ENLARGEMENT OF THE BRONCHIAL ARTERIES, AND THEIR ANASTOMOSES WITH THE PULMONARY ARTERIES IN BRONCHIECTASIS *

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The double arterial blood supply of the lungs has attracted interest and discussion since its discovery. Branches from the aorta to the bronchi were known to Galen, but they were generally forgotten, and even denied by some, such as Columbo, until rediscovered by Dominico de Marchettis, and later by Ruysch.[1,2] There has been controversy concerning the existence of communications between the two circulations; some, like Küttner,[3] maintaining their presence, and others, like Cohnheim and Litten,[4] vigorously denying this. The confusion has been resolved to the satisfaction of most anatomists by the careful work of W. S. Miller [2,5] and of Ghoreyeb and Karsner.[6] The former, in man and dog, could find no precapillary communications between the two systems. When Miller injected the pulmonary artery with a gelatin suspension of Berlin blue, it passed through the capillaries into the pulmonary veins, but not into the bronchial arteries. When the pulmonary venous pressure was increased by clamping the pulmonary vein, there was partial injection of the bronchial artery, through the capillary networks along the respiratory bronchioles. When the injection was carried out through the pulmonary vein, the pulmonary artery was completely, and the bronchial arterial system partially, injected. When the pulmonary artery was clamped, the bronchial arterial system was completely injected from the pulmonary vein, and the pulmonary artery could then be injected from the proximal end with a contrasting material, lead chromate in gelatin. The differences in interpretation of injection experiments previous to those of Miller probably resulted from failure to correlate the results of injections with the finer anatomic detail of cleared specimens observed as three-dimensional objects. Some of the confusion resulted also from the fact that the bronchial artery is the source of the vasa vasorum for the pulmonary vessels. Furthermore, the anatomists, when dealing with human material, often failed to take cognizance of the effects of disease of the lung which may produce profound changes in the circulation. Braus,[7] although claiming the existence

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of anastomoses in normal material, stated that they are much more common in diseased specimens.

A most revealing study of the bronchial artery in disease has been made by Wood and M. Miller of Stanford.[8] They used Hill's mass (bismuth oxychloride in gum acacia).[9] This material was injected into the bronchial artery and roentgenograms were taken of the lungs in their inflated state. Enlargement of the bronchial arteries and numerous large anastomoses with the pulmonary artery were noted especially in subjects with tuberculosis, but also in association with chronic passive congestion, Ayerza's disease, silicosis, emphysema, asthma, and "congenital cystic disease" of the lung. One case of bronchiectasis was mentioned by Wood and Miller. In this specimen the main bronchial artery was described as being slightly dilated and quite tortuous.

In the observations to be reported it was especially in lungs showing bronchiectasis that the most notable expansion of the bronchial arterial circulation was evident. The anastomoses were of such great size and number as to suggest that they possess physiologic importance.

Materials and Methods

Eighteen surgical specimens were prepared as vinylite bronchovascular casts by a method that has been described in detail elsewhere.[10] The bronchial arteries were identified during the course of lobectomy or pneumonectomy for bronchiectasis by their intimacy with the walls of the bronchi, tortuosity, vigorous pulsations, relatively thick walls, and content of bright red blood. They were tagged with longer sutures than the other vessels. The largest vessels were cannulated, washed with water followed by acetone, and were then injected with black plastic. After this procedure the pulmonary arteries and veins were cannulated and the lungs were inflated in a vacuum jar. Red plastic was injected into the pulmonary artery and green plastic into the pulmonary vein through tubes brought out through the cover of the jar. As this material was in the process of hardening, and while the lungs were maintained in their distended state, white plastic containing lead chromate or carbonate was introduced in a similar fashion into the respiratory tree, at first by the negative pressure within the lungs, and then under positive pressure from an injection chamber. After hardening of the plastic, sections for histologic study were cut from significant portions of the specimen. In many instances roentgenograms were made for correlation with the clinical bronchograms. Finally, digestion of the tissue was carried out in concentrated hydrochloric acid. A cast then remained of the respiratory and vascular trees.

Observations

Incidence of Enlargement of the Bronchial Arteries and Pulmonary-Bronchial Arterial Communications

It was obvious in most instances at the time of the surgical operation that the bronchial arteries were greatly enlarged. During the process of injection of the bronchial arteries, moreover, there was usually found an abundant outflow of the black plastic from the cut ends of the pulmonary arteries at the hilum; it was never seen to issue from the veins. Since the plastic as employed for the injection was much too viscid to penetrate the capillaries, this observation at once suggested the existence of sizable anastomoses with the pulmonary arteries. When the casts were examined after injection, striking bronchial arterial enlargement and anastomoses with the pulmonary artery were found in 15 of the 18 specimens. In 11, large branches of the bronchial artery had been identified during the operative dissection or after removal of the specimen, and these were cannulated, washed, and injected directly. In 4 specimens, however, the bronchial arteries were not identified as such, until after injection of the pulmonary arteries from which they had been injected retrogradely. This was to be expected, since the reverse, injection of the pulmonary arteries from the bronchials, was commonly observed, as has been stated. The result was the same as when the arteries were injected separately, except that the objective of demonstrating the two systems in contrasting colors was not achieved. Nevertheless the bronchial vessels were easy to identify by criteria that will be detailed. An example of retrograde injection of the bronchial arteries from the pulmonary side is illustrated in Figure 1. Here the arterial system appears to be at least doubled and often many times compounded for each branch of the respiratory tree, in contrast to the simple arborization of the normal pulmonary arterial tree, where a single branch follows the course of each bronchus or bronchiole.

In 2 of the 3 specimens in which neither direct nor indirect injection of the bronchial arterial system was achieved, the bronchiectasis was of very minor degree. In the third there was severe bronchiectasis of the right middle and lower lobes but anastomoses of the bronchial and pulmonary arterial systems were not demonstrated.

The Bronchial and Pulmonary Arteries Contrasted

In the casts, the bronchial arteries are seen to be more intimately applied to the bronchi than the pulmonary vessels. This is to be expected since the former richly supply the mucous membrane and other elements of the walls of the bronchi themselves, while the pulmonary artery does not yield such vessels nor any terminal branches until the respiratory bronchiole is reached.* The pulmonary arteries pursue a rectilinear course roughly parallel to the branches of the respiratory tree. The bronchial arterial trunks, however, tend to spiral in relation to the long axis of each bronchus. The pulmonary arteries are truly end arteries and communications exist only among the finer capillary networks; on the contrary, even the larger bronchial vessels, especially in bronchiectasis, are arranged in a dense communicating network. Often the communicating branches are as large as the trunks which they unite. They resemble the arcades of the mesenteric arteries (Fig. 2). It is not rare for a bronchial artery to transgress the boundaries even of a segment. This probably results from the course of some of these arteries within the septa, where vessels from adjacent segments may meet. The plexiform arrangement of the bronchial arteries accounts for the impossibility of cutting off the systemic arterial supply of a bronchus.[11] So numerous are the sources of collateral supply, from branches of the subclavian, internal mammary, pericardiophrenic, esophageal, and numerous intercostal and other derivatives of the aorta, that the effect of ligating the larger identifiable bronchial arteries at their sources is always defeated by an immediate overgrowth of the accessory vessels. The major bronchi are supplied at least by pairs of vessels. Even when a compressive ligature is applied to a major bronchus, the deep mucosal vessels, or perhaps collaterals coursing within the septa or as vasa vasorum, will assure the vitality of the distal tissues.

Location and Nature of the Communications Between the Pulmonary and Bronchial Arterial Systems

An attempt was made to relate the sites of anastomosis of the two systems of vessels to the order of branching of the bronchi. For this purpose, in order to avoid ambiguity, the main segmental bronchus of each segment (in the sense of Brock,[12] or of Jackson and Huber [13] as modified by Boyden [14]) was considered to be of the first order, each of its first two subdivisions of the second order, and so on. No anastomoses were found proximal to the third order bronchi within the segments.† The actual observations are presented in Table I. In most instances the

* An injection so fine as to reach these structures, although easily possible with the vinylite method, was expressly avoided by selecting 12.5 per cent material containing lamp black. With this material no vessels of a diameter less than 50 μ were injected; for the most part the injection was coarser than this.

† This is in contrast to what we have observed in congenital pulmonic stenosis. In this condition the tremendously enlarged bronchial arteries may communicate directly with the pulmonary arteries in the region of the segmental bronchi, or even of a lobar bronchus.[15]

anastomoses were first found along branches of the fourth order in relation to the walls of the large bronchiectatic sacs (Fig. 3). These sacculations, in 15 of our 17 cases of saccular bronchiectasis, begin either in the third or fourth orders of branching. Additional anastomoses, usually multiple and of large size, were often found far beyond the last injected sac (Fig. 1). Many of these probably occur within scar tissue; for in histologic sections it is evident that bronchi and bronchioles which

TABLE I

Results of Bronchovascular Vinylite Injections in Bronchiectasis

Specimen	Mode of injection of bronchial arteries	Location of anastomoses			Maximum size of anastomoses
		Lobe	Segment	Segmental branch where first observed	
					mm.
39865	Direct	R.l.l.	Basal	V	>1.0
40279	Retrograde	L.l.l.	Post. basal	IV	0.75
			Mid-basal	V	
40280	Direct	L.l.l.	All	IV	<1.0
40281	Direct	R.l.l.	Ant. basal	IV	1.0
			Post. basal	V	
40282	Retrograde	L.l.l	Mid-basal	V	<1.0
40716	Direct	L.l.l.	Basal	IV	1.0
41089	Retrograde	L.l.l.	Post. basal	V	1.0
			Ant. basal	IV	1.0
41814	Direct	L.l.l.	Post. basal	V	
			Mid-basal	V	>1.0
41855	Direct	L.l.l.	Post. basal	IV	1.0
			Mid-basal	IV	1.0
42688	Retrograde		Ant. basal	VII	1.0
42689	Direct	L.u.l.	Apical	V	
			Subapical	V	
			Lingula	IV	<1.0
		L.l.l.	Ant. basal	IV	
			Post. basal	IV	
42690	Direct	L.u.l.	All	IV	<1.0
		L.l.l.	Apical	IV	
42691	Direct	L.u.l.	All	IV	
		L.l.l.	All		<1.0
42987	Direct	R.m.l.	Lateral	VII	<1.0
		L.l.l.	All		
43651	Direct	L.u.l.	Lingula	IV	<1.0
		L.l.l	All	IV	

branch from the dilated sacs often have minute lumina embedded within highly vascular granulation tissue, or else their lumina have become completely obliterated. Indeed it may well be that the atelectasis and fibrosis associated with this process produce the force that expands the bronchi,[16] and that the chief locus of the original disease is not so much in the walls of the present bronchiectatic sacs, as distal to them.

Before the actual junction with the pulmonary arteries is reached the bronchial vessels often spiral in a very remarkable fashion (Fig. 4). Spiraling of the pulmonary artery may occur also, but the coils of the bronchial vessel are tighter, wider, and more numerous. The bronchial arteries normally pursue a spiral course about the bronchi and when fibrosis of the lung occurs, as a result of the mechanisms described, these spirals are compacted and so are more obvious.

In like manner the contraction of scar tissue from the region of the obliterated small bronchioles toward the walls of the large bronchiectatic sacs probably explains why the anastomoses often occur apparently so close to the hilum, when ordinarily the branches of both systems communicate only by the capillaries about the more distal ramifications—the respiratory bronchioles.

Size of the Anastomoses

In most instances the plexuses of bronchial arteries about a single bronchus communicate at many points with the pulmonary arterial system. At each point the bronchial artery is of the same size or slightly smaller than the pulmonary twig which it joins (Fig. 5). It must be remembered that shrinkage of the vinylite occurs after injection, more in the case of the black plastic used for the bronchial vessels, which was of 12.5 per cent concentration, than of the 28 per cent "filled" material, that usually was employed for the pulmonary arteries and veins. The former shrinks an estimated 10 per cent. In 2 specimens the largest communications exceeded 1 mm. in diameter. In 5 they were 1 ± 0.1 mm. in diameter and in 8 they were smaller (Table I). In the vicinity of the sacs the major bronchial arteries often approached the diameter of the pulmonary arterial trunk at the same level, and this was occasionally true even at the hilar end of a segment. In the instance illustrated in Figure 6 the relative diameters of the bronchial and pulmonary arteries were, respectively, 3.1 and 4.2 mm. These data apply only to vessels easily visible grossly. They suggest a much greater blood supply from the bronchial vessels than from the pulmonary arteries, when the greater pressure impelling the blood in the former is considered.

Mechanism of the Enlargement of the Bronchial Arteries

It remains to inquire in what manner the expansion of the bronchial arterial circulation and its anastomoses is associated with the processes that lead to bronchiectasis. Necrosis with the formation of pulmonary-bronchial arterial fistulas is probably not concerned, since otherwise one would expect to find gross communications between the bronchial arteries and the pulmonary veins. But no instance of such communications was found in the abundant material that came under study (Fig. 7).

At least three changes occur during the development and after the establishment of bronchiectasis which could not exist without an increased supply of oxygenated blood from the aorta: (1) The most significant is the organizing pneumonitis that, according to Mallory [16] and other observers, usually precedes the bronchiectasis (Figs. 8 and 9). At that time the newly budding capillaries that supply oxygen to the leukocytes and other elements of the granulation tissue may be derived from both systems, and these may join. Thus the peripheral capillary bed of the bronchial artery becomes markedly increased and these vessels enlarge. Similar enlargement of systemic vessels which feed large masses of granulation tissue may be observed elsewhere, and large arterial channels may persist even in a well organized scar. Since the pulmonary and bronchial trunks are immediately adjacent, it is not surprising that certain of the larger vascular channels may bring them into free communication and that these channels may persist after organization is complete. That the bronchial vessels may enlarge promptly even in acute pneumonic processes is suggested by the observations of Mathes, Holman, and Reichert [17] on distemper in the dog. (2) The second change is the considerable hypertrophy of bronchial smooth muscle that occurs in the walls of some of the expanded bronchi in certain cases of bronchiectasis (Fig. 10). (3) The third is the increase in lymphoid tissue which may form huge follicles, both in the walls of some of the sacs and in the proximal bronchi. An example is shown in Figure 11. A persistent large bronchial artery in a healed process is shown in Figure 12.

Physiologic Importance of the Expanded Bronchial Circulation and Its Anastomoses

The enlarged bronchial vessels which exist in the walls of the bronchiectatic sacs may be injured by bacterial agents, a frequent occurrence. The bright red blood under systemic pressure may pour into the respiratory tree with serious or even fatal consequences. A similar explanation has been given by Wood and Miller [8] for the large hemorrhages that may occur in some tuberculous cavities.

The anastomoses between the bronchial and pulmonary arteries account in part for the fact that there is usually little or no desaturation of the systemic arterial blood even in severe cases of bronchiectasis. The pressure in the pulmonary arteries that enter the diseased tissue is increased by their communication therein with the branches of the systemic circulation. Thus there is a shunting of pulmonary arterial blood away from the anastomoses into healthy parenchyma capable of more efficiently oxygenating the contained venous blood. In a patient recently observed at the New Haven Hospital, all parts of the left lung were involved in bronchiectasis; the oxygen saturation of blood obtained from the radial artery was 94.4 per cent. In this patient the vital capacity was 1080 cc., and bronchospirometry showed an uptake of oxygen by the left lung of only 2 cc. per minute, while that of the right lung was 230 cc. per minute. When prepared as a bronchovascular cast, the left lung showed extreme enlargement of the bronchial arteries and numerous anastomoses of these vessels with the pulmonary arteries. Other factors concerned in shunting of blood within the lung are discussed by Hamilton, Woodbury, and Vogt.[18]

It is obvious that in these cases the output of the left ventricle must exceed that of the right by the amount of blood that passes in the circle: Left ventricle→aorta→bronchial artery→pulmonary vein→left auricle →left ventricle. Some conception of the magnitude of the collateral circulation that may exist in the lung under somewhat similar circumstances is gained from experimental observations on dogs after ligation of the pulmonary artery of one lung. In such animals the blood flow of the ligated side can be estimated during bronchospirometry by applying a modification of the Fick principle.[19] A flow of blood through the bronchial vessels in excess of 900 cc. per minute has been observed 18 months after the ligation, although normally the flow through these vessels does not exceed 27 cc. per minute.[20] It seems possible, from the fact that the bronchial vessels in human bronchiectasis are much larger even than those of dogs on the side of the pulmonary arterial ligation, that the collateral blood flow in the bronchiectatic lungs may well be in excess of 1 liter per minute. In dogs one might expect that this would place a burden on the left side of the heart, yet in such animals Schlaepfer [21] has observed hypertrophy of the right ventricle. Further quantitative studies of this subject are necessary. In patients with bronchiectasis the anastomoses open another avenue for the return of blood which reaches the lung via the bronchial arteries. In the normal lung most of the blood that enters the tissue through the bronchial arteries returns to the heart via the pulmonary veins. In many cases of bronchiectasis, however, the bronchial arteries are so large in relation to the pulmonary arteries and the anastomoses with these vessels are so numerous and wide, that it seems reasonable to suppose that there may actually be a reverse flow through some of the peripheral pulmonary arterial branches toward the heart. This hypothesis, which is based merely on anatomic observation, requires confirmation by measurement of the pressures in each of the pulmonary arteries in severe cases of unilateral bronchiectasis, and by the analysis of blood from each of these vessels. If reverse flow exists, the pressure in the proximal pulmonary artery of the involved side should be higher and the blood richer in oxygen. If backflow does not occur, it is improbable that unilateral bronchiectasis will produce pulmonary arterial hypertension. This statement is based on the evidence brought forward by Cournand [22] that in man, even when the entire cardiac output is forced through a single lung after pneumonectomy, the remaining capillary bed is sufficiently adaptable so that no increase in pulmonary arterial pressure results. In severe bilateral bronchiectasis, however, when no more than a relatively small amount of intact pulmonary substance may remain, the high pressure transmitted from the region of the anastomoses may contribute to pulmonary hypertension and ultimately to the development of cor pulmonale.

Summary

In 15 of 18 specimens of lung removed surgically from patients with bronchiectasis, and prepared as casts by the vinylite corrosion technic, great enlargement of the bronchial arteries and numerous anastomoses of these vessels with the pulmonary arteries were observed. The communications were multiple and usually occurred in the walls of the bronchiectatic sacs which involved branches of the fourth order, or more distal branches, of the segmental bronchi. In half of the specimens the anastomoses equalled or exceeded 1 mm. in diameter.

The enlargement of the bronchial vessels is associated with the development of granulation tissue during the course of the organizing pneumonitis that usually precedes bronchiectasis, and with the metabolic demands of hypertrophied muscle and hyperplastic lymphoid tissue that are often observed. The anastomoses may represent persistent communicating channels, originating in the granulation tissue, that originally received vessels from both the bronchial and pulmonary arterial systems.

The anastomoses are so large and numerous as to suggest that they have physiologic importance: (a) In shunting pulmonary arterial blood away from the diseased tissue into relatively intact parenchyma, where the pulmonary blood pressure is presumably lower; (b) as a factor producing hypertension in the pulmonary circulation.

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[*Illustrations follow*]

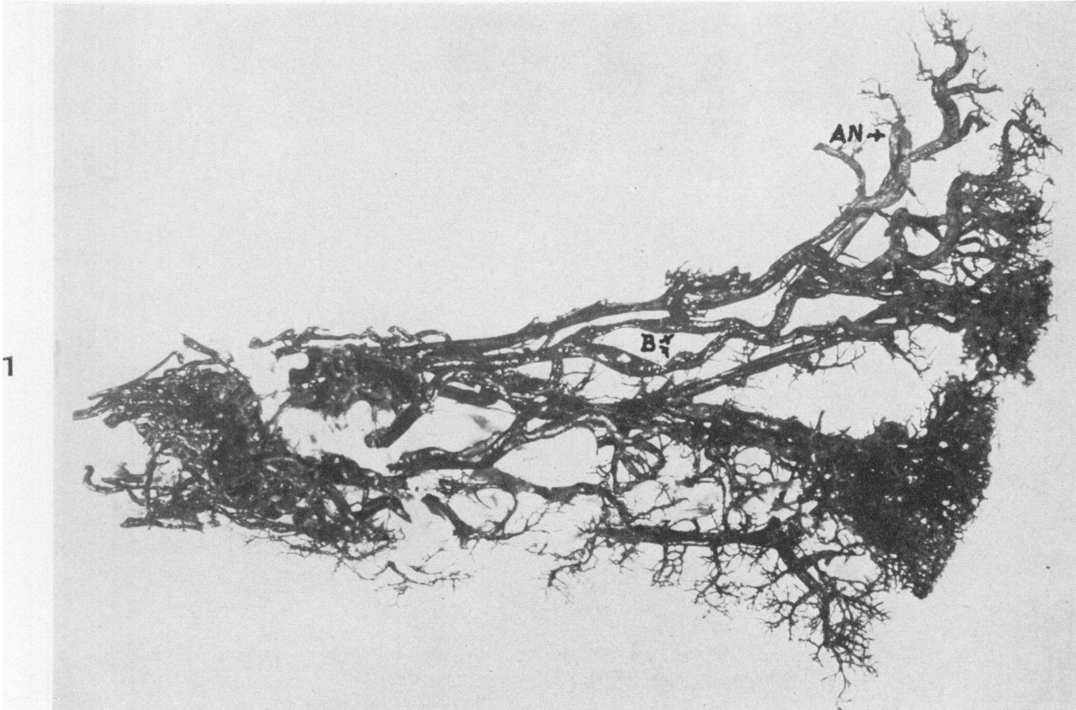
DESCRIPTION OF PLATES

PLATE 27

FIG. 1. Retrograde injection of the bronchial arterial system from the pulmonary arteries. Several branches of the pulmonary artery are shown terminating in the usual arborizing fashion. A bronchial artery (B) is seen below the uppermost pulmonary branch. The bronchial artery has a large anastomosis (AN) with this branch and with at least two other branches of the pulmonary artery. × 2.

FIG. 2. One large pulmonary artery (red) is distributed to each saccular bronchus (yellow) within the segment. In contrast, the bronchial arteries (black) form a dense rete in closer relation to the lumen. Multiple communications exist between the bronchial and pulmonary arteries, best seen among the uppermost branches in the photograph. The veins are injected with green plastic. × 1.75.

1



2

Liebow, Hales, and Lindskog

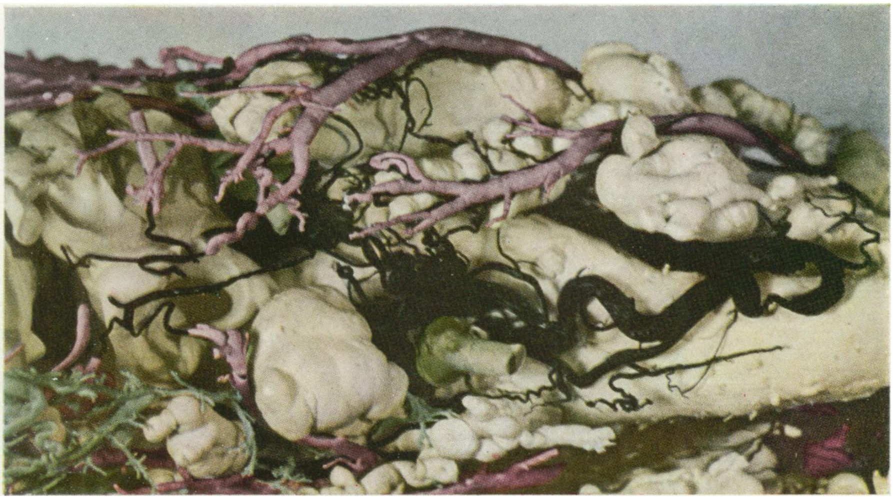
Bronchial Arteries in Bronchiectasis

PLATE 28

FIG. 3. Posterior basal segment of left lower lobe. In relation to expanded, saccular, fourth order branches of the segmental bronchus, a series of branches of the bronchial artery come into communication with branches of the pulmonary artery. Three anastomoses are clearly seen at the left in the photograph. Actually at least five are visible in the original specimen. The plexiform arrangement of the bronchial vessels again may be noted. Colors are as before. × 1.5.

FIG. 4. Above the longest of the injected vessels is a branch of the pulmonary artery which communicates (at AN) with a bronchial artery. As the vessels are traced proximally, the latter is seen to spiral about the former and to reappear as a somewhat attenuated vessel. There has been admixture of plastic across the large anastomosis. × 1.75.

3



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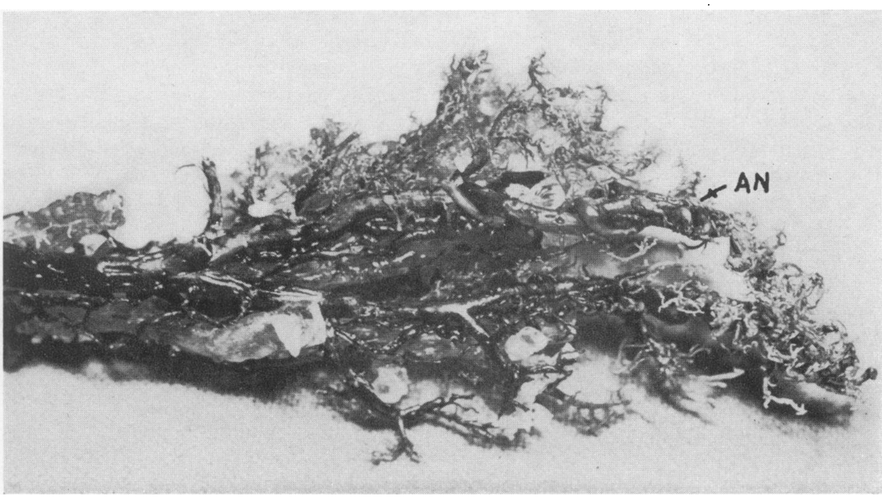

PLATE 29

FIG. 5. An anastomosis between the bronchial and a pulmonary artery is shown in relation to a bronchiectatic sac. In this instance no visible admixture of the red and black plastics has occurred across the anastomosis. The main bronchial artery is only slightly smaller than the pulmonary arteries of the same subsegment. The anastomosing branches are of approximately equal size. Of note is the more intimate relation of the bronchial artery to the lumen of the sac. × 7.5.

FIG. 6. The large size of the main bronchial artery to a segment is shown. In this instance the bronchial artery seen below the main segmental bronchus at the left has a diameter of 3.1 mm., and the pulmonary artery of the same segment has a diameter of 4.2 mm. In its distal course the bronchial artery divides into a plexus of vessels which, in the original specimen, are injected proximally in black and distally with red plastic from the pulmonary artery by retrograde flow. In the black and white photograph the red plastic appears pale gray. Actual size.

5

6

Plate 30

Fig. 7. The point of confluence of two bronchial arteries with a large pulmonary vessel is shown below the bronchiectatic sac. Some admixture of plastics across the anastomosis has occurred. There is no communication with the pulmonary vein (green). × 4.5.

Fig. 8. A large bronchial artery is seen high in the lamina propria. The trabeculations of the mucous membrane are produced by masses of highly vascular granulation tissue. These are seen under higher magnification in Figure 9. The thick wall and relatively narrow lumen of the bronchial artery may be noted. (41855.) × 32.

Fig. 9. Abundant vascular granulation tissue elevating the pseudostratified ciliated columnar epithelium that lines a bronchiectatic sac. (41855.) × 50.

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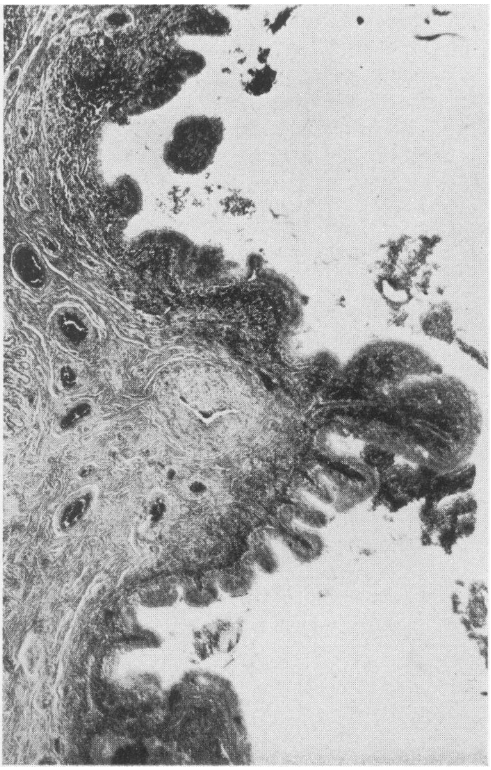

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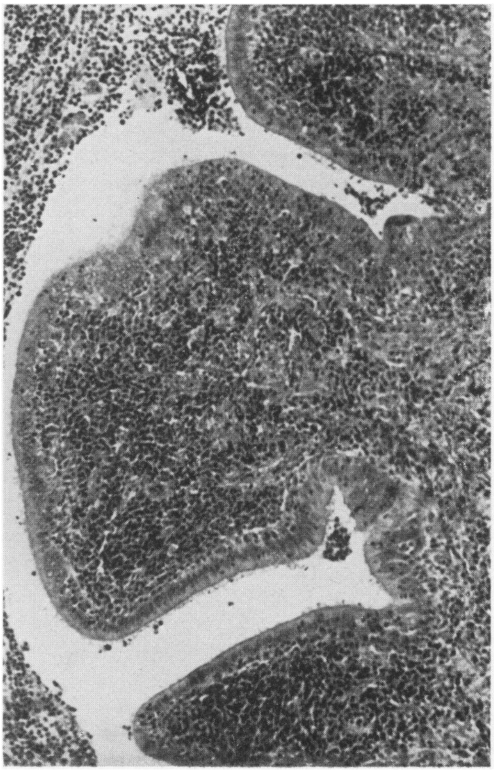

PLATE 31

FIG. 10. Thick bundles of smooth muscle in the wall of a bronchiectatic sac. These receive their blood supply from the enlarged bronchial vessels, one of which is shown near the lower margin of the photograph. (41814.) × 52.

FIG. 11. Wall of a large bronchus in bronchiectasis. Large lymph follicles with prominent germinal centers are seen in the lamina propria. There is also diffuse mucosal infiltration, chiefly of lymphocytes and plasma cells. A large branch of a bronchial artery with a thick muscular wall is seen in the lamina propria. Bound to the external wall of the bronchus is a branch of the pulmonary artery. Pneumonia in process of organization involves the parenchyma surrounding the bronchus. (41910.) × 32.

FIG. 12. Large bronchial artery in the wall of a bronchiectatic sac. An obliquely cut branch traverses the deeper layers of the wall. (41855.) × 50.

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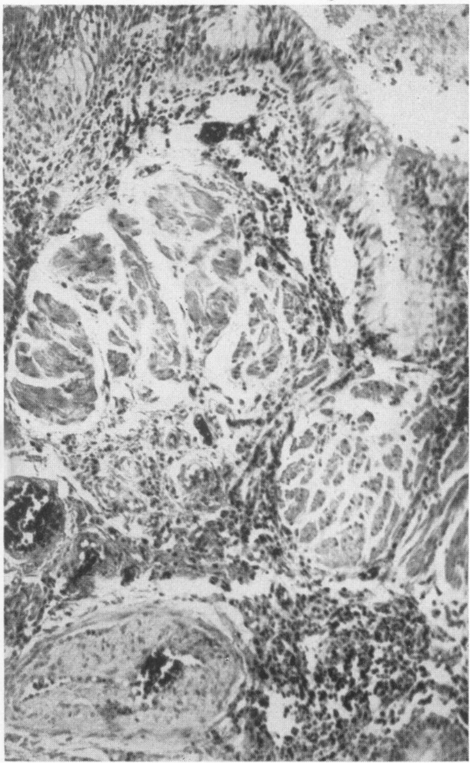


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