cases of pulmonary fibrosis

Case number	Arterial Blood				Pulmonary Capacity,							
	CO_2 content	O_2 content	O_2 capacity	O_2 saturation	Vital capacity		Mid capacity		Residual air		Ratio Residual air / Total capacity	Ratio Mid capacity / Total capacity
					Observed value	Difference from normal	Observed value	Difference from normal	Observed value	Difference from normal		
	volumes per cent	*volumes per cent*	*volumes per cent*	*per cent*	*liters*	*per cent*	*liters*	*per cent*	*liters*	*per cent*	*per cent*	*per cent*
1	44.25	21.14	22.08	95.7	3.02	−36.0	2.53	+10.0	1.79	+34.6	37.2	52.5
2	46.20	18.88	23.25	81.2	2.32	−41.8	1.85	− 5.1	1.31	+15.9	36.0	50.9
3	39.62	19.30	20.32	95.4	2.10	−52.0	2.06	− 3.7	1.72	+38.7	45.0	53.9
4	42.70	19.39	21.08	92.0	1.54	−55.7	1.55	− 8.3	1.21	+23.5	44.0	56.3
5	44.95	20.80	22.46	92.7	3.00	−29.2	2.68	+30.1	1.94	+63.0	39.2	54.2
6	46.62	17.93	20.69	86.6	2.18	−62.9	2.87	0	2.13	+26.0	49.4	66.6
7	43.85	20.23	22.34	91.0	3.90	−25.4	4.80	+88.2	3.16	+115.0	44.8	67.9
8	42.09	20.88	22.76	91.7	2.78	−30.0	1.33	−31.1	1.11	− 0.8	28.5	34.1
9	42.00	21.60	22.57	95.7	2.68	−41.3	2.10	− 5.8	1.68	+30.3	38.5	48.1
10	43.87	19.26	20.77	92.2	2.22	−41.7	2.65	+48.6	2.11	+97.2	48.7	61.2
11	47.39	19.99	22.90	87.3	2.24	−50.3	2.23	+ 1.4	1.75	+37.8	43.8	55.8
12	44.73	17.50	20.37	85.9	2.30	−42.3	2.03	+ 4.1	1.71	+51.3	42.6	50.6
13	43.34	21.35	22.54	94.7	2.84	−29.1	1.79	− 8.2	1.37	+21.2	32.6	42.5
14	47.63	18.17	19.87	91.4	3.36	−27.2	3.00	+33.3	2.48	+92.2	42.5	51.3
15	47.53	20.35	21.95	92.7	3.08	−39.9	3.03	+21.2	2.09	+44.1	40.4	58.6
16	55.21	21.18	26.27	80.6	1.44	−71.8	2.22	−10.8	1.86	+29.1	56.4	67.3
17	46.54	18.67	19.98	93.4	2.92	−30.4	2.08	+ 1.9	1.14	− 3.4	28.1	51.2
18	41.40	19.50	20.82	93.6	3.26	−34.5	2.94	+21.4	2.20	+57.1	40.3	53.8
19	46.15	17.04	18.70	91.1	2.88	−28.7	1.98	+ 0.5	1.14	0	28.3	49.2
20	39.35	19.79	21.16	93.5	3.49	−28.2	2.95	+24.4	2.35	+71.5	40.3	50.5
21	46.57	18.20	19.59	92.9	3.15	−33.4	2.44	+ 6.0	1.84	+38.3	36.9	48.9
22	45.11	22.45	24.86	90.3	1.56	−59.3	1.34	−28.3	1.14	+ 5.5	42.3	49.6
23*	41.75	21.20	22.57	93.9	3.26	−33.4	2.20	− 7.9	1.52	+10.1	31.8	45.9
24	48.37	18.42	20.04	91.9	2.20	−43.3	1.84	− 2.6	0.68	−37.6	23.6	63.8
25	47.80	18.70	19.78	94.5	3.52	−14.1	2.21	+10.5	1.57	+35.3	30.9	43.4
26	40.65	21.85	22.61	95.0	3.68	−20.6	1.66	−26.2	1.22	− 6.1	24.9	33.8
27	44.08	17.75	18.92	93.9	4.04	−13.7	2.45	+ 7.4	1.69	+28.0	29.5	42.8
28	43.08	20.88	22.76	91.7	3.18	−29.7	1.26	−42.7	0.94	−25.9	22.8	30.6
29	46.86	20.94	24.13	86.7	1.72	−67.6	2.54	− 1.9	2.38	+52.0	58.0	61.9
30	42.09	16.89	18.07	93.5	3.55	−26.0	2.15	− 8.1	1.65	+22.0	31.7	41.3
31	43.26	19.91	20.67	96.3	3.79	−14.6	2.04	− 5.5	1.32	+ 5.6	25.8	39.9
32	42.85	19.79	20.22	97.8	3.06	−26.8	1.55	−23.6	0.99	−15.4	24.4	38.2
33	45.66	19.92	20.70	96.2	3.08	−31.1	2.83	+29.8	2.27	+80.1	42.4	52.9
34	46.07	19.58	20.72	94.5	3.96	−28.3	3.55	+31.9	2.53	+63.2	38.9	54.7
35	44.37	18.75	20.15	93.0	3.14	−29.9	1.75	−19.7	1.13	−10.3	26.4	40.9
36	42.90	19.00	19.28	98.5	2.73	−32.2	1.57	−19.9	0.87	−23.0	23.9	43.2
37	51.83	16.39	17.49	93.7	2.26	−57.3	3.91	+51.4	3.07	+106.0	57.6	73.4

* Diagnosis of bronchiectasis also made.

TABLE IV

Summary of the values with respect to arterial blood and pulmonary capacity in cases of pulmonary fibrosis and emphysema

	Pulmonary Fibrosis (37 cases)				Pulmonary Emphysema (24 cases)			
	Mean	Standard deviation	Coefficient of variation	Variations	Mean	Standard deviation	Coefficient of variation	Variations
			per cent				*per cent*	
Arterial Blood								
CO_2 content, *volumes per cent*	44.89±0.34	3.06	6.8	39.35 −55.21	47.67±0.60	4.38	9.2	40.73 −58.16
O_2 content, *volumes per cent*	19.50±0.16	1.44	7.4	16.39 −22.45	18.75±0.27	1.96	10.4	14.34 −22.80
O_2 capacity, *volumes per cent*	21.20±0.20	1.83	8.6	17.49 −26.27	21.29±0.24	2.22	10.4	15.58 −25.76
O_2 saturation, *per cent*	92.0 ±0.47	3.9	4.2	80.6 −98.5	88.2 ±0.92	6.7	7.6	72.9 −97.7
Pulmonary Capacity								
Vital capacity, *liters*	2.87±0.07	0.69	24.0	1.44 − 4.04	2.63±0.13	0.92	34.9	0.86 − 4.95
Mid capacity, *liters*	2.32±0.08	0.73	31.4	1.33 − 4.80	3.79±0.14	1.02	26.9	2.17 − 6.56
Residual air, *liters*	1.71±0.06	0.56	32.7	0.68 − 3.16	3.12±0.15	1.09	34.9	1.63 − 5.82
Ratio residual/Total capacity, *per cent*	37.1 ±1.07	9.7	26.1	22.8 −58.0	53.7 ±1.82	13.2	24.6	31.5 −80.7
Ratio Mid/Total capacity, *per cent*	50.7 ±1.08	9.8	19.3	30.6 −73.4	66.0 ±1.72	12.5	18.9	46.8 −86.5

cases (70.3 per cent) it was below the lower normal limit of 94 per cent. In contrast with the group having emphysema it was below 90 per cent in only six patients, 16.2 per cent. These results show that the saturation of the arterial blood with oxygen is affected less in cases of pulmonary fibrosis than in those with emphysema. The oxygen combining power was almost identical in both groups of cases but in the group with fibrosis the average oxygen content of the arterial blood was higher.

Carbon dioxide content. The mean value for the carbon dioxide content of the arterial blood in the cases of pulmonary emphysema was 47.67 volumes per cent, with the extreme variations between 40.73 and 58.16 volumes per cent. The values observed were scattered between the normal limits of variation, and in only three cases did the results indicate an abnormally high content.

In the patients with pulmonary fibrosis the mean value observed was 44.89 volumes per cent with variations between 39.35 and 55.21 volumes per cent. Referring to Figure 1, it will be noted that most of the results obtained in this condition were grouped near the lower normal limits of variation, and in one case only was the value abnormally high. These observations indicate that a higher carbon dioxide content is found in cases of pulmonary emphysema than is usual with those of fibrosis.

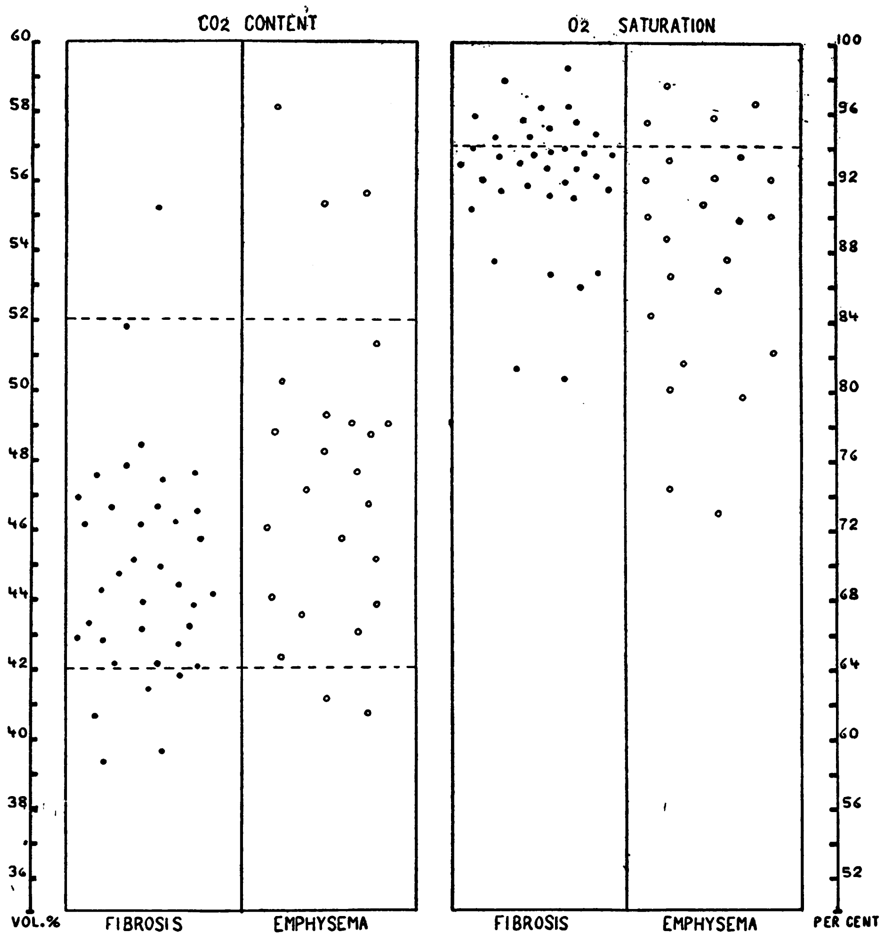

FIG. 1. CARBON DIOXIDE CONTENT AND OXYGEN SATURATION OF THE ARTERIAL BLOOD IN 24 CASES OF PULMONARY EMPHYSEMA (CIRCLES) AND 37 CASES OF PULMONARY FIBROSIS (DOTS).

TABLE V

O_2 saturation of the arterial blood and its relationship to the pulmonary capacity in cases of pulmonary fibrosis and emphysema

O_2 saturation	Average Values							
	Vital capacity *per cent from normal*		Mid capacity *per cent from normal*		Residual air *per cent from normal*		Ratio $\frac{\text{Residual air}}{\text{Total capacity}} \times 100$	
	Fibrosis	Emphysema	Fibrosis	Emphysema	Fibrosis	Emphysema	Fibrosis	Emphysema
per cent								
94 to 100	−29.6	−20.9	+1.0	+34.1	+24.0	+ 57.3	33.1	35.9
90 to 94	−34.8	−45.2	+9.3	+49.9	+34.8	+114.2	36.4	52.3
85 to 90	−55.7	−48.9	+0.9	+38.9	+41.8	+ 90.0	48.4	51.2
80 to 85	−56.8	−60.9	−7.7	+83.5	+22.5	+185.7	46.2	67.6
75 to 80		−54.2		+43.7		+ 90.9		54.1
70 to 75		−73.1		+92.6		+192.5		76.6

Correlation of the gaseous content of the arterial blood with the pulmonary capacity

Oxygen saturation. The relationship of the oxygen saturation of the arterial blood to the various observations of the pulmonary capacity is summarized in Table V. We have been especially interested in the comparison of the degree of anoxemia with the ratio $\frac{\text{Residual air}}{\text{Total capacity}} \times 100$. From observations which we have made in cases of pulmonary emphysema and fibrosis it appears that this ratio gives, as a rule, a fair index of the abnormality of the respiratory mechanism in these conditions and that it is well correlated with the degree of disability.

A comparison of the degree of oxygen saturation of the arterial blood with the value of the ratio in cases of pulmonary emphysema is presented in Figure 2. It reveals a definite tendency for the saturation to decrease as the ratio in-

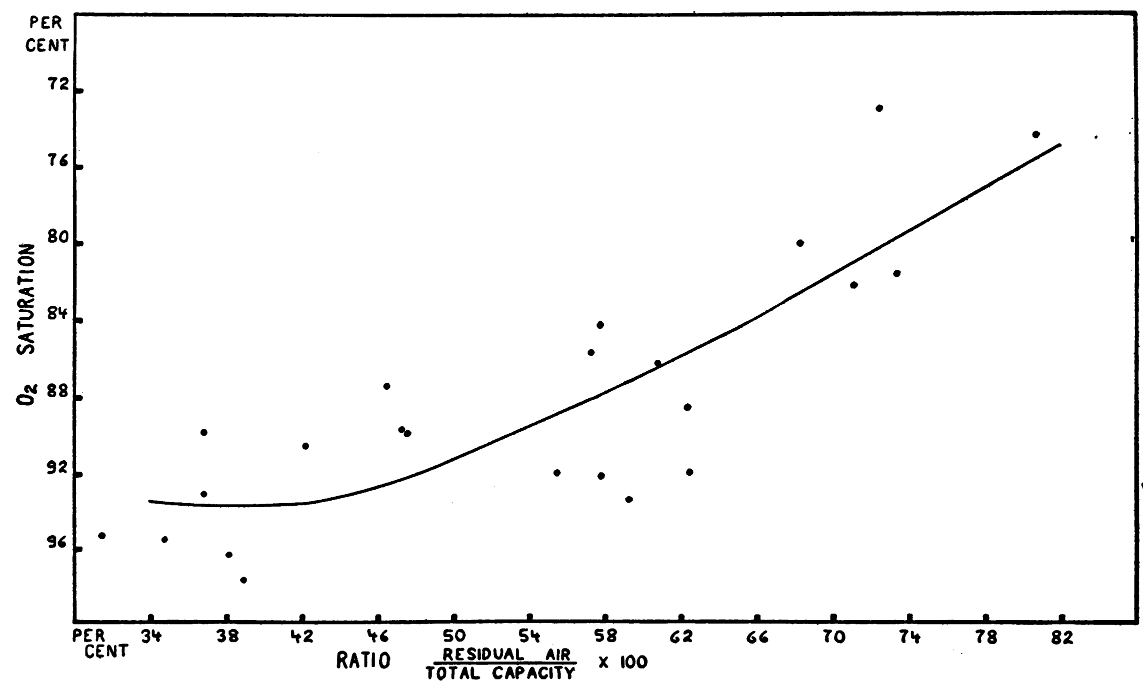

FIG. 2. CORRELATION OF THE OXYGEN SATURATION OF THE ARTERIAL BLOOD WITH THE RATIO OF RESIDUAL AIR TO TOTAL PULMONARY CAPACITY IN 24 CASES OF PULMONARY EMPHYSEMA.

Curve is a mathematically calculated logarithmic curve.

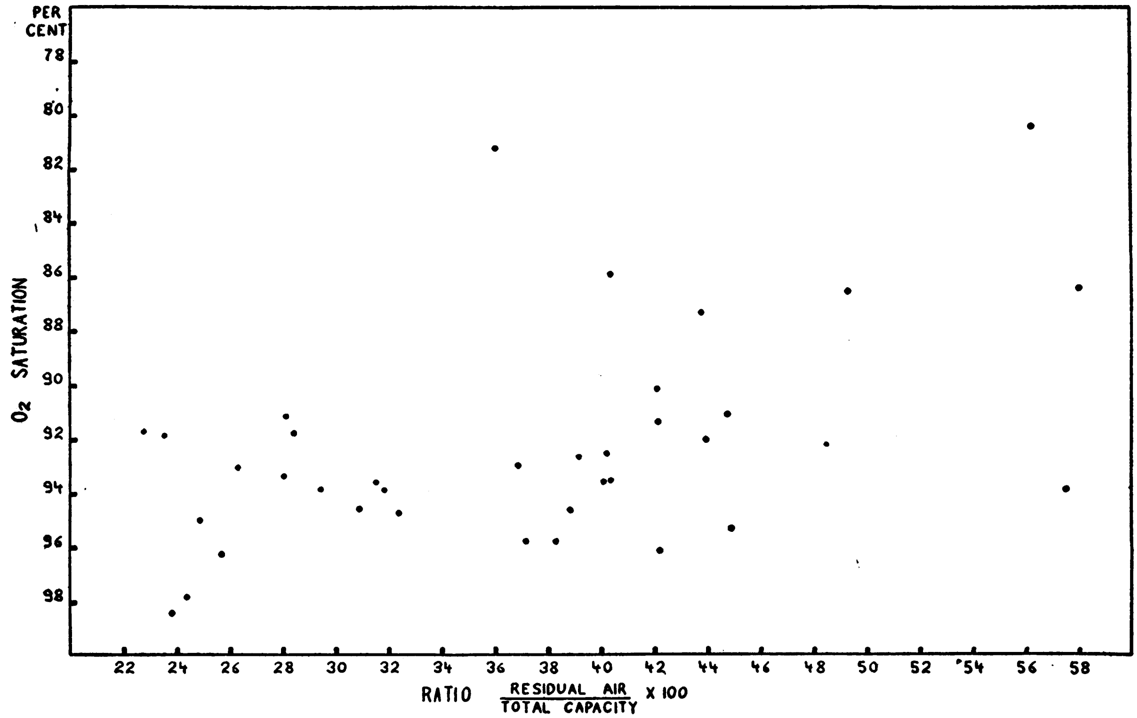

FIG. 3. COORDINATION OF THE OXYGEN SATURATION OF THE ARTERIAL BLOOD AND THE RATIO OF RESIDUAL AIR TO TOTAL PULMONARY CAPACITY IN 37 CASES OF PULMONARY FIBROSIS.

creases, although the relationship does not appear to be linear in character. Some degree of anoxemia was present in all instances in which the ratio exceeded 40 per cent. In all cases, but one, in which the ratio was greater than 60 per cent the degree of anoxemia was extreme. The relationship of these same factors in cases of pulmonary fibrosis is shown in Figure 3. Whenever the ratio $\frac{\text{Residual air}}{\text{Total capacity}} \times 100$ exceeded 45 per cent, all cases, but one, showed some degree of unsaturation, but below this limit there appeared to be no correlation between these two factors. The arterial blood may or may not be saturated with oxygen when the ratio was low, but the degree of anoxemia is very slight in those circumstances, being in no case below 91 per cent. In general the statement is true that when the residual air constitutes 45 per cent or more of the total capacity of the lungs it is usual to find some

TABLE VI

CO_2 content of the arterial blood and its relationship to the pulmonary capacity in cases of pulmonary fibrosis and emphysema

CO_2 content	Average Values							
	Vital capacity *per cent from normal*		Mid capacity *per cent from normal*		Residual air *per cent from normal*		Ratio $\frac{\text{Residual air}}{\text{Total capacity}} \times 100$	
	Fibrosis	Emphysema	Fibrosis	Emphysema	Fibrosis	Emphysema	Fibrosis	Emphysema
volumes per cent								
36 to 40	−40.1		+10.3		+55.1		42.6	
40 to 44	−31.5	−29.6	+ 2.1	+22.8	+22.2	+ 54.7	33.0	38.2
44 to 48	−37.0	−50.1	+ 7.4	+57.7	+36.3	+126.9	38.4	55.2
48 to 52	−50.3	−49.5	+24.4	+67.5	+34.2	+137.5	40.6	57.9
52 to 56	−71.8	−74.8	−10.8	+77.2	+29.1	+184.6	56.4	77.0
56 to 60		−68.0		+36.7		+ 76.7		60.9

degree of anoxemia of the arterial blood and that the degree of anoxemia tends to increase as the ratio increases beyond this limit.

Carbon dioxide content. In Table VI there is a comparative study of the carbon dioxide content of the arterial blood and the pulmonary capacity. The correlation between the ratio

$$\frac{\text{Residual air}}{\text{Total capacity}} \times 100$$

and the carbon dioxide content in all cases investigated, both of pulmonary emphysema and fibrosis, is presented in Figure 4, which shows a definite tendency for the carbon dioxide content to vary directly with the ratio. When all of the cases are grouped on the basis of the relative value of the residual air the average values observed of the oxygen saturation and carbon dioxide content of the arterial blood in each group show a striking relationship to the ratio. The critical value of the ratio at which the average values of the blood gases become definitely abnormal are between 40 and 50 per cent.

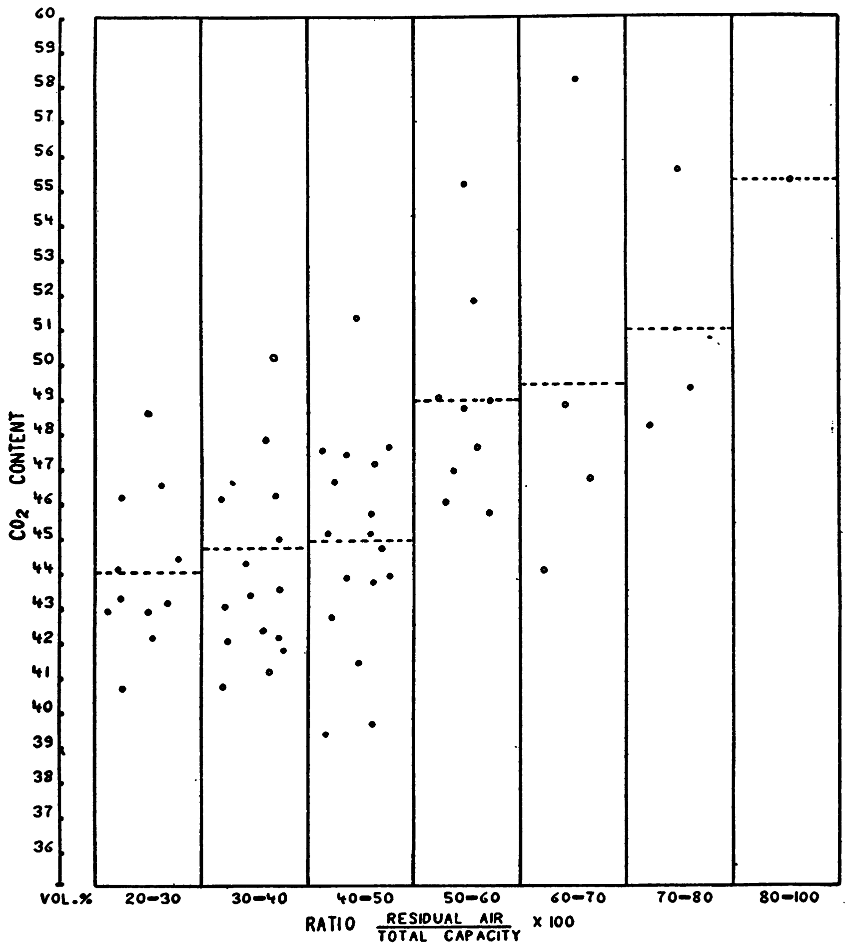

FIG. 4. CORRELATION OF THE CARBON DIOXIDE CONTENT OF THE ARTERIAL BLOOD TO THE RATIO OF RESIDUAL AIR TO TOTAL PULMONARY CAPACITY IN 24 CASES OF PULMONARY EMPHYSEMA (CIRCLES) AND 37 CASES OF PULMONARY FIBROSIS (DOTS).

Broken lines represent the average carbon dioxide content in each group.

DISCUSSION

Although the elimination of carbon dioxide and the absorption of oxygen are mutually dependent processes in certain respects, they may be considered separately. Difficulty in the elimination of carbon dioxide may be partly compensated by an increase in the alkaline reserve of the blood. If, however, some of the blood flowing through the lungs escapes complete aeration the mixed pulmonary blood in the left auricle will be incompletely saturated and arterial anoxemia will be inevitable no matter how much the ventilation and blood flow through normal portions of the lung may be increased.

The factors (apart from a low barometric pressure) which will operate in causing a diminution in the oxygen saturation of the arterial blood are numerous, but they may be ultimately considered from three general points of view: (1) deficient alveolar ventilation (lack of proper mixing, anatomical alterations preventing a free flow of air, shallow breathing); (2) reduced permeability for diffusion (in the alveolar and capillary walls or in the blood itself), and (3) the influence of the abnormalities just mentioned will be modified by the preservation or suppression of the circulation through the affected lung zones. It is evident from this brief consideration that anatomical as well as functional abnormalities of the lung parenchyma may play an etiological rôle in the production of anoxemia, and we may investigate first the extent to which these abnormalities are present in pulmonary emphysema.

Christie (23) has recently published a most complete study of the functional pathology of emphysema. Our own observations of the pulmonary capacity in this condition have been published (1). In both papers the factors entering into the deficient alveolar ventilation and resultant anoxemia of this condition have been reviewed, particularly with reference to the loss of elasticity, the increase in intrapleural and venous pressure, the dilatation of the alveoli, the increase in residual air and the decrease in vital capacity. In the present paper we have endeavored to bring out the relationship between the last two factors and the gas content of the arterial blood.

There is much to suggest that there are great inequalities in the efficiency of ventilation of the alveoli in different parts of the lungs with the result that the mixed pulmonary blood in the left auricle is incompletely saturated with oxygen. By making fractional analyses of a single expiration, Nielson and Sonne (34) have recently demonstrated that the alveolar air is not uniform in composition, even in normal individuals, and suggest that it is quite likely that this lack of uniformity is more pronounced in pulmonary disease. Further studies of this type are being carried on in our laboratory with an improved apparatus. Meakins (6) observed a decrease in the saturation of the arterial blood following the induction of shallow breathing in normal individuals, and expressed the opinion that it is an important mechanism in the anoxemia observed in patients with pneumonia (35). A study of the respiratory tracings in our cases does not disclose the presence of shallow breathing, and it appears that at least during rest it is not a significant factor in the altered haemo-respiratory exchange.

Alterations in the alveolar permeability probably play no rôle in the imperfect oxygenation of the blood in cases of emphysema. Krogh (36) in 1914 found a normal permeability and diffusion constant in three cases of emphysema. Although the possibility of a disturbed permeability cannot be entirely dismissed our observations suggest that deficiency in alveolar ventilation is probably the most important factor.

The explanation of the anoxemia found in pulmonary fibrosis is more difficult. Although there is some evidence (2) to indicate that alterations in elasticity of the lungs probably exist in this condition, the question has not been definitely settled. it is interesting to observe that anoxemia is mainly found when the ratio of residual air to total capacity is over 45 per cent. In this condition, as in pulmonary emphysema, an insufficient alveolar ventilation is a factor which accounts for the anoxemia in part. However, the nature of the anatomical changes in pulmonary fibrosis indicated that in well advanced cases there are dense areas which in all probability receive little or no ventilation, and, if the blood is incompletely shunted from these regions anoxemia will result. We have been unable to find a definite correlation between the degree of anoxemia and the extent of the fibrotic lesions as seen in the roentgenographic film (see Table VII).

Although considerable thickening of the alveolar walls is frequently found at autopsy in cases of pulmonary fibrosis, suggesting that a decreased diffusion of oxygen ("pneumoniosis") may exist in this condition, there is no experimental or direct proof in favor of this assumption.

TABLE VII

*CO_2 content and O_2 saturation of the arterial blood in cases of pulmonary fibrosis arranged in groups according to the roentgenographic appearance.**

Groups*	Number of cases	CO_2 content		O_2 saturation	
		Average	Variations	Average	Variations
		volumes per cent	*volumes per cent*	*per cent*	*per cent*
Group I	17	43.72	39.35–47.80	94.1	91.4–98.5
Group III	12	45.08	39.62–55.21	90.1	80.6–96.3
Group IV	3	44.13	42.00–46.54	93.8	92.2–95.7
Group V	3	48.91	47.39–51.83	91.2	87.3–93.7
Group VI	2	47.61	46.86–48.37	89.3	86.7–91.9

* Group I. Cases which showed increased linear markings in the lung fields.
Group III. Patients included in this group showed nodular shadows.
Group IV. In this group the nodular shadows showed a tendency to agglomerate, giving a mottled appearance.
Group V. Patients in this group presented large dense shadows chiefly in the upper portions of the lung and in addition showed marked emphysema at the bases of the lungs.
Group VI. A fine and diffuse reticular fibrosis involving the whole of the lung fields was present in the cases included in this group.

It should not be assumed that the existence of anoxemia indicates a high degree of disability. To be sure it represents a partial failure of respiratory function, however it has been observed that the natives of high altitudes may live in a condition of constant and marked anoxemia and still exhibit a most surprising adaptation to physical and mental work (37) (38). It is quite possible that the anoxemia which follows the development of chronic anatomical alterations in the lungs leads to some unknown adaptative mechanism, which in this way differs in its significance from the one which results from an acute loss of respiratory function, such as that which occurs in pneumonia, or as a result of a sudden decrease in barometric pressure.

The carbon dioxide content of the arterial blood seems also to have some relationship to the degree of the alterations in pulmonary capacity. An abnormal increase in the content of CO_2 is chiefly observed in cases of pulmonary emphysema in which these alterations are especially marked. This suggests that the same functional abnormalities which have been mentioned in connection with the development of anoxemia are partly responsible for the accumulation of carbon dioxide. However, one finds a severe anoxemia not uncommonly accompanied by a normal carbon dioxide content of the arterial blood. The high carbon dioxide content usually found in cases of pulmonary emphysema is accompanied by an increase of blood bicarbonates. Since the work of Scott (24) this has been interpreted as a mechanism by means of which the emphysematous patient is able to compensate, at least in part, the difficulties in the elimination of carbon dioxide during physical activity.

SUMMARY AND CONCLUSIONS

The oxygen saturation and the carbon dioxide content of the arterial blood have been studied in 24 cases of pulmonary emphysema and in 27 cases of pulmonary fibrosis. Most of the latter were cases of pneumonokoniosis. The findings have been correlated with the degree of alteration in the pulmonary capacity simultaneously determined, and lead to the following conclusions:

1. Anoxemia is a very frequent finding in cases of pulmonary fibrosis and emphysema, but it appears to be much more pronounced in the latter disease.
2. The carbon dioxide content of the arterial blood has been found to be increased chiefly in cases of pulmonary emphysema. Most cases of fibrosis exhibit a rather low normal content of this gas.
3. The degree of unsaturation of the arterial blood with oxygen appears to be definitely correlated with abnormalities in pulmonary capacity, this being chiefly evident in cases of emphysema.
4. When the residual air constitutes 45 per cent or more of the total capacity a certain degree of anoxemia is almost invariably present, both in pulmonary emphysema and fibrosis.
5. Abnormally high values of carbon dioxide in the arterial blood are found in association with a marked increase of the ratio of residual air to total capacity.
6. Though many factors must be considered in connection with the anoxemia of pulmonary emphysema and of pulmonary fibrosis a deficient alveolar ventilation is probably the most important

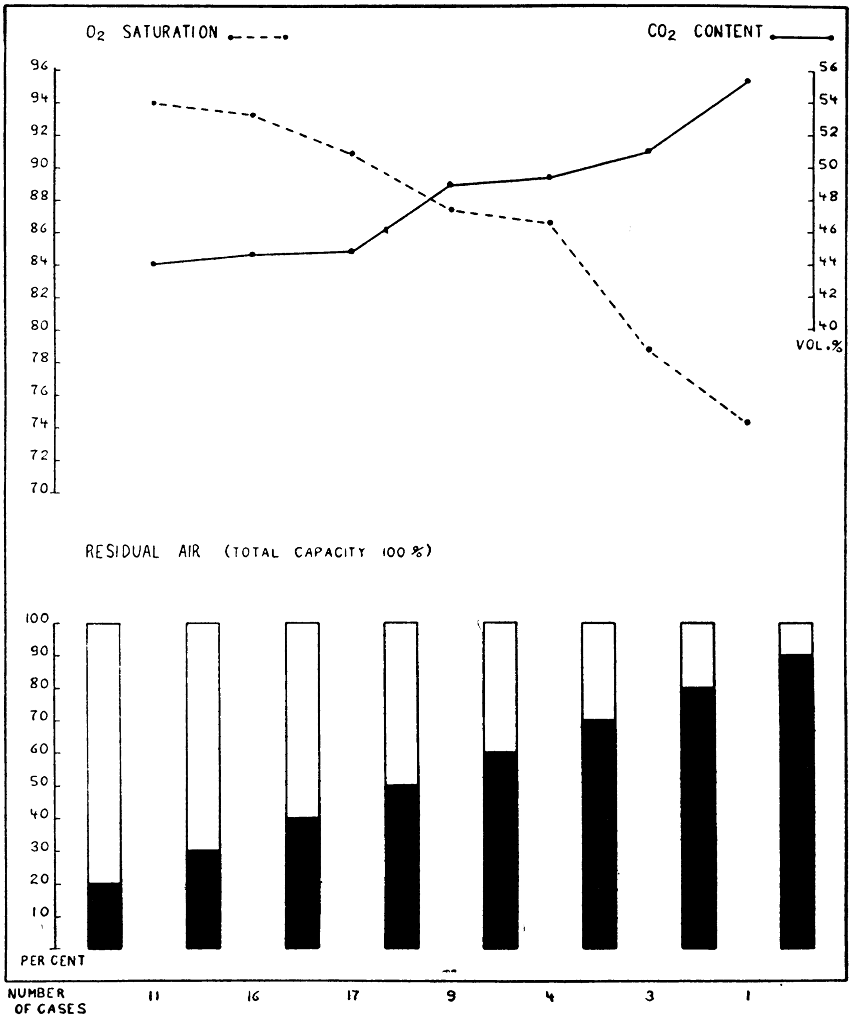

FIG. 5. AVERAGE OXYGEN SATURATION (BROKEN LINE) AND CARBON DIOXIDE CONTENT (SOLID LINE) OF THE ARTERIAL BLOOD OF 61 CASES OF PULMONARY EMPHYSEMA AND FIBROSIS GROUPED ACCORDING TO THE OBSERVED RATIO OF RESIDUAL AIR TO TOTAL CAPACITY.

factor, the best index of which is found in the ratio of residual air to total capacity.

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