THE GENESIS AND FUNCTIONAL IMPLICATIONS OF COLLATERAL CIRCULATION OF THE LUNGS*

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Foreword

Those with the good fortune to be directly under the spell of M. C. W. will not soon forget how frequently and ringingly he uses the word "opportunity." He has become a master at providing opportunity, in his own Department and School, and now in a larger sphere. A few years ago, with the help of the Office of Naval Research, he provided the idea and the means for a collaborative study of pulmonary disease. In encouraging the collaboration of surgeons and pathologists he was striking another blow at departmental barriers that he had always regarded as an impediment to investigation. This progress report covers one phase of the joint effort. Herein, we shall heed the admonition "Respice; Adspice; Prospice." Let us be forgiven if, in the last, we may gaze into the realm of conjecture, rather than upon work accomplished. But, that we not offend him whom we seek to honor, speculation shall be kept separate from fact.

In his Harvey Lecture of 1936, de Burgh Daly[9] stated: "Concerning the significance of the bronchial-arterial system in health and disease, we are still largely in the dark, but that this may be a fruitful field for investigation is unquestionable." Recent observations in several laboratories have to a degree, confirmed his prophecy; still, much darkness remains to be dispelled.

It was known to Galen that the lungs had a double blood supply, but Luschka's[26] concept of the *vasa publica* and *vasa privata* had to await Harvey's elucidation of the course of the circulation. To William Snow Miller[30, 31, 32] is owed much of our knowledge of the vasculature of the lung. A single pulmonary artery slavishly follows and is joined by fascia to each branch of the bronchial tree, but yields it no branches until the first alveoli appear in the walls of the respiratory bronchioles; the pulmonary veins, on the contrary, are as far removed as possible from the broncho-arterial ray. The pulmonary arteries are end arteries; there are no vessels that traverse the lobule to join adjacent branches and there is no confluence of their separate streams except in the capillary beds at the very periphery of the lobule. The bronchial arteries contrast in that, characteristically, even

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though there be but one major trunk from an intercostal or from the aorta to a lung, a plexus is soon formed with at least two major branches, joined by many laterals, distributed within the wall of each bronchus. Thus, the bronchial is the direct antithesis of an end-artery. Normally, communication with the pulmonary artery is only by means of a capillary bed in the walls of the respiratory bronchioles. How much of the blood from the bronchial arteries, if any, normally reaches the walls of the alveoli themselves is not known.

Normally, blood brought to the lung via the bronchial arteries may follow one of two courses in returning to the heart: In the proximal thirds of the major bronchi, some of this blood is brought via the azygous veins to the right auricle; more distally in the bronchial tree, drainage is into the pulmonary veins which thus come to carry small amounts of unoxygenated blood. We have observed in certain lungs, moreover, that even proximally, drainage may be into the pulmonary venous system and that branches of the pulmonary veins may actually extend far out into the mediastinal tissues in company with bronchial arteries, presumably draining tissues supplied by these vessels. It is thus apparent that most of the drainage is into the pulmonary veins.

The bronchial arteries in disease. In chronic disease of the lung in man notable changes take place in the vasculature. It has often been observed[13] that as the capillary bed is reduced by fibrosis, the pulmonary artery may become thickened and restricted in lumen by subendothelial proliferation of connective tissue. Some of the pulmonary arteries, as is common in tuberculosis, may also become thrombosed and recanalized. Less well known, but probably at least as important, are the changes in the bronchial arteries; in fact they have often been mistaken for pulmonary vessels as is apparent in many published illustrations and descriptions. In most types of chronic pulmonary disease the bronchial arteries become markedly enlarged in lumen, although also somewhat varicose and thick-walled. Peripherally, within the diseased tissue they often approach the size of the pulmonary artery at the same level since the latter diminishes much more rapidly in lumen. At the same time, precapillary anastomoses develop between the bronchial and pulmonary arterial systems, but not with the pulmonary veins. The enlargement of the bronchial arteries about tubercles was noted as early as 1845 by Guillot[15] and was demonstrated in various pathological conditions of the lungs by Wood and Miller,[43] who employed a radio-opaque injection mass and roentgenographic technique. In our experience the most striking changes are observed in bronchiectasis where they had not previ-

ously received adequate study. In bronchiectasis, as demonstrated in vinylite bronchovascular casts,[24] the bronchial arteries usually form a dense plexus of sizable, thick-walled, but large-lumened channels, and their anastomoses with the pulmonary artery may have a diameter as large as 2 mm. (Figs. 11 and 12). We have not found evidence of precapillary connections between pulmonary arteries and veins, as suggested by the observations of Prinzmetal[33] and his co-workers, except in congenital "hemangiomas" of the lung. In congenital heart disease with pulmonic stenosis, the plexuses of collateral vessels may become very extensive[16] (Fig. 1). In this condition, the bronchial arteries may directly join pulmonary arteries close to the hilum, while in bronchiectasis, the anastomoses are situated distally in the walls of the bronchiectatic sacs that usually involve branches of the segmental bronchi of the third and fourth orders. In tuberculosis and other chronic fibrosing disease, where much of the alveolated tissue and its rich capillary bed have been destroyed, the bronchial arteries and their anastomoses are less well developed than in bronchiectasis where there is usually less destruction of the parenchyma. In pulmonary infarcts, there is likewise a rich collateral circulation.[3] Carcinoma tissue in the lung also derives its blood supply from the bronchial vessels (Fig. 2), as has been demonstrated by Wright.[44]

Estimation of volume of collateral blood flow. A knowledge of the volume of blood passing through the collateral channels would be of interest in evaluating the effect on the heart. A method has been developed for measuring the collateral circulation in congenital heart disease by the indirect Fick procedure, which involves measuring the CO_2 produced and estimating the CO_2 content of the pulmonary arterial and venous blood by analysis of gas samples obtained from the lungs under appropriate conditions of equilibration. In the hands of Bing[1] and his collaborators it has yielded interesting information in congenital heart disease, often demonstrating collateral flows as high as 2 liters/min./M^2 in children with tetralogy of Fallot. This procedure is technically difficult and has a high error in that collateral flows of less than 30 per cent of the cardiac output cannot be reliably detected,[14] and is not applicable to the diseased lung where collaterals pass through scar tissue and where there is the additional possibility of reverse flow into the pulmonary artery, as will be discussed later.

Consequently, an experimental approach was chosen in order to obtain some estimate, by more direct methods, of the magnitude of collateral flow as it develops. It has been known that a collateral circulation will appear in the lung after interruption of the pulmonary artery.[22, 23, 29, 37, 38, 40] Experi-

ments in this laboratory[2] show that the collateral is already manifest anatomically, and functionally in a markedly increased flow, two weeks after ligation of the left pulmonary artery. A month or more later the collateral is immense (Figs. 3-5). Precapillary communications with the pulmonary artery develop, thus making directly accessible the entire capillary bed of the lung to the blood brought in from the aorta by the bronchial arteries.[23] Proximally the pulmonary artery usually stays open beyond the ligature and can be injected retrogradely in its entirety from the aorta; it is, so to speak, a diverticulum of the bronchial-arterial system. In view of these anatomical findings the very large calculated flows are not so surprising.

The collateral flow is estimated with the animals under sodium pentobartital anesthesia and with a broncho-spirometric cannula in place, from the following formula: $F = \frac{a}{c - b}(100)$ where F is the blood flow in cc./min. of the side whose pulmonary artery has been ligated (the left side in these experiments), a = cc. of oxygen absorbed/minute by the left lung through the broncho-spirometric cannula from a spirometer containing pure O_2, c = the O_2 content in volumes per cent of the blood in the pulmonary vein, and b, the O_2 content of the systemic arterial blood. It was found in ancillary experiments, as would be expected on theoretical grounds, that the left lung would absorb a significant volume of oxygen only if the systemic arterial blood was not fully saturated. This condition is met as a result of the anesthesia and from the partial obstruction of the airway produced by the bronchospirometric cannula. The value "b" is determined by analysis of the femoral arterial blood whose O_2 content is representative of that in the bronchial artery. The value of "c" is assumed to be the same as that of the systemic arterial blood when both lungs were breathing O_2, an analysis performed in each instance during the first part of the experiment. It is obvious from the formula that if c were lower, then the divisor would be smaller, and the calculated flow therefore greater. Also "F" represents only the effective collateral flow, i.e., that blood passing through well-ventilated functional pulmonary substance. For these reasons, F represents a minimal value for the magnitude of the collateral circulation.

When the oxygen uptake of a lung with interrupted arterial flow (the value "a" in the above formula) is measured at intervals after ligation, it is found to rise with time, a statistical trend line having a significant upward slope for at least a year.[2] This is the case despite the fact that such a lung appears to be less efficient than the normal in the transfer of gases across the walls of the alveoli. Observations on this point, using the left lung as a tonometer, were interpreted as suggesting that the permeability of the alveolar membranes may be impaired after ligation of the pulmonary artery,[19] although with ordinary methods the histological structure did not appear to deviate strikingly from that of the normal lung.[22, 37, 38]

The collateral flow as calculated from the formula was found to rise strikingly, often reaching levels in excess of a liter per minute after the fourth month.[2] This represents at least a forty-fold increase over the volume of blood brought to both lungs from the aorta by the bronchial arteries in the

normal dog, as determined by Bruner and Schmidt[4] with the bubble flow meter.

Functional significance of collateral circulation and pulmonary-bronchial arterial anastomoses. That the burden of this collateral circulation must fall on the left side of the heart is at once apparent from a consideration of the course of the blood (Fig. 13). Blood brought from the lung to the aorta is returned, largely via the pulmonary veins, immediately to the left auricle without first passing through the right side of the heart as does all other blood in the aorta beyond the ostia of the coronary arteries. Stated otherwise, the collateral represents a shunt from the aorta to the left auricle. Thus, the output of the two ventricles differs by the amount of the collateral, i.e., the output of the left ventricle in these animals is approximately one-third greater than that of the right.

It remains to be determined how much added work this collateral flow imposes upon the left ventricle. At first thought, considering the low resistance imposed by the capillaries of the normal lung, it would seem that this burden would not be large, despite the great volume of the flow. Yet the situation is analogous to the shunt encountered in peripheral arteriovenous fistulas where the blood volume is known to rise and the heart undergoes hypertrophy.[20] Speculation is, however, no substitute for the experiment that is planned to determine the effect of establishing such a collateral in some small and well-standardized species such as the rat, where large numbers of controls can be employed. It will also be of interest to determine the blood volumes in animals with a large collateral circulation in the lungs.

Returning to the chronically diseased lung in man, where there is also a vastly expanded bronchial arterial circulation, certain similarities and certain differences will be noted in comparison with the experimental dog just described. In lungs the seat of massive fibrosing disease the collateral flow can only be inferred from the vast anatomical development of the bronchial arteries, since much of the collateral is "hidden", i.e., inaccessible to measurement with present methods for the reason that it does not pass through alveolated parenchyma capable of gas exchange. One may expect it to be large from comparison of the size of the bronchial arteries with those in the dogs and with those in patients with tetralogy of Fallot, where estimates of the actual quality of blood carried by these channels are available. Whatever the volume, that portion of blood which arrives from the aorta by way of the collateral vessels and passes through the pulmonary capillaries represents added work for the left ventricle. This burden helps to account for

the hitherto unexplained hypertrophy of the left ventricle often observed in cor pulmonale[39] in the absence of systemic hypertension. The aortic-left auricular shunt may also be a contributing or determining factor in the excessive total blood volumes sometimes encountered in patients with cor pulmonale.[35] Except in congenital pulmonic stenosis or atresia[7] and in a few patients where there had been operative[21, 36] or embolic[6] obstruction of the pulmonary artery, the diseased lungs of the patients under discussion differ from those of the experimental dogs, in that in the former there has also been some destruction of pulmonary substance with consequent obliteration of the capillary bed.

The existence of the high pressure collateral circulation accounts for the hemorrhages, sometimes massive, of bright red, obviously oxygenated blood, often observed in patients with bronchiectasis or other chronic pulmonary disease, as Wood and Miller[48] have pointed out. The large arterial vessels, containing blood under systemic pressure, are often situated within the lamina propria of bronchi, so superficially that renewed ulceration can easily result in their rupture.

It has long been known that even in massive disease of one lung, there may be no desaturation of the systemic arterial blood, an indication that none of the venous blood in the pulmonary artery traverses non-respiring diseased pulmonary substance. One mechanism responsible for this phenomenon involves the anastomoses between the bronchial and pulmonary arteries. It is obvious that here a high-pressure circulation, the bronchial, comes into direct communication with the low-pressure pulmonary arterial system. It is not surprising, therefore, that blood in the pulmonary artery is shunted from the diseased tissue where anastomoses exist into the normal parenchyma where oxygenation will take place. Evidence for this shunting may be obtained during life by angiocardiography in patients with massive chronic pulmonary disease of one side. Thus in a 32-year-old man with severe bronchiectasis of many years standing, involving all segments of the left lung, the radio-opaque material enters only the normal side (Fig. 7). Steinberg and Robb[40] made similar observations in the earliest angiocardiograms although the explanation has been obscure. Mere collapse and immobilization of a lung, as has been done experimentally in the dog in this laboratory* with silk mesh, although it reduces markedly the amount of blood flow, does not prevent opacification of the pulmonary arteries in the angiocardiogram.

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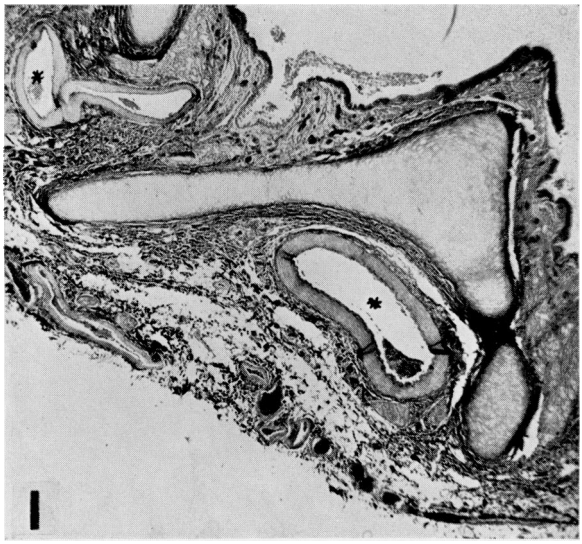
* Unpublished experiments.



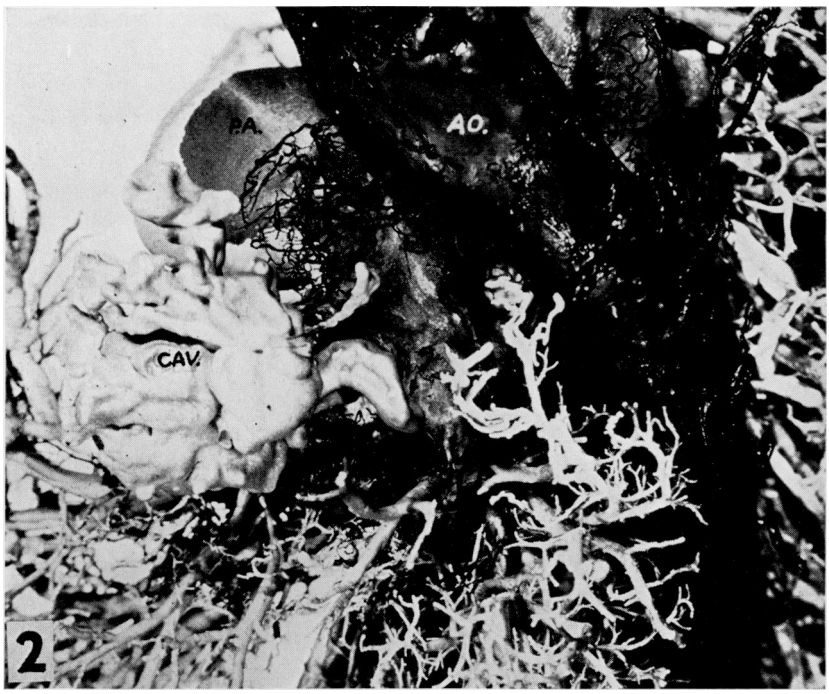
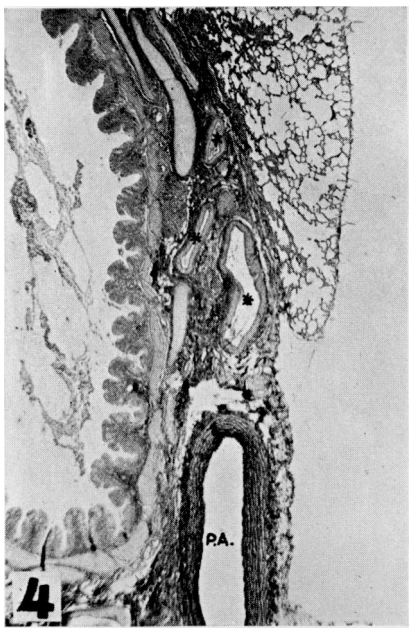


FIG. 1. Histological section of the main bronchus of a patient with tetralogy of Fallot, who died at the age of 17 years. The bronchial arteries are greatly enlarged and have thick muscular walls. Compare with the vessels of the dog shown in Figures 4 and 5.

FIG. 2. Bronchovascular cast of lung with carcinoma arising in wall of tuberculous cavity. Posterior view. The aorta (AO.) curves obliquely downwards and to the right. The pulmonary artery is labeled P.A. The cavity has been filled with plastic seen as the large, almost white, rose-shaped mass (CAV.). About the cavity is shown a tangled mass of bronchial vessels, injected in black from the aorta. They represent the vascular skeleton of the tumor.



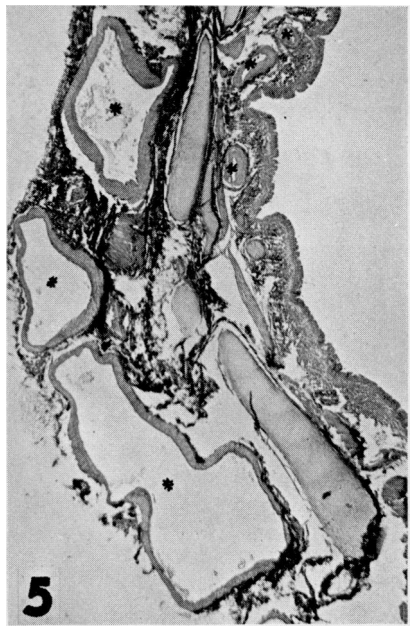
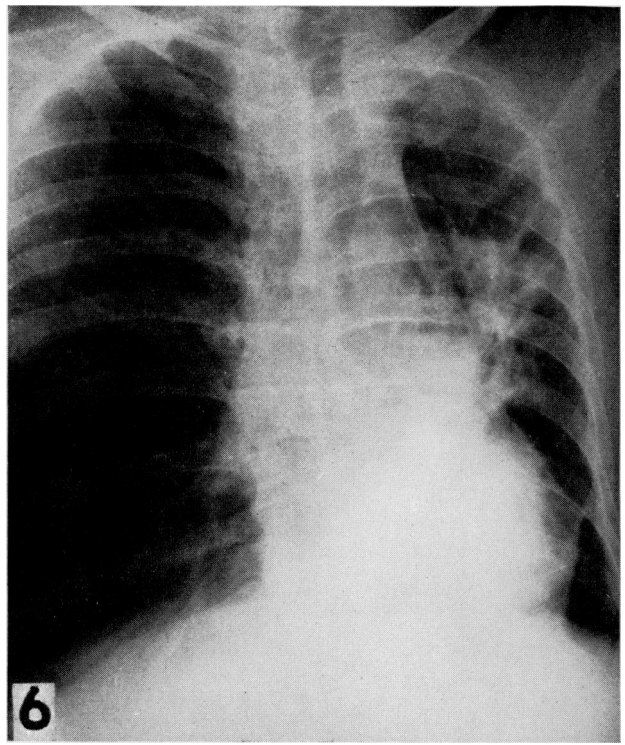


FIG. 3. Bronchovascular cast of twelve-week-old puppy whose left pulmonary artery was ligated and whose right pulmonary artery was constricted with a band of irritating polyethylene, when the animal was less than 48 hours old. There is only a slight increase in the collateral supply of the right lung, while the left displays a tremendous plexus of large bronchial arteries which ramify into the pulmonary substance. The left pulmonary artery has been retrogradely injected through anastomoses with the bronchials at many points on the periphery. The distal segment of the right pulmonary artery (RPA) (beyond the constricting band) is greatly dilated.

FIG. 4. Section of the main bronchus of the right lower lobe (on the side of constriction) of an animal prepared in the same fashion as the one described in the legend of Figure 3, but surviving to the twentieth week. There is a moderate increase in the size of the bronchial arteries*. These are much larger than normal but are not nearly so expanded as they are on the side of complete ligation (Fig. 5).

FIG. 5. Section of the main bronchus of the left lower lobe (on the side of ligation) from the same animal (Fig. 4). The bronchial arteries (marked with an *) have enormous lumina and thick muscular walls.



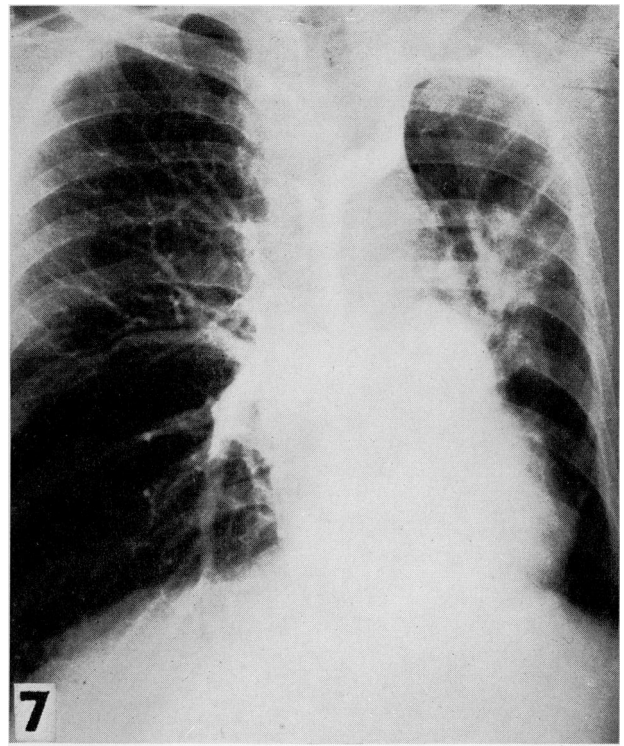
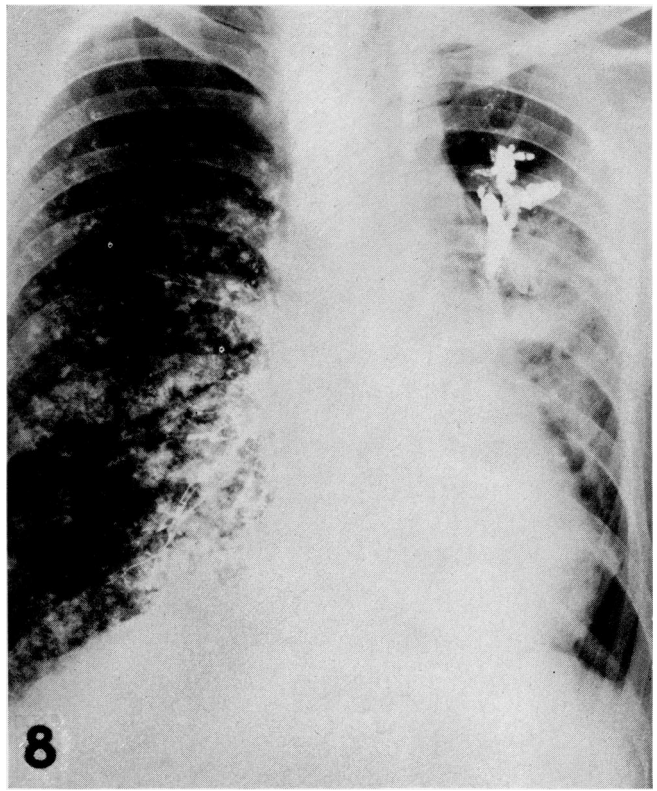


FIG. 6. Roentgenogram of chest of a patient with bronchiectasis of the left lung, made in January 1949. Fibrosis is demonstrated in the left lower lobe, but there is also much radiolucent tissue especially in the left lower lobe, despite the universal bronchiectasis of all segments (Figs. 8 and 9).

FIG. 7. Angiocardiogram, 3½ seconds after injection of diodrast. made on the same day as the film reproduced in Figure 6. The radio-opaque material is seen within the branches of the pulmonary artery only on the normal right side. The left pulmonary artery is "physiologically amputated."



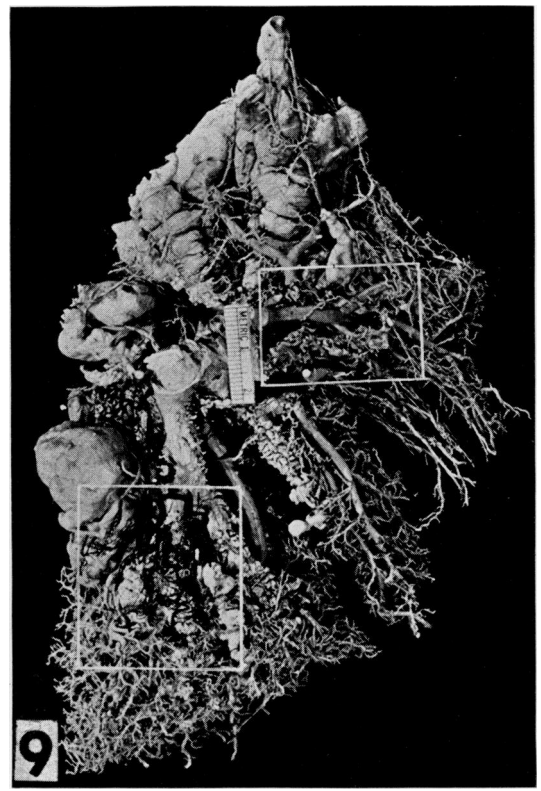


FIG. 8. Bronchogram made in November, 1943, showing bronchiectasis of left upper lobe. Compare with cast shown in Figure 9.

FIG. 9. Bronchovascular cast of left lung removed surgically in January, 1949. There is bronchiectasis of all segments. The greatly enlarged bronchial artery to the lower lobe has been injected with black plastic. In the upper lobe there is retrograde injection of the bronchial arterial plexuses. Close-ups of fields delineated by the white lines are shown in Figures 10 and 11.

FIG. 10. A portion of the pectoral segment of the left upper lobe outlined by the rectangle in Figure 9 is shown in close-up. A bronchial arterial plexus seen as the vermiform mass of intercommunicating vessels about the ectatic bronchus has been injected retrogradely from the pulmonary artery through the large anastomosis (AN).

FIG. 11. Close-up of the portion of the left lower lobe delineated in the lower rectangle in Figure 9. Two large communications of bronchial (BA) and pulmonary (PA) arteries are shown; there are many others of equal or smaller size. Mingling of black and originally red plastic injection media has occurred across the anastomoses (AN). Two of the communicating vessels cross, one above the other, before reaching the branches of the pulmonary artery.

Since the anastomoses in the diseased tissue often involve bronchial and pulmonary arterial vessels of large and almost equal size, and are themselves so large, the possibility of a flow from the bronchial collaterals backwards within the pulmonary arteries towards the hilum suggests itself. It would be difficult to demonstrate such a reverse flow within individual pulmonary segments and subsegments. In the patient with universal bronchiectasis of the left side whose angiocardiagram is illustrated in Figure 7,

TABLE 1

OXYGEN CONTENT AND SATURATION AND BLOOD PRESSURE IN PATIENT WITH BRONCHIECTASIS INVOLVING ALL SEGMENTS OF LEFT LUNG

Source	O_2 *vol. %*	*% sat.*	*Mean pressure*[b]	*Resting pressure*[c]	*Lowest pressure*[d]
Prox. rt. ventricle	12.11	67.5	21.6	54/-1	49/-8
Outflow rt. ventricle	12.04	67.1	21.3	37/12	32/8
Prox. pulm. art.	12.64	70.3	33.3	46/29	42/23
Lt. pulm. art.	16.23	90.3	(36)[b]		44/27
Rt. pul. art.	11.43	63.7	29.4	43/21	34/17
Brachial art.[a]	16.55	92.2			

[a] CO capacity of brachial arterial blood = 17.95 vol. %.
[b] "Mean pressure" = pressure over an entire respiratory cycle obtained by planimetric integration, except for lt. pul. art. where the mean pressure of the lowest pulse curve only could be measured (see Fig. 12).
[c] "Resting pressure" = pressure during interval between respirations; could not be calculated for lt. pul. art. (see Fig. 12).
[d] "Lowest pressure" = pressure of lowest pulse curve, in the inspiratory phase.

however, suggestive evidence was obtained by catheterization of the two pulmonary arteries* (Table 1 and Fig. 12). Blood obtained from the left pulmonary artery had an oxygen saturation close to that of the systemic arterial blood while blood from the right pulmonary artery was venous in character. Since it is possible to suck blood from the pulmonary veins back into the catheter,[11] great care was taken to exert no suction on the syringe but to allow the blood to enter under its own pressure. Pressures were measured with the Hamilton manometer in the two arteries, but a regularly recurrent artifact, presumably due to obstruction of the catheter tip at certain phases of the cycle while in the left pulmonary artery, renders the read-

* Catheterization performed by Dr. Frank D. Gray, Jr. of the Department of Internal Medicine.

ings difficult to interpret. Nevertheless, it is notable that both the systolic and diastolic readings of the lowest pulse curves with the catheter in the left pulmonary artery were higher than the highest with the catheter on the right side. The surgically resected left lung showed universal bronchiectasis

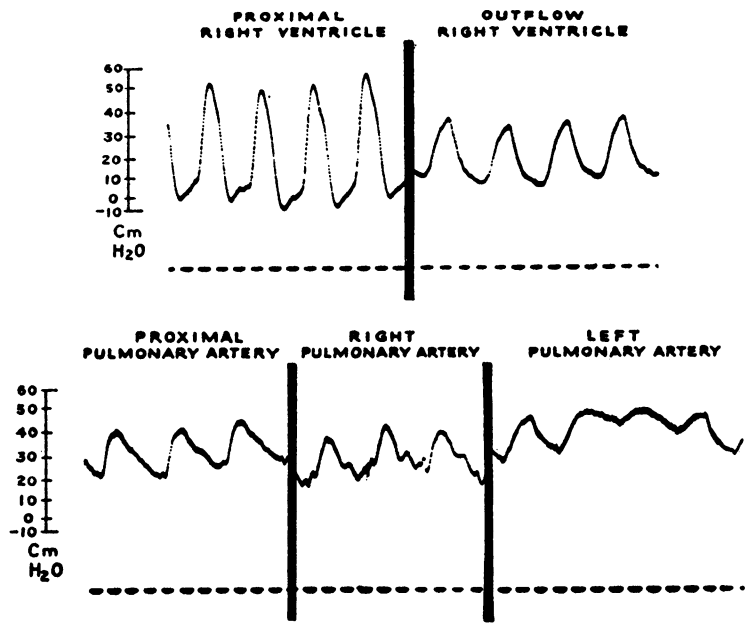


FIG. 12. Pressure curves obtained with a Hamilton manometer in close succession, during catheterization of the patient whose roentgenograms and bronchovascular casts are shown in Figures 6 to 11. There is damping of the pulse wave in the outflow tract of the right ventricle. An artifact recurs regularly during the expiratory phase. For this reason only pressures of the lowest pulse wave during the inspiratory phase are measured and recorded in Table 1.

and innumerable large anastomoses between the bronchial and pulmonary arterial systems (Figs. 9, 10, 11). Further observations of this type are obviously necessary, but patients with massive unilateral bronchiectasis who will submit to the necessary technical procedures are not common. It is important in seeking confirmation to obtain individuals with universal involvement of all segments, for although reverse flow may take place locally, it may not be possible to obtain the evidence in the main pulmonary artery unless all the segments are involved. Attempts are being made in this laboratory to produce unilateral bronchiectasis in dogs by obstructing the

left main bronchus with a timothy grass plug.[5] The condition has developed in some of these animals, but the incidental mortality has been high and we have not as yet been able to obtain a complete study. It is also planned to re-anastomose the distal and proximal ends of the pulmonary artery in dogs who have survived a ligation of this vessel for many months and developed an extensive collateral circulation. Then the circulatory analogue of the massive bronchiectasis should be available for study. The re-anastomosis should be possible since the pulmonary artery remains patent distally despite its ligation.[23]

In the patient with chronic pulmonary disease, the collateral circulation may thus take two courses: the part that enters what remains of the pulmonary capillary bed is transferred to the left auricle, and is thus a burden upon the left heart alone, as in the dog with the ligated pulmonary artery. In contrast with the experimental animal, however, the pulmonary artery in the patient is patent proximally and thus some of the collateral may flow in reverse within the pulmonary arterial system impelled by the higher pressure in the bronchial arteries, to be distributed to normal pulmonary substance where it is added to the output of the right ventricle.

It is clear that the sizable anastomoses between a bronchial and pulmonary artery represent points of increased peripheral resistance within the lung whose significance in producing pulmonary hypertension, as suggested by Wood and Miller,[43] must be evaluated. Blood from the right heart that is shunted away from these points of resistance, together with blood that may actually be flowing backwards through the anastomoses, is directed into the remaining capillaries. The capillary bed of the lung is, however, adaptable to a high degree and even a fraction of it can accommodate an enormously increased flow without pulmonary arterial hypertension. In our own laboratory, the dogs with a ligated pulmonary artery, in whom a single lung obviously received the entire output of the right ventricle, when run at 4 miles per hour on a treadmill have not shown any increase in the right ventricular pressure.* Furthermore, Cournand[8] has recorded observations on patients with patent ductus arteriosus in whom there was a flow from the aorta into the pulmonary artery of as much as 8 liters/min., without pulmonary hypertension. These observations indicate that the points of communication of the pulmonic with the systemic circulation must be very numerous before one may expect them to increase significantly the resistance against which the right ventricle has to work. They will do so when the remaining normal capillary bed has been sufficiently diminished.

* Unpublished experiments.

Of particular interest will be the study by the injection method of emphysematous lungs. We have not as yet encountered in the necropsy series an instance of "pure" emphysema, without more localized fibrous lesions, in which there was cor pulmonale.

Mechanisms concerned in the development of collateral circulation. The exact nature of the stimulus to the development of the collateral circulation is obscure; in some instances several mechanisms may be involved. By reference to William Snow Miller's[39] drawing of the region of the respiratory bronchiole and the tissues beyond, the course of events after ligation of the pulmonary artery may be visualized. It is evident that an elongated meshwork of capillaries derived from the pulmonary artery separates the capillary beds in the terminal alveolated portions of the respiratory tree from the end branches of the bronchial arteries in the walls of the respiratory bronchiole. Peripheral passage of blood entering the latter vessels is resisted by the friction of the capillaries and by counter pressure within the distal capillaries transmitted from the pulmonary artery. When the ligature is applied, this counter pressure is reduced, permitting a further progress of bronchial arterial blood into the capillaries of the alveoli. Having thus available the entire capillary bed, where the peripheral resistance is low, it is not surprising that there should be an increase in blood flow within the bronchial arteries. The exact mechanism responsible for the subsequent enlargement of the latter is not clear. In recent experiments[36] with newborn dogs where the left pulmonary artery was ligated while the right pulmonary artery was constricted to a degree sufficient to produce within three months a very extensive hypertrophy of the right heart with ultimate failure, it was observed that a very extensive collateral developed on the side of the complete ligation, while on the right side there was only a moderate increase in the collateral circulation (Figs. 3-5). This suggests that complete interruption of the pulmonary artery is a much greater stimulus than merely a moderate reduction in the pressure within this vessel. Reduction in the pressure distal to the constriction is suggested by the thin wall and great dilatation of the pulmonary artery—the post-stenotic dilatation that can be produced by similar means in the aorta.[18] There the pressure is known to be much less beyond the ligature.

The existence of a hormonal factor in the genesis of collateral circulation is suggested by the fact that in the growing puppies the collateral on the side of the complete ligation is very much greater than we had observed in a comparable three- to five-month interval in any of a series of adult animals. Whether growth hormones can affect the development of collateral

circulation remains to be tested in control experiments. The converse effect of the adrenocorticotrophic hormone of the pituitary on the formation of granulation tissue, including its capillaries, has received attention recently.

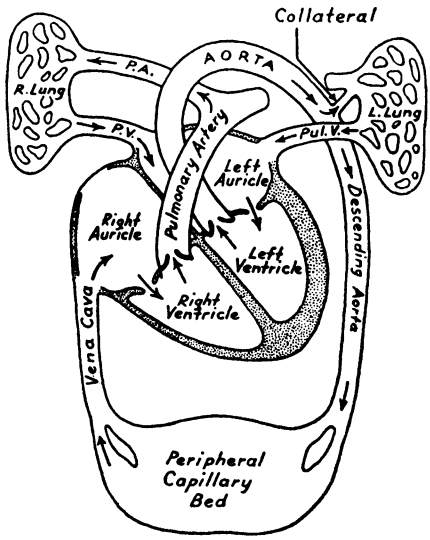


FIG. 13. Schematic representation of the course of the circulation in the dog whose left pulmonary artery has been ligated some months previously. The extensive collateral is represented as a large branch from the aorta. It is obvious that blood entering the left lung from the aorta is returned through the capillary bed of the lung immediately back to the left auricle, pursuing a circle independent of the right heart. The output of the left ventricle thus exceeds that of the right by the volume of the collateral, which is thus a burden only on the left side of the heart.

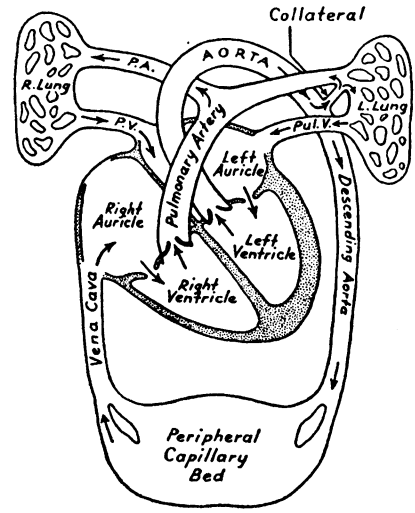


FIG. 14. Schema of the course of the circulation when an extensive collateral circulation has developed in chronic pulmonary disease of the left side (e.g. bronchiectasis involving all segments of the lung as in Figures 9-11). Some of the blood entering the left lung by the collateral channels, represented here as a large branch of aorta, may be distributed through the remaining capillaries of the lung, to pursue the same course as in Figure 13 and with the same physiological connotation. Some blood may, however, enter the pulmonary artery through the anastomoses which exist, impelled by the higher pressure in the collateral channels to flow in reverse, toward the hilum, within the pulmonary artery.

Difficult to visualize also is the process by which the macroscopic stomata develop between the bronchial and pulmonary arteries as the collateral expands, unless it be by gradual dilatation under the stimulus of increased flow in certain originally capillary channels, as during embryogenesis. We have not observed in any of this material, nor in diseased lungs, precapillary

communications with the pulmonary veins; why these should be spared when the arteries are involved is not clear.

In human disease, obstruction of the pulmonary artery or its branches takes place under certain circumstances and thereby, if the experimental dog sets the pattern, contributes to the development of collateral circulation. In tetralogy of Fallot, Rich[24] has demonstrated a high incidence of recent and organizing thrombi in the pulmonary vessels and we have had opportunity to confirm this observation.[16] Thrombotic and endarteritic processes are also frequent in chronic fibrosing conditions of the lung such as tuberculosis and silicosis.[18]

In disease there may be additional demands in the pulmonary substance for oxygenated blood that are met, by mechanisms largely unknown, in the expansion of the collateral circulation. Among them is the support of the elements of the granulation tissue that precedes the fibrosis, the hypertrophied muscle, and excessive lymphoid substance found in the bronchi of many patients with bronchiectasis.[24] Presumably the capillaries in the granulation tissue are derived from both the bronchial and pulmonary arterial systems. Such capillaries may come to join as is common in developing networks of the finest vessels, and then they may enlarge and persist as the anastomoses that have been described; such enlarged vessels have been found in granulation tissue elsewhere.

Summary

In chronic pulmonary disease and in certain forms of congenital heart disease there may develop an extensive collateral circulation and large anastomoses of the bronchial with the pulmonary arteries. Similar changes can be induced in the dog by ligation of the pulmonary artery, and the collateral vessels in the experimental animal come in time to carry very large quantities of blood, equal at the end of 18 months to approximately one-third of the output of the right ventricle. Since this blood from the aorta is returned by the pulmonary veins directly to the left auricle, it is a burden entirely on the left side of the heart whose output then is greater than that of the right by a volume equal to the collateral flow. In human lungs where the pulmonary artery is patent proximally, there may be a division of the collateral stream. The part that passes through the capillaries of the lung is, as in the experimental dog, added to the work of the left heart; but another part impelled by the higher pressure in the bronchial artery may pass via the anastomoses into the pulmonary artery against the direction of the normal stream, toward the hilum of the lung to be directed

together with the output of the right heart into undamaged parenchyma. Shunting of blood away from diseased pulmonary tissue is suggested in angiographic observations, and by the absence of desaturation despite involvement of as much pulmonary substance as that of an entire lung. The anastomoses between the bronchial and pulmonary arteries represent points of increased resistance that, when sufficiently numerous, will increase the work of the right ventricle.

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