During a study of the distensible behavior of the pulmonary artery in vivo, it was necessary to preserve its vasa vasorum to maintain the nutritional integrity of the vessel wall. In contrast to descriptions of the vasa vasorum of the normal aorta and other systemic arteries,\textsuperscript{1-8} the pulmonary artery vasa have received only passing comment.\textsuperscript{8-10} Winter-nitz, Thomas, and LeCompte\textsuperscript{8} noted that the degree of intramural vascularity of the pulmonary artery lies between the systemic veins and arteries; they did not further amplify or illustrate their observations. Both Miller\textsuperscript{9} and von Hayek\textsuperscript{10} in monographs on the lung, mentioned vasa vasorum of the pulmonary arteries and described them as originating from the bronchial arteries; but they specifically referred to branches of the pulmonary artery and did not provide details of this vasal bed. In the absence of precise information about the pulmonary artery vasa, it was essential to determine the anatomical details of the arterial and venous vasa vasorum of the pulmonary artery from its origin to the entrance of the right and left pulmonary arteries into the lung.

The variety of methods used to demonstrate vasa vasorum\textsuperscript{8} indicates the unsatisfactory result achieved with any one. While making silicone rubber injection casts of the circulation in this laboratory, consistent filling of some arterial vasa vasorum was noted. Subse-quently, methods were developed to fill the vasa vasorum of the pulmonary artery in the living rabbit and to demonstrate their course and connections.

\textbf{Methods}

The intravascular injection of an appropriate silicone rubber results in essentially complete and undistorted filling of a selected vascular bed including the microcirculation. Since this has not been possible with other known injection masses, details of the materials and methods used in this study are presented.

\textbf{SILICONE RUBBER INJECTION MASS}

Special physical and chemical properties of silicone rubber make it a desirable injection mass. The nonvulcanized or liquid material has a low surface tension and spreads readily. A desirable low viscosity can be achieved with an appropriate diluent. Water repellent characteristics of silicone rubber enable a homogeneous cast to be made without alteration of the injection by the formation of gelatinous masses. The change from liquid to a rubber-like state during curing or vulcanization results from catalytic polymerization at room temperature (RTV compounds) without appreciable change in volume or heat production. The rate of catalysis can be controlled by the type and concentration of catalyst to provide a selected working time. The pure elastomer is colorless, and color is imparted by appropriate filler during compounding by the manufacturer.

The injection material was a General Electric Company RTV silicone rubber\textsuperscript{*} specially prepared in this laboratory for intravascular injection by careful control of viscosity\textsuperscript{t} and particle size. Viscosity of the noncatalyzed material was approximately 30 centipoises, determined in the Brookfield Viscometer Model LVF, no. 1 spindle, at 26 C. After addition of the liquid catalyst dibutyl tin dilaurate\textsuperscript{f} to a final concentration of 3 per cent by volume, viscosity increased slowly for one hour to provide an adequate working time. Catalysis

\textsuperscript{*}General Electric silicone rubber RTV-200 series. These silicone rubbers are specifically compounded for use as an injection mass and are available through the Silicone Products Department, General Electric Company, Waterford, New York. Accompanying data sheets give full technical information on this series of materials.

\textsuperscript{t}Compound CE-1025, Silicone Products Depart-

\textsuperscript{f}Thermolite-12, Obtainable from Metal and Thermit Corporation, Rahway, New Jersey.
FIGURE 1

Schema of arterial vasa supply, ventral view.
Artery of ligamentum arteriosum (ALA); arcuate artery (AR); arterial vasa confluence (AVC); ligamentum arteriosum (LA); left basilar artery (LB); left coronary artery (LC); long spiral artery (LS); right basilar artery (RB); right coronary artery (RC).

was complete in three hours. Particle size did not exceed 1 μ.

ANIMAL PREPARATION

The arterial vasa vasorum of the pulmonary artery were initially observed to arise from adjacent coronary arteries. Accordingly, an injection procedure was designed to fill retrograde the thoracic aorta and aortic arch as rapidly and completely as possible. Since the injection mass rapidly traversed a capillary bed, a venous vent or run-off was used to permit vascular washout and detailed small vessel filling.

Female albino rabbits, weighing approximately 1 Kg., were anesthetized with urethane 2.5 Gm./Kg., administered parenterally. The trachea was exposed and cannulated, and the animal ventilated mechanically. Through a midline abdominal incision, the lowest portion of the diaphragmatic investment of the aorta was separated and an infusion cannula inserted cephalad into the aorta, secured by a ligature placed immediately above the celiac artery. A soft polyvinyl tube was passed from the inferior vena cava a predetermined distance to the approximate level of the heart, and the animal ventilated mechanically. Through a midline abdominal incision, the lowest portion of the diaphragmatic investment of the aorta was separated and an infusion cannula inserted cephalad into the aorta, secured by a ligature placed immediately above the celiac artery. A soft polyvinyl tube was passed from the inferior vena cava a predetermined distance to the approximate level of the right atrium. The cannula and polyvinyl tubing were filled with heparin-saline solution and closed with one-way stopcocks prior to insertion. The animal was subsequently heparinized, 2 mg./Kg. body weight. The electrocardiogram was observed on a cathode-ray oscilloscope.

The infusion system consisted of a 50-ml burette connected above to a pressure reservoir and a mercury manometer and below to the aortic cannula through an appropriate length of polyvinyl tubing and fittings.

PROCEDURE

Fifty ml. of specially prepared silicone rubber was catalyzed in a 50-ml syringe and the pressure infusion system filled from below. Immediately before infusion of silicone rubber, the effective heart beat was stopped with a rapid injection of 200 mg. disodium ethylenediamine tetraacetic acid dihydrate* (100 mg./ml.) into the aortic cannula. This eliminated the opposing head of pressure of the heart and permitted retrograde aortic infusion to be carried out in the range of physiological pressures.

The initial infusion pressure was 140 mm. Hg. After 5 ml. was injected, the vent (vena caval) catheter stopcock was opened and, after a total of 10 ml. was injected, the infusion pressure was reduced to 80 mm. Hg, where it was maintained until 50 ml. was injected. The time of these manipulations—opening of vent, reduction of pressure, and total infusion—averaged, respectively, 5, 15, and 150 seconds. Discrete silicone rubber globules appeared in the venous catheter blood within a few seconds after opening the stopcock, and at the completion of the infusion, the vent catheter was usually filled with silicone rubber.

Fifteen minutes after completion of the retrograde aortic infusion, the left chest was opened, the left pulmonary artery cannulated, and approximately 100 ml. 0.9 per cent saline slowly instilled into the inferior vena caval catheter at approximately 150 mm. saline pressure. This washed out residual liquid silicone rubber from the right heart and pulmonary artery through the left pulmonary artery cannula. Three hours later, a white silicone rubber mass was manually injected through the pulmonary artery cannula to fill, but not distend, the pulmonary artery. This provided a white background on which to visualize the vasa vasorum.

After an additional eight hours, the thorax was removed in toto, the anterior chest cage excised, pericardium opened, and the remaining thorax and its viscera placed in glycerin (U.S.P.) in which it was shaken gently for 48 hours, with a single change of glycerin at 24 hours. Specimens were stored in glycerin.

Examination and dissection of the specimen were done with the aid of an optical loupe and a stereoscopic dissecting microscope at magnifications up to 30 diameters. The Leitz Aristophot camera assembly was used for macrophotography.

*Sequestrene-Alrose. Supplied by Don Baxter, Inc., Glendale, California.
†General Electric silicone rubber RTV-11.
FIGURE 2
Vasa vasorum of pulmonary artery, rabbit. Silicone rubber injection preparation. (A) Base of pulmonary artery and aorta, anterior view. Origin of right coronary from aorta and right basilar from right coronary (X 6). (B) Pulmonary artery at base. Specimen manipulated to show long spiral artery on right lateral wall (X 6). (C) Pulmonary artery, left anterior view. Origin of left basilar artery and arcuate branches and arcuate supply to arterial wall (X 6). (D) Pulmonary artery, anterior view. General pattern of vessel. Vascular confluences, spiral palisades, and concentration of basilar branches at commissures (X 6).
FIGURE 3
Tracing of figure 2 (A through D) to indicate specific vessels. Aorta (AO); arcuate (AR); arterial vasal confluence (AVC); commissure basilar artery branch at valve commissures (CB); ligamentum arteriosum (LA); left basilar artery (LB); left coronary artery (LC); left coronary vein (LVC); long spiral artery (LS); pulmonary artery (PA); right basilar artery (RB); right coronary artery (RC); right coronary vein (RVC); venous vasal confluence (VVC).

Results
Observations have been made on over 100 normal rabbits. The vasa vasorum of the pulmonary artery consist of arteries and veins paired in course and distribution. They are readily distinguished by the slightly smaller size and origin of the arteries and the ultimate drainage pathway of the veins. In the absence of prior specific identification, the major arterial and venous vasa are named according to their course and described to the limits of their distribution in the blood vessel wall up to, but not including, the microvascular bed.

The size of these vessels varies from in excess of 100 μ at their origin to approximately 25 μ proximal to the microvasculature. Major arteries and veins, 100 to 50 μ in diameter, course superficially in the adventitia; smaller vessels, 50 to 35 μ, are found in the adventitia and outer media; and the minute arteries or arterioles, 35 μ and less, rapidly taper as they pass into the midzone of the media.

ARTERIAL VASA VASORUM
There are three distinct sources of vascular supply to the wall of the pulmonary artery from its origin at the pulmonary valve to the entrance of the right and left pulmonary arteries into the lung: (1) right and left coronary arteries, (2) arteries of the ligamentum arteriosum, and (3) arteries of contiguous mediastinal structures (fig. 1).

From the right coronary artery two vessels supply the right and anterior surfaces of the pulmonary artery wall: (1) right basilar and (2) long spiral, the latter arising from the former. The right basilar (80 to 100 μ) artery arises from the right coronary artery immediately below its origin from the aorta and courses to the left over the junction of the pulmonary artery and the right ventricle (figs. 2A and 3A). A number of branches leave the right basilar artery along its course to supply the proximal third of the right anterior and right lateral pulmonary artery wall at its base, as well as the adjacent myocardium. These longitudinally coursing minute vessels are more concentrated over the valve commissures, although they occasionally pass over the bulge of the valve pocket (figs. 1, 2D, and 3D).

Subsequent right-angle branching results in multiple parallel circumferentially placed vessels which exhibit a spiral course and terminate in a microvascular bed in the wall of the pulmonary artery without notable interconnections.

The long spiral artery (60 to 80 μ) arises a short distance from the origin of the right basilar artery. In its subsequent spiral ascending course on the right lateral wall of the pulmonary artery, it passes from posterior to anterior (figs. 2B and 3B). Numerous secondary branches (30 to 40 μ) leave the long spiral, pass circumferentially over the anterior surface of the pulmonary artery, and spiral or corkscrew as they form a palisade.
of parallel small vessels which either terminate in their own microvascular bed or occasionally anastomose with similar arterial twigs from the left side (figs. 2D and 3D). The long spiral artery continues to the anterior surface of the pulmonary artery proximal to the ligamentum arteriosum, where it almost invariably ends by joining with other small arteries in a common structure, arterial vasal confluence. (See below.)

The left coronary artery is the source of the principal supply to the left and posterior walls of the pulmonary artery through two vessels: (1) left basilar and (2) arcuate. These vessels arise from the left coronary artery immediately below its origin from the aorta, singly or via a common trunk which immediately divides (figs. 2C and 3C). The left basilar artery (80 to 100 μ) is similar in its course and distribution to the right basilar, passing to the right over the junction of the pulmonary artery and the right ventricle with secondary branches ascending the pulmonary artery primarily at the anterior commissure (figs. 2D and 3D). Final branching results in multiple parallel vessels directed circumferentially to the right and left. A longitudinal vessel frequently extends to and participates in the arterial vasal confluence.

The arcuate vessel (50 to 70 μ) is directed slightly posteriorly as it ascends in the concavity of the pulmonary artery. Along its course it gives off multiple parallel branches (30 to 40 μ) which spiral circumferentially anteriorly around the pulmonary artery and terminate as described for branches of the long spiral artery above (figs. 2C and 3C). Not infrequently the major circumferential branches arise from the arcuate close to the left coronary artery and fan out as they pass up and over the pulmonary artery. The arcuate artery contributes one or more vessels to the vasal arterial confluence.

Artery of the Ligamentum Arteriosum (80 to 100 μ)

This discrete vessel arises from the left highest intercostal artery just below its origin from the subclavian, descends along the spine, and penetrates the mediastinal connective tissue to the concavity of the aortic arch. It accompanies and supplies the connective tissue around the ligamentum arteriosum and terminates in the wall of the pulmonary artery as part of the arterial vasal confluence (figs. 2D and 3D).

Arteries from Contiguous Mediastinal Structures

Small arterial twigs (50 to 70 μ) from the trachea, bronchi, and adjacent mediastinal connective tissue supply the wall of the right and left pulmonary arteries and the pulmonary artery at its bifurcation. The arterial vasa accompany the right and left pulmonary arteries to their entrance into the lung. At the bifurcation of the pulmonary artery, an arterial palisade extends over the crotch from behind forward and outward around both right and left pulmonary arteries and the main pulmonary artery proximal to its bifurcation. A few of these latter vessels communicate directly with the vasal confluence on the anterior surface of the pulmonary artery.

Arterial Vasal Confluence*

This anastomotic vascular structure lies on the anterior surface of the main pulmonary artery proximal to the ligamentum arteriosum. It is formed by a confluence of one or more arterial branches from the major vessels supplying the pulmonary artery wall: the long spiral, right and left basilaris, arcuate, and artery of the ligamentum arteriosum (figs. 1, 2D, and 3D). Smaller communications between the confluence and the arterial supply to the region of the bifurcation are also present.

VENOUS VAS VASORUM

These vessels drain the wall of the pulmonary artery. In their course they parallel the arterial supply, and the following drainage routes are recognized: (1) right and left ear-

*The precise descriptive term for this structure posed a problem. Since the observed interconnection of vessels indicated functional significance, the term confluence was selected to fulfill nomenclature criteria. The help and advice of Dr. Paul Paddock are acknowledged.
diac veins, (2) veins of the ligamentum arteriosum, and (3) veins of contiguous mediastinal structures. Some of the anatomical architectural patterns seen in the arterial vasa are also seen in the venous vasa, especially spiral palisading in the regions of convexity, the vasal confluence, and a predominance of longitudinally directed vessels on the lateral surfaces and at the valve commissures.

The right and left cardiac veins drain the proximal two-thirds of the pulmonary artery wall and in turn join the coronary sinus. The right cardiac vein drains the right lateral and anterior surfaces of the pulmonary artery through numerous tributary vessels which course proximally down the pulmonary artery to enter the right cardiac vein at the base of the pulmonary artery. Although gradual merging of veins occurs, large collecting veins are usually not found. Inconstantly, a right lateral spiral vein is present on the right lateral wall. The left cardiac vein drains the left lateral and posterior surfaces of the pulmonary artery wall via multiple merging vessels. Inconstantly, an arcuate vein is present in the concavity of the pulmonary artery.

**Discussion**

From the descriptions and illustrations of the vasa vasorum of major arteries in the literature, the rich pattern of the vasa of the pulmonary artery noted in these experiments could not have been expected. The extensive filling of these nutrient vessels has no counterpart in other studies and apparently resulted from the properties of the silicone injection mass, the technique of the procedure, and the available vasal bed to be filled.

The properties of the silicone elastomer used in these experiments have been described above. In view of the highly desirable characteristics and ease of handling, the silicone rubbers should become a valuable tool to study blood vessels in their near physiological state. Further alterations in the compounding of the silicone rubber may provide other materials with highly selected and special properties to do a precise task.

Once a desirable injection material was available, filling the pulmonary artery vasa was facilitated by the special hemodynamics of the pulmonary vascular bed. The normal low pressure of the pulmonary circuit results in low intramural tension of the pulmonary artery, in turn producing little obstruction to flow in these arterial vasa which originate from systemic arteries. This is in contrast to vasa vasorum of systemic arteries which invariably arise from the lumen of the vessel whose wall they supply. In this latter circumstance, attempts to fill vasa vasorum more completely by increased intravascular pressure may be self-defeating, since the concomitant increased intramural tension results in increased resistance to vasal flow.

It is difficult to categorize the true extent of the vasa vasorum of a vessel. The total vasal tree may bear no relationship to that physiologically active at the precise moment it is filled during an experimental procedure. Indeed, although the vascular pattern is consistent from specimen to specimen, the local filling patterns may vary considerably. Short of physiological procedures which result in maximal opening of the total vasal bed, as well as quantitative physiological and anatomical methods for measurement of the bed, the full extent of the vasa vasorum cannot be determined.

Some features of these vessels need special comment. The spiral palisade of arteries and veins is uncommon and exquisitely adapted to maintain circulation in varying states of blood vessel stretch. Spiral nutrient vessels have not been previously noted in other large blood vessels, although they are commonly found in the uterus, ovary, and corpus cavernosum. This suggests that additional search for spiral arteries in other tissues and organs with these materials and methods may be worthwhile.

The arterial and venous vasal confluence are unusual, and no description of a similar vasal structure has been found. The purpose of this peculiar vascular anastomosis is not obvious. Since the confluence is apparently in the area of maximal stretch of the unsupported pulmonary artery wall, it may...
be an anatomical-physiological adaptation for stretch. The opulent arterial and venous connections to the many supply and drainage sites could further ensure circulatory continuity of the pulmonary artery wall under varying distention.

Until blood flow is measured in the vasa vasorum, the role of these vessels in nutrition of the pulmonary artery wall can only be hypothesized. It seems unlikely that such rich supply and drainage and the intervening microvascular bed are not physiologically significant. If this is indeed so, our ideas of blood vessel wall metabolism, as well as methods of blood vessel study, will need some modification.

Summary

In the rabbit, the arterial and venous vasa vasorum of the pulmonary artery from its origin to the entrance of the right and left pulmonary arteries into the lung were studied and described through the use of a specially prepared silicone rubber injection mass. The physical-chemical characteristics of this material allowed detailed filling of the vascular bed under physiological conditions. Special features of the rich arterial and venous vasa vasorum of the pulmonary artery include: (1) spiral palisading of small vessels and (2) arterial and venous vasa confluences that result from the junction of branches from multiple supply and drainage sites. Both of these may be special adaptations for the normal rapid stretch of the pulmonary artery.

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