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The Junction Between the Left Atrium and the Pulmonary Veins

An Anatomic Study of Human Hearts

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THE SPHINCTER-LIKE FORMATIONS and the myocardial sleeves which have been described around the pulmonary veins in the dog have been generally found to be better developed in the superior than in the inferior vessels.[1] The present study on human hearts was undertaken because, to the best of our knowledge, no detailed description of the structural differences in the various pulmonary veins at their junctions with the atrium have hitherto been reported. Apart from anatomic accuracy it is believed that such differences in the atrial-venous junctions may be of physiological and pathological importance. In addition, with further development of surgical techniques, knowledge of these differences may prove to be of value to the cardiac surgeon.

Methods

The study was made on 16 hearts obtained from autopsies performed in the Jacobi Hospital,* New York. These included whites and Negroes, both males and females. The patients were aged 16 to 63 years. The hearts were removed together with the pulmonary vessels and a part of the lungs. The superior caval vein was cut above the opening of the azygos vein; the inferior caval vein was cut at the level of the diaphragm. The atria were separated from the ventricles at the level of the atrioventricular sulcus. They could then be examined from both the inner and outer sides. The thickness of the posterior wall of the left atrium was measured by means of a micrometer caliper provided with a ratchet stop, which allowed measurement at a constant pressure, and a vernier, which permitted reading with an accuracy of 0.1 mm. Measurements were made between the entrance of: (1) the right and left superior pulmonary veins; (2) the right and left inferior pulmonary veins; (3) the right superior and inferior pulmonary veins; (4) the left superior and inferior pulmonary veins.

Each specimen was cleaned of remnants of pericardium, fascia, vessels, and nerves, in order to expose the myocardial fibers as clearly as possible. Stuffing of the atria and the large vessels with cotton facilitated the dissection. The natural color of the myocardium was better retained in fresh specimens or those preserved at 4 C, while Formalin fixation was satisfactory for following the course of the fibers and fascicles. Particular attention was paid to the atrial-venous junction and the extension of the myocardial fibers in the pulmonary veins. The length of the myocardial venous sleeves at the various sites of the venous wall and the length of the extrapulmonary portion of the veins were also measured. Schematic drawings of the course of the myocardial fibers and photographs of the dissected specimens were made in all cases.

Observations and Descriptions

A common pattern in the arrangement of the superficial myocardial fibers of the atria was observed in most of the specimens and will be described first. Individual variations from the common pattern, as well as particular characteristics of the atrial venous junction of each of the pulmonary veins, will then be given in detail.

Common Basic Patterns (Fig. 1)

The common basic pattern consists of a main circular fascicle of fibers (a, a′, a″, a‴) running peripherally around the area of the openings of the pulmonary veins in the left atrium. The upper part of this fascicle (a), running horizontally above the right and left superior pulmonary veins, is formed by:

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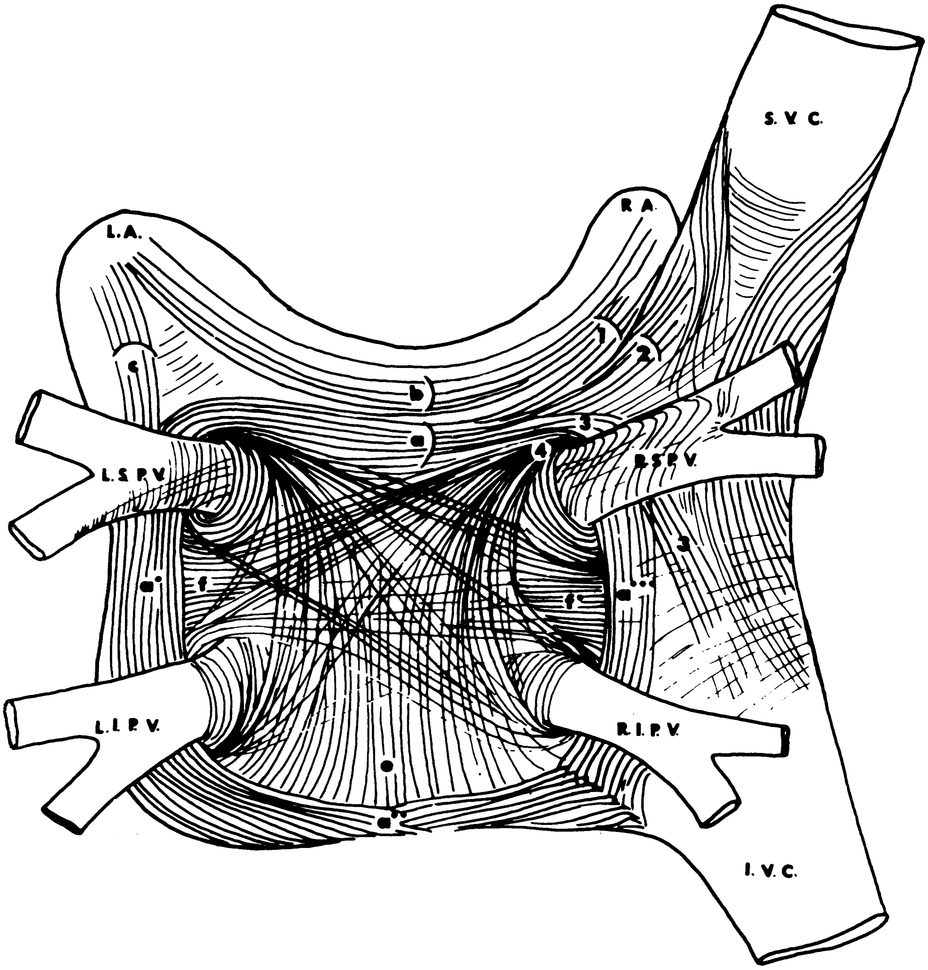

Figure 1

The common pattern of the superficial myocardial fibers of the left atrium (posterior aspect). A main circular fascicle (a, a′, a″, and a‴) runs peripherally around the area of the openings of the pulmonary veins. An interatrial fascicle (b) runs between the right (RA) and the left (LA) atrium. Some fibers (c) descend from the left atrium into the left part (a′) of the main circular fascicle. Circular fibers leaving the main fascicle turn around the openings of the pulmonary veins, forming sphincter-like structures; other fibers extend over the veins as myocardial sleeves. Loops of fibers coming from the atrium are seen over the right superior pulmonary vein (R.S.P.V.) and returning to the atrium. Oblique, vertical (e), and transverse (f, f′) fascicles of fibers are also seen on the posterior atrial surface. L.A. = left atrium; R.A. = right atrium; S.V.C. = superior vena cava; I.V.C. = inferior vena cava; R.S.P.V. = right superior pulmonary vein; L.S.P.V. = left superior pulmonary vein; R.I.P.V. = right inferior pulmonary vein; L.I.P.V. = left inferior pulmonary vein.

(1) fibers descending from the right atrial appendage; (2) fibers descending from the wall of the superior caval vein; (3) fibers ascending from the right atrium; and (4) fibers of the right side of the same main circular fascicle (a′″), which ascend and turn to the left, around the right superior pulmonary vein. A bunch of fibers descending from the right atrial appendage forms a broad "interauricular fascicle" (b) which ends in the left atrial appendage. Most of the fibers of this interatrial fascicle run parallel and intermingle partially with the upper part (a) of the main circular fascicle. Other fibers (c)

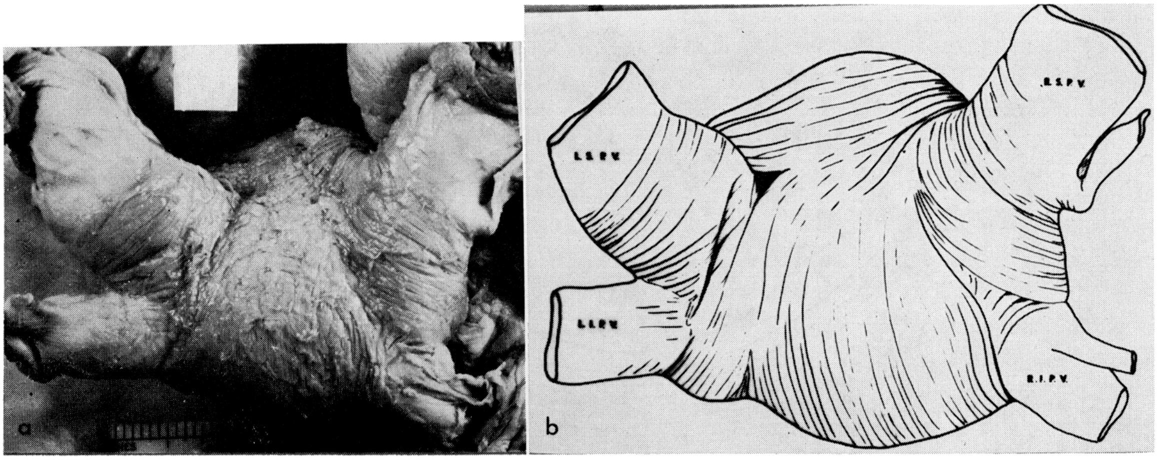

Figure 2

Predominant vertical pattern: (a) posterior aspect of left atrial specimen; (b) schematic representation. Note that the myocardial sleeves are better developed around the superior pulmonary veins than around the inferior veins.

descend from the left atrium into the left part (a′) of the main circular fascicle. Many fibers of the main circular fascicle end in the atrioventricular fibrotic rings, while new fibers arise from these rings. In the immediate vicinity of each of the pulmonary veins, muscle fibers leave the main fascicle and turn around the opening of these veins, forming a sphincter-like structure; some of these circular fibers may extend to a greater or lesser degree over the vein, contributing to the formation of the myocardial sleeves which cover the venous walls to a variable distance. Other fibers leaving the main fascicle run obliquely on the posterior surface of the left atrium toward the openings of other pulmonary veins, forming more or less conspicuous oblique fascicles. Another layer of fibers is seen appearing from beneath the main circular fascicle (e, f, and f′) on the posterior surface of the left atrium. The fibers of this layer, which are situated between the right and left inferior pulmonary veins, run a vertical course (e), while those between the superior and inferior right or left pulmonary veins run a transverse horizontal course.

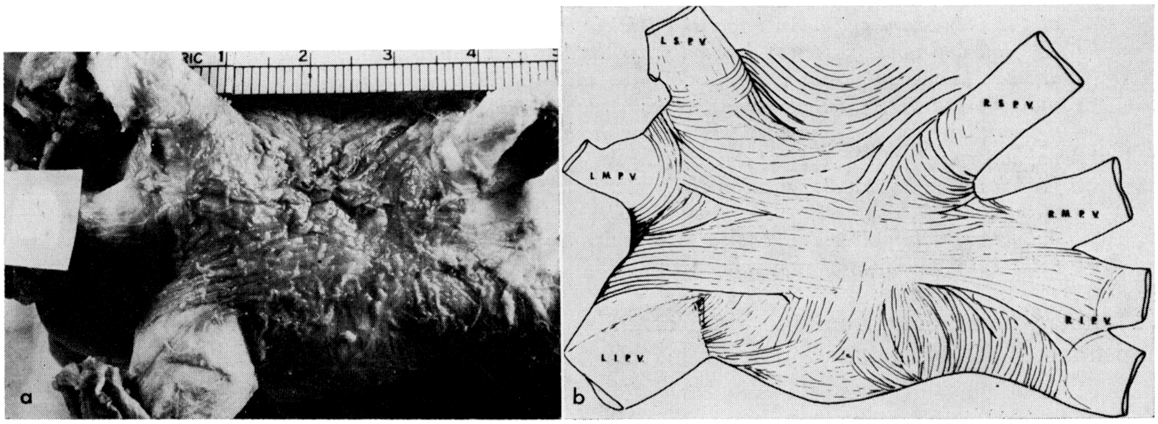

Figure 3

Predominant horizontal pattern: (a) posterior aspect of left atrial specimen; (b) schematic representation. Three veins are present on each side.

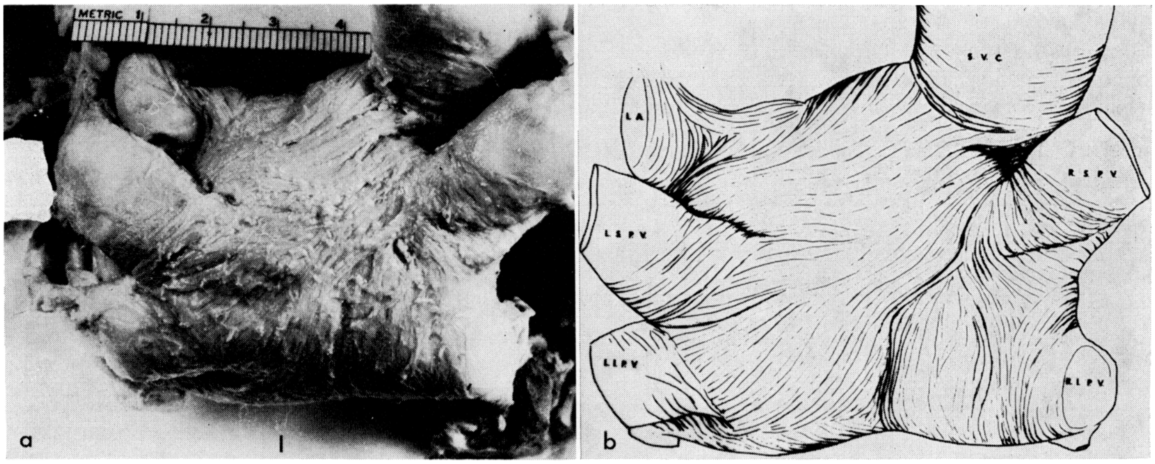

Figure 4

Predominant oblique pattern: (a) posterior aspect of left atrial specimen; (b) schematic representation. The sphincters are better developed around the superior than around the inferior pulmonary veins. The right inferior pulmonary vein was cut close to the atrium.

Therefore, the area of the left atrium, circumscribed by the openings of the pulmonary veins, is crossed by myocardial fibers running in all directions, obliquely, transversely, and vertically, intermingling and decussating each other. The predominance of certain groups of fibers running in the same direction but more superficially than the others gives the individual characteristics to each specimen (figs. 2 to 5).

Individual Variations in Arrangement of Myocardial Fibers in the Left Atrium, Atrial-Venous Junctions, and Myocardial Venous Sleeves

The predominant direction of the fibers in the posterior surface of the left atrium, between the various pulmonary veins, is variable, and different patterns were found. The most frequent patterns, according to the direction of the fibers, were the following: (1) vertical, where the main predominant fascicles are

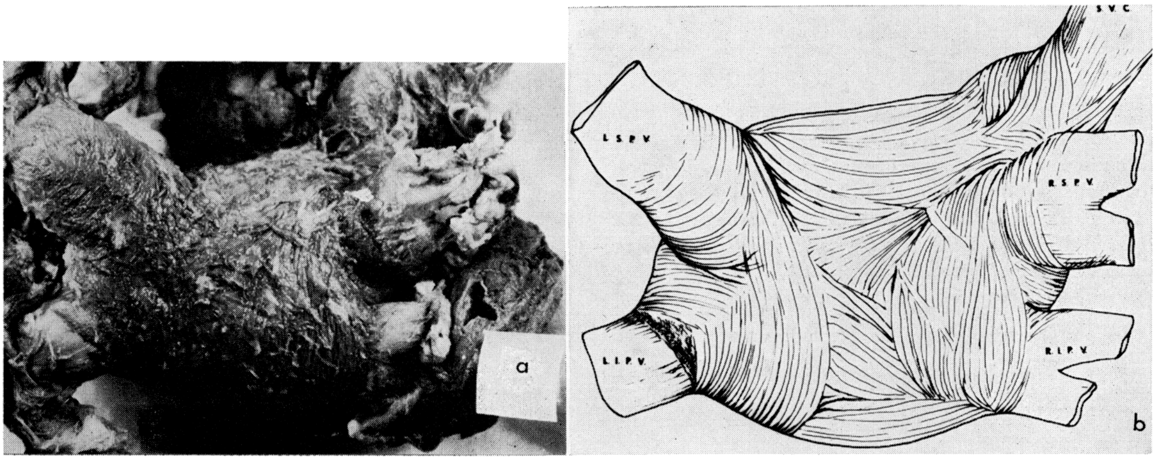

Figure 5

"Mixed" pattern: (a) posterior aspect of left atrial specimen; (b) schematic representation. Fascicles of vertical fibers are seen close to the pulmonary veins on both sides. Oblique fibers are seen between the vertical fibers. The myocardial sleeve and the sphincter of the left inferior pulmonary vein is less conspicuous than those of the other veins.

formed by the vertical fibers (fig. 2); (2) horizontal, where the superficial fascicles are formed predominantly by the transverse fibers (fig. 3); and (3) oblique, where the predominant superficial fascicles ascend obliquely, most frequently from left to right (fig. 4).

The oblique and vertical patterns are the most common, while the horizontal is less frequent. In some cases the fibers cross each other and intermingle in such a manner that no predominance of direction is observed (fig. 6). In other cases (fig. 5), a predominant fascicle running in a certain direction is split, and fibers running in other directions appear between the cleaved fibers.

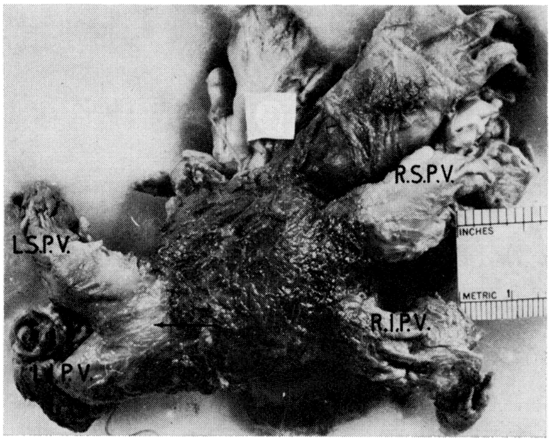

Figure 6

"Mixed" pattern: The muscular fibers in this specimen intermingle with each other with no predominant direction. The left part of the atrial wall, adjacent to the left superior and inferior pulmonary veins (arrow), is devoid of myocardium. In contrast to the right pulmonary veins, the left pulmonary veins have no myocardial sleeves and sphincters.

The results of the measurements show that the atrial wall is not uniformly thick (table 1). The upper part of the left atrial wall, particularly the area between the right and left superior pulmonary veins, was consistently found to be thicker (average 1.8 mm) than the inferior part, between the right and left inferior pulmonary veins (average 1.0 mm). The former area appears as a decussation center of the main fascicles of the posterior atrial wall. No significant differences were found between the thickness of the right and left sides of the posterior atrial wall (average 1.0 and 0.8 mm, respectively). In some specimens, the atrial wall adjacent to the openings, generally of the inferior pulmonary veins, appeared totally devoid of muscle fibers (fig. 6). The atrial wall at these sites was very thin and consisted only of endocardium covered with some connective tissue and the pericardium.

Atrial-Venous Junctions and Myocardial Sleeves Extending over the Pulmonary Veins

The atrial-venous junctions, as mentioned previously, were formed mostly by the sphincter-like fibers which, leaving the mean circular atrial fascicle, turn around and embrace the openings of the pulmonary veins (fig. 1). Longitudinal fibers from the main circular and the oblique fascicles may also continue over the veins. Marked variations, however, may be found between the pulmonary veins of the same specimen as well as between different specimens. The sphincters around the superior pulmonary veins were in general somewhat thicker and more conspicuous than those around the inferior veins (figs. 2, 4, and 7). In most of the specimens, myocardial sleeves extended over the pulmonary veins

Table 1

Thickness of Posterior Surface of Left Atrial Wall at Four Different Sites (Between the Pulmonary Veins)

	Thickness of left atrial wall (mm) between			
	RSPV-LSPV	RIPV-LIPV	RSPV-RIPV	LSPV-LIPV
Range	1.0 – 4.2	0.6 – 1.8	0.6 – 1.7	0.4 – 1.4
Average	1.8	1.0	1.0	0.8

RSPV and LSPV = right and left superior pulmonary veins; RIPV and LIPV = right and left inferior pulmonary veins.

for a variable distance (table 2). In some veins the sleeves extended as far as the hilus of the lung, or even beyond it. On the other hand, some veins, more often the inferior than the superior ones, had no myocardial extensions (figs. 2, 4, and 7). Furthermore, as previously mentioned, the atrial wall adjacent to these veins sometimes appeared devoid of myocardium (fig. 6).

The myocardial sleeves were formed by one or more layers of fibers running in circular, longitudinal, oblique, and spiral directions. Loops of fibers leaving the atrium and returning to it after covering the venous wall to a variable distance were seen very often (fig. 1). The free border of the muscular sleeves generally ran an oblique course, that is, its distance from the atrium was different on the various sides of the venous wall. Here, again, the superior pulmonary veins were found to have longer and better developed myocardial sleeves than the inferior veins (table 2) (average values R.S.P.V., 13 mm; R.I.P.V., 8 mm; L.S.P.V., 18 mm; L.I.P.V., 10 mm) (figs. 1, 2, 4, 5, and 7). When a pulmonary vein branched off, the myocardial sleeve, if present, was sometimes seen to accompany both branches (fig. 7); in other cases, however, it continued in only one of the branches. Measurements of the length of extrapulmonary portions of the pulmonary veins, as well as the length of the veins from the heart to the first division, are also presented in table 2.

Variations in the number of pulmonary vein openings into the atrium are well known and were also observed in our specimens. The general pattern of arrangement of the myocardial fibers varied accordingly in each of these cases.

A very conspicuous myocardial sleeve consistently extended from the right atrium over the superior caval vein, at an average distance of 24 mm (table 2), while over the inferior caval vein such extensions were either absent or very small (fig. 1).

Embryological Considerations

The variations in the pattern of arrangement of the atrial myocardium at the atrial-venous junctions and the myocardial extensions over the veins should be analyzed in the light of the embryological development of the atrium and the veins.[2-8] It is well

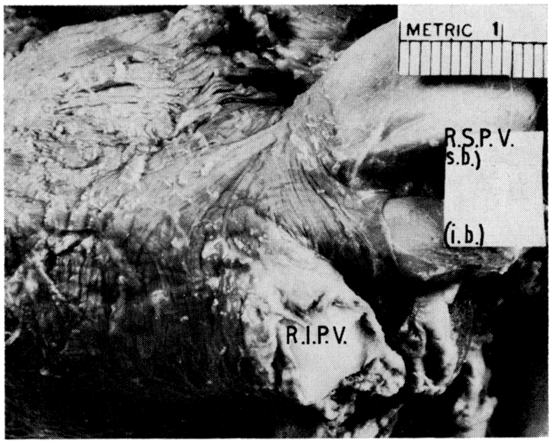

Figure 7

The right superior pulmonary vein (R.S.P.V.), which divides into two branches close to the atrium, has a very well developed muscular sphincter and a myocardial sleeve which extends beyond its division over both branches. On the other hand, the right inferior pulmonary vein (R.I.P.V.), cut close to the atrium, shows no muscular extension.

Table 2

Measurements of Myocardial Sleeves Covering the Pulmonary and Caval Veins and the Total Extrapulmonary Portion of the Pulmonary Veins (Fifteen Specimens)

	Length of the myocaordial sleeves extending over the veins (mm)						Length of extrapulmonary portions of pulmonary veins (mm)			
	Pulmonary veins				Venae cavae					
	RS	RI	LS	LI	S	I	RS	RI	LS	LI
Range	5 – 25	1 – 17	8 – 24*	1 – 19	15 – 33	8 – 10†	20 – 42	10 – 30	12 – 38	13 – 31
Average	13	8	18	10	24	9	30	21	29	20

*In one specimen there was no myocardial sleeve.
†Sleeves were found in only three specimens.

known that the atria arise developmentally from two different parts: (1) the original atrial part of the cardiac tube, and (2) the venous sinus and the originally single pulmonary vein, which are absorbed and incorporated in the right and left atrial walls, respectively. Like the myocardium of the ventricles, the myocardium of the original atrium develops early from the epimyocardial mantle. On the other hand, the atrial wall of venous origin is totally devoid of myocardium at the beginning,[3] and the muscle develops only in the later stages. We were unable to find specific descriptions of the embryological process of myocardial formation in the venous part of the atrial wall and the muscular sleeves extending over the pulmonary veins. As far as we are aware, it is not known whether this myocardial formation results from a differentiation of the mesodermal tissue around the venous wall or from invasion of muscle fibers of epimyocardial mantle origin. Whatever the process may be, it seems that the formation of the atrial wall by absorption of the embryonal pulmonary vein and its main branches and by its later muscularization is a main factor in determining the anatomic variations in this area, that is, the different number and length of the main pulmonary veins, variations in the arrangement of the myocardial fascicles in the posterior wall, the venous junctions, and the myocardial venous sleeves.

Discussion

Most anatomic treatises confine themselves to very general descriptions of the superficial cardiac musculature of the atria, mentioning in particular the horizontal interatrial fascicle, the vertical fascicle, and the circular fibers around the venous openings. Although detailed descriptions of the atrial musculature may be found in the literature,[9–12] to the best of our knowledge no descriptions of the *variations* of the superficial fascicles on the posterior atrial wall and the atrial-venous junctions are available. The myocardial-venous sleeves, although mentioned by Wale[13] as early as 1641, have usually been neglected both by anatomists and physiologists.

In his early description, Wale[13] reported the presence of the "fleshy fibers" covering the vena cava in the proximity of the heart of man, ox, and dog. He also observed that every heart movement starts in the vena cava. Striated muscle in the walls of the pulmonary veins was described by Rauschel,[14] in 1836, and later by Elischer,[15] Arnstein,[16] and Stieda.[17] The last two authors[16, 17] used the term "atrial sheath" and described its presence in several species including man. Since then the presence of striated cardiac muscle around the pulmonary veins in different species, including man, has been confirmed both macroscopically and histologically by numerous investigators.[18–31] The distance to which striated muscle stretches into the pulmonary veins has been found to vary from one species to another, and in many cases it reaches the small vein divisions in the lungs.[18] According to Favaro[19] the smaller the animal the deeper the cardiac muscle penetrates in the veins within the lung. In the albino rat striated muscle occupies the entire medial layer of the pulmonary veins which, significantly enough, are devoid of smooth muscle.[28] Benninghoff[20] and Bargmann and Doerr[27] described the myocardial sleeves in man as extending to the pericardial reflexion line, while Amano[21] observed them as far as 15.8 mm beyond that line, and in fetuses even in the intrapulmonary portion of the veins. Our own observations in the present and previous studies[1] have confirmed that, in man and dog, atrial striated muscle may extend as far as the lung border and beyond it.

The function of the cardiac muscle in the pulmonary venous wall has not been investigated thoroughly. Three possible functions have been considered:

1. Throttle Valve Action

It is generally believed that the venous sphincters and sleeves exert a valve action that prevents reflux of blood from the atrium into the veins during systole.[22–26] This concept has been supported by the roentgenological observations of contraction of the atrial-venous junction during systole in man.[32] Closure of the atrial-venous junctions has also been described in dogs[33] in experimental conditions, when the pulmonary venous pressure falls below 6 to 7 mm Hg.

2. Active Expulsion of Blood into Left Atrium

The finding of striated muscle in the entire media of the pulmonary vein of the rat has led to the assumption that its contraction in association with the cardiac activity facilitates the filling of the left atrium during diastole. Systolic contractions of the extrapulmonary portion of the pulmonary veins have actually been observed in the rat and mouse.[13, 30, 34–36] In hypothermic newborn mice the sequence of contractions was found to be: veins, atria, and ventricles.[30] Interestingly, Hooker and associates[30] observed that the veins may sometimes transmit their contractions to the ventricles without a visible atrial contraction. Carrow and Calhoun[31] suggested that a peristaltic or "milking" action toward the heart was produced by the contractions of the myocardial fibers which run from the atrium over the veins and back to the atria again.[31]

3. Regulation of Pulmonary Venous Pressure and Blood Flow

The basic tonus of the striated muscle and its possible changes due to various physiological and pharmacological stimuli may be of importance in the regulation of the pulmonary venous pressure and blood flow. The pressure-flow relationship of the extrapulmonary portion of the pulmonary vein in dogs has been recently investigated; increasing flow rates were found to raise the pulmonary venous pressure and decrease the venous resistance.[37] A similar decrease in pulmonary venular resistance with increased flow rates was later reported by Kuramoto and Rodbard.[38]

The pulmonary veins are also capable of reacting to many different pharmacological and physiological stimuli. Spasm of the large pulmonary veins in vitro has been produced by anoxia, acetylcholine, epinephrine, and histamine.[39, 40] A venoconstrictive effect of carbon dioxide in the isolated perfused lung of the cat[41] and dog[42] has also been demonstrated. Other stimuli causing pulmonary venous constriction in intact animals or man are: hypoxia,[43–45] steam inhalation,[46] starch embolization,[47] endotoxin,[48] alloxan,[49] serotonin,[37, 50–53] histamine,[37, 50, 51] epinephrine and norepinephrine,[37, 50] acetylcholine,[37] and hypertonic solutions.[1, 54] Stimulation of the stellate ganglion[37] as well as of the aortic body chemoreceptors[52] also lead to pulmonary venoconstriction. In all of these cases, however, no effort has been made to differentiate between smooth and striated muscle contraction as the factor responsible for the spasm. Furthermore, the nerve supply of the extracardiac striated muscle as related to the myocardium of the heart should be investigated more thoroughly.

Differences in structure between the atrial junction of the superior and inferior pulmonary veins was first described in dogs by Eliakim and associates.[1] The present study on human hearts confirms that, in general, like in the dog, the atrial wall is thicker between the superior pulmonary veins than between the inferior pulmonary veins. Likewise, the sphincter-like formation and the myocardial venous sleeves are more developed around the superior pulmonary veins than around the inferior ones, although the differences do not seem to be as marked as in dogs. The significance of these differences in structure is entirely unknown. It is well established that, in healthy individuals, the blood flow through the lower lobes is slightly larger than the flow through the upper lobes, while the reverse is true in patients with advanced mitral stenosis.[55–58] Pulmonary venous hypertension following the administration of hypertonic solutions into dogs is more pronounced or may be confined to the superior pulmonary veins;[1] these findings are in keeping with the more developed sphincters described around these veins.[1] A sphincter mechanism, more pronounced in the superior pulmonary veins, was also demonstrated following occlusion of the opposite pulmonary artery, hypoxia, or administration of epinephrine or serotonin to dogs.[59]

Whether the anatomic variations in this region play any role in the regulation of the blood flow through the various lobes of the lung in man, both in health and in pathological conditions, remains to be proved.

A detailed knowledge of the anatomy of the left atrial-pulmonary venous junction may perhaps be of help to the cardiac surgeon because of the occurrence of isolated lesions involving the pulmonary veins. Congenital stenosis of the pulmonary venous-left atrial junction has been described in man.[60–62] In the case of Reyke[60] there was atresia of the right upper lobe vein and stenosis of all others. Another patient described by Ferenz and Damman[61] had atresia of the left lower pulmonary vein and stenosis of the upper lobe vein. Still another case was described by Bernstein and associates.[62] These lesions, if unrecognized and untreated, invariably lead to severe pulmonary hypertension, early heart failure, and death.

Summary

Some anatomic features of the posterior wall of the left atrium, the atrial-pulmonary venous junctions, and the myocardial sleeves extending over the pulmonary veins, as observed in 16 human hearts, are described.

Different patterns of direction of the myocardial fibers of the atrial wall were found in the different specimens. The atrial wall between the upper pulmonary veins was consistently thicker than that between the lower ones. Similarly, the sphincter-like structures of the atrial-pulmonary venous junctions were generally more conspicuous, and the myocardial venous sleeves better developed in the superior than in the inferior pulmonary veins. The physiological and pathological implications of these findings are discussed.

Acknowledgment

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Otto Loewi (Nobel Prize in Medicine, 1936)

In the night of Easter Saturday, 1921, I awoke, and jotted down a few notes on a tiny slip of paper. Then I fell asleep again. It occurred to me at six o'clock in the morning, that during the night I had written down something most important, but I was unable to decipher the scrawl. That Sunday was the most desperate day in my whole scientific life. During the night, however, I awoke again, and I remembered what it was. This time I did not take any risk; I got up immediately, went to the laboratory, made the experiment on the frog's heart . . . and at five o'clock the chemical transmission of nerve impulses was conclusively proved.—A. C. Corcoran: *A Mirror up to Medicine*. Philadelphia, J. B. Lippincott Co., 1961, p. 261.