ON THE MUSCULAR ARCHITECTURE OF THE VENTRICLES OF THE HUMAN HEART

FRANKLIN P. MALL

Professor of Anatomy, Johns Hopkins University, Baltimore, Md.

TWENTY-TWO FIGURES

The present study is to be considered as a continuation of John Bruce MacCallum's, whose ill health prevented him from continuing his work. MacCallum was a brilliant student, a man of marked artistic temperament, whose untimely death has been a very great loss to scientific anatomy. At the beginning of his medical career, while he was yet a student of histology, he made important observations on the histogenesis of the heart muscle cell[1] which he believed to show that the main growth of the wall of the ventricle takes place immediately under the endocardium, —possibly in the Purkinje fibers. In order to give this question a fuller test, he made a study of the growth of the sartorius muscle,[2] for it was thought that in this simple organ a key to the growth of the muscle walls of the heart might be found. Although the hypothesis regarding Purkinje fibres has proved to be erroneous and although the study of the sartorius has been found to be of little value in the study of the heart muscle, he did succeed in unrolling the wall of the left ventricle into a single sheet or scroll of muscle fibers.[3] His presentation of the archi-

[1] J. B. MacCallum, On the histology and histogenesis of the heart muscle cell. Anatom. Anzeiger, 13, 1897.

[2] J. B. MacCallum, On the histogenesis of the striated muscle fiber, and the growth of the human sartorius muscle. Johns Hopkins Hospital Bulletin, 1898.

[3] J. B. MacCallum, On the muscular architecture and growth of the ventricles of the heart. Welch Festschrift, Johns Hopkins Hospital Reports, vol. 9, 1900.

tecture and growth of the ventricles of the heart marks a milestone in this study, the like of which is found only in Gerdy's some seventy-five years before. Both Gerdy[4] and MacCallum studied the heart muscle as a whole and did not deal with it in fragments. MacCallum, as Gerdy, did his work while still a medical student, but unlike him, presented his work in a masterly way. His paper is comprehensive. When we recall that MacCallum unraveled the heart musculature of the foetal pig in the brief period of a week, conceived his illustrations in a second week, and wrote his beautiful paper in a third week, we realize that he was possessed with genius of a very high order. Ill health checked his studies in this direction and his untimely death brought them to an end. However, the problem and his spirit of work have lingered with us, and it was first Knower[5] who showed that what MacCallum had found in the foetal pig's heart could be confirmed in the human adult. This has made it possible to round out the work of MacCallum in order to make it of use to anatomists and physiologists. The desire to do this MacCallum had often expressed to me, and I consider it a privilege and a duty to a friend and to our science, to carry out, in a measure at least, a plan which he was compelled to abandon.

The first good analysis of the musculature of the heart was given by Winslow about two hundred years ago and we see some progress in this line of study in Paris through his pupils and successors until the brilliant work of Gerdy published in his doctor's thesis about a century later. The connection of the fiber bundles at the base of the heart, which turn upon themselves at its apex, was well known to Lower,[6] and a good description of the arrangement of the external fibers was given by Winslow,[7] and later by C. F. Wolff.[8]

[4] Gerdy, Recherches, discussions et propositions, etc., Thèse, Paris, 1823.

[5] Knower, Demonstration of the interventricular muscle bands of the adult human heart. Anatom. Record, 2, 1908.

[6] Lower, Tractatus de corde. London, 1669.

[7] Winslow, Mémoires de l'Academie Roy. des Sciences, Paris, 17 1.

[8] Wolff, Acta, Acad. Sci. Imp. Petropal., vols. 2–10, 1780–92.

The heart muscle problem comes up anew in the great edition of Hildebrand's anatomy by E. H. Weber nearly a century ago.[9] He also considered the organ as a whole and did not neglect the study of its function, a distinction which has characterized the work of the Leipzig anatomists and physiologists since his time, as the publications of C. Ludwig,[10] Krehl,[11] His, Sr.,[12] and His, Jr.[13] bear witness. All this illustrates that progress in anatomy is most likely to occur when its problems include the study of growth and function, as well as of structure.

Although MacCallum found that he could unroll the foetal pig's heart by macerating it in a modified Krehl's mixture of nitric acid, this is by no means necessary. Hearts that have been boiled in water slightly acidulated with acetic acid are of very great value for the study of the course of the fibers. Unfortunately this method causes the hearts to shrink—puts them into the systolic state—and softens the tendons at their base. For these reasons I boil only two hours or less or until the outer connective tissue and fat can be easily removed without softening the tendons too much. For careful dissection, however, it is well to have the hearts distended and somewhat tougher than the boiled hearts are. Such specimens can be made by fixing either distended or contracted hearts in a 3 per cent solution of carbolic acid. Specimens prepared in this way may be kept in stock, but their dissection is slow and tedious. The outer connective tissue must be stripped off before the muscle bundles may be separated with the forceps and fingers. The disadvantage of the carbolic acid is apparent, but I have found that the acid can be washed out in flowing water in the course of several days. Weak alcohol and other macerating fluids are also of value, but since most of the hearts used came from cadavers which had

[9] E. H. Weber, Hildebrand's Handbuch der Anatomie des Menschen. Braunenschweig, 1831, Bd. 3.

[10] C. Ludwig, Zeit. für rat. Med., Bd. 7, 1849.

[11] Krehl, Abhandl. d. K. S. Ges. d. Wiss. Math.-phys. Cl., Bd. 17, 1891.

[12] His, Sr., Anatomie mensch. Embryonen, Bd. 3, Leipzig, 1885, and Beiträge zur Anatomis des mensch. Herzens, Leipzig, 1886.

[13] His, Jr., Abhandl. d. K. S. Ges. d. Wiss. math.-phys. Classe Bd. 18, 1891. Arbeiten aus der med. Klinik zu Leipzig, 1894.

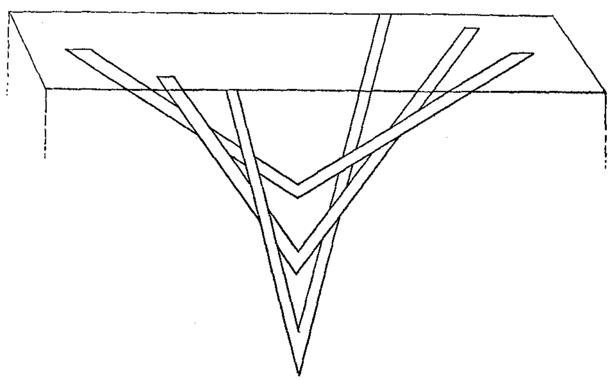
been embalmed with carbolic acid, there was little opportunity to use other methods with the human heart. However, carbolic acid specimens may be further prepared nearly as well as fresh hearts by boiling and such secondary treatment was also employed. Either boiled or fresh hearts that are to be dissected subsequently or preserved permanently may be kept perfectly well in a 3 per cent solution of carbolic acid or in formalin.

Before discussing the architecture of the heart musculature it is necessary to define a fiber. It is now well-known that heart muscle cells form a syncytium in which may be found the primitive fibrils of the cells. The bundles in general are parallel in direction with numerous lateral branches which pass out of a single group of cells at very acute angles. On account of the numerous large clefts between the cells, to make room for blood vessels as well as strands of connective tissue, groups of cells can be separated into larger bundles or fasciculi which are clearly recognizable to the naked eye. These are the so-called fiber bundles which are not entirely free but anastomose constantly with adjacent fiber bundles. It thus happens that no bundles are single but they are a portion of a continuous network which is a repetition on a larger scale of the primitive fibrils seen under the microscope. The fasciculi have a general parallel direction which, however, are constantly shifting in direction as they penetrate the heart wall, so that ultimately the fibers on the outside of the heart lie at right angles to those under the endocardium.

The direction of the fibers is also of physiological significance; the fibers always shorten and widen in contracting, so that a square centimeter of surface becomes shorter and not wider in the direction of its fibers, but thicker in the direction of the thickness of the heart wall. In the change of shape from diastole to systole the external surface of the heart becomes smaller and the thickness of wall becomes greater. This is all well known.

In stripping off the fibres it is found that successive bundles are constantly passing under one another so that they overlap much as do the shingles of a roof. The outer fibers which arise at the base send small bands into the depth which have a tendency to turn upon themselves to return to the base. This is more marked on the right side of the heart than on the left and in front than behind. The most sharply defined parallel fibers are found crossing the posterior longitudinal sulcus.

I shall speak of a group of fibers as a fasciculus and a number of them side by side, sufficiently collected to be pulled off together, as a sheet. I wish to repeat that the fasciculi and sheets are never fully separated from adjacent fasciculi or sheets, but are in constant communication with them. The fasciculus marks the chief direction of the fibrils which can be stripped off with considerable ease, and pass in the direction in which the muscle shortens in contracting.



Schema A. The outer and inner bundles are continuous at the apex as V-shaped loops with very acute angles. Somewhat deeper the angle at the point of turning is a right angle and in the middle layer the bend forms an obtuse angle.

No simple schema can be given which applies equally well to all portions of the heart wall. In general the wall is composed of V-shaped loops lying within one another, the outer forming very acute angles at the heart apex, with one stem of the V on the outside of the heart and the other on the inside (Schema A). Passing towards the middle of the ventricle wall the V-shaped loops do not reach to the apex, and the angle is less acute. Finally as they come to lie in the middle of the wall the V's form quite obtuse angles. This change may be said to be due to the lateral anastomoses of fasciculi becoming greater than the main bundles. This simple schema becomes distorted because the V-shaped loops are not limited to a relatively flat portion of the ventricle wall but they encircle the whole ventricle and are also "tucked up" into the septum, especially at its anterior border. The fasciculi and sheets which I shall describe are marked by their points of origin, their ending, and especially by their relation to the vortex of the left ventricle as well as by the muscular septum of the ventricles.

There is an agreement among authors regarding the course of the muscular fibers on the external surface of the heart. However, it is well, in studying their course, to prepare several specimens of adult hearts as well as those of children, in order to determine variations in case they exist. This is best done by cleaning the muscle of the ventricles of hearts which have been well fixed in carbolic acid or in alcohol, and by removing the atria entirely. The superficial blood vessels of the heart should be removed also. By comparing a number of such specimens it will easily be seen that in general the fibers over the right ventricle are in a transverse direction and over the left in a perpendicular direction. All this is clear when it is remembered that the apex belongs entirely to the left ventricle and towards it most of the muscle bundles stream to form the great vortex of the left ventricle which surmounts the apex. Fibers on the right side must cross both anterior and posterior longitudinal sulci to reach the great vortex upon the apex, thus giving these a transverse direction while those on the left side simply stream downward to the apex. The transverse direction of the fibers over the right ventricle is maintained somewhat more on the posterior surface of the heart than on the anterior, because the posterior fibers stream towards the small vortex of the right ventricle which is higher up, while the anterior stream toward the great vortex of the left ventricle which is lower down. What has been said may be seen easily by superficial observation of any heart which has had all of the epicardium removed.[14]

[14] This is well shown in MacCallum's diagram, fig. 15, which is reproduced in Piersol's Anatomy, fig. 664.

All of the superficial fibers may be described as arising around the tendinous rings at the base of the heart to which the valves are also attached. However, these rings are intimately related to the aorta and pulmonary artery through the membranous septum, which marks the inter-ventricular opening in the embryo. In fact it may be considered to represent much more than this, for it extends upward to include the aorta and pulmonary artery, the tendon between these baving been well described by Krehl. The tendinous rings inclose both atrio-ventricular openings and extend to include the membranes which close the openings between the right and left hearts in the embryo. The extent of this tendinous band is well shown in fig.1, in which the inter-ventricular membrane is marked *X* and its extension to the pulmonary artery *X'*. It is further seen that the course of the muscle fibers from these tendons is not uniform in all directions showing marked differences in each portion of the heart. The fibers from the left side of the heart, *A*, pass downward towards the apex, those around the right side, *B'*, *B''*, are transverse, while those around the pulmonary artery, *A'*, are circular. Those marked *A* pass directly to the great vortex forming its posterior horn[15] (fig. 2, *A*,) while those marked *B* cross the posterior longitudinal sulcus to the vortex of the right ventricle and finally across the anterior longitudinal sulcus to the anterior horn of the great vortex, (fig. 2, *B*).

In general, then, the superficial fibers of the wall arise from the tendinous structures at its base and converge toward the apex to form the great vortex of the left ventricle. Those arising from the conus, the left side of the aorta and the left side of the left ring,(fig. 1, *A*, *A'*), pass to the posterior horn of the vortex, and ultimately to the septum, while those arising mostly from the right fibrous ring posteriorly, (fig. 1, *B*, *B'*), pass around to the anterior side of the heart to form the anterior horn of the vortex,

[15] In Haller's Physiology, London, 1764, vol. 1, p. 75, we find the vortex described as being composed of two horns to correspond with the two main bands of muscle which penetrate the heart here. According to Haller one group is inserted into the septum and the other penetrates the left ventricle and returns in a contrary direction to the base. This is substantially correct.

(fig. 2, *B*), and ultimately enter the papillary muscles of the left ventricle. It follows, then, that there is one group of superficial fibers of the heart which belongs to the left ventricle and one to the right. Since these two muscle groups have been recognized for a very long time and since I have been able to define them with even greater precision through the horns of the vortex, it is well for the sake of easy description to give them specific names. The bundle from the conus and the root of the aorta, —the aortic bulb,—takes a spiral course to the vortex and then enters the septum. It may be termed the bulbo-spiral. The other group arises from the venous (sinus) end of the embryonic heart and takes a complementary course. It may be termed the sino-spiral bundle. Each group falls into two chief layers, a superficial and a deep, so we have superficial and deep bulbo-spiral bands, and superficial and deep sino-spiral bands. When the modifying term is not used, the superficial band, the band to the vortex, is meant.

E. H. Weber[16] states expressly that the vortex of the heart is limited exclusively to the left ventricle, while the superficial fibers of the right ventricle do not form a vortex at its apex, but pass into the heart along the anterior longitudinal sulcus as well as at the apex of the right ventricle. They also pass over the posterior longitudinal sulcus to blend with the superficial fibers of the left ventricle. The fibers which pass into the depth are shown in fig. 7, *A*. A similar figure has been published by C. F. Wolff.[17] In general this description is correct, but we notice from time to time a vortex of the right ventricle spoken of in the literature.[18] The examination of a number of well preserved human specimens from which the pericardium and connective tissue have been carefully removed will show definitely that there is a vortex at the tip of the right ventricle as well as at that of the left. This is shown, giving also the course of the main muscle bundles, in fig. 2. This figure has been drawn with care and through its interpretation we learn the course of the main muscle

[16] Weber, *l.c.*, vol. 3, p. 146.

[17] Wolff, *l.c.*, 1780, Fig. 3. This figure was copied by Lodor, Anatom. Tafeln, Weimar, 1794, Bd. 4, Taf. 114, Fig. 2.

[18] For example, Krehl, *l.c.*, page 351.

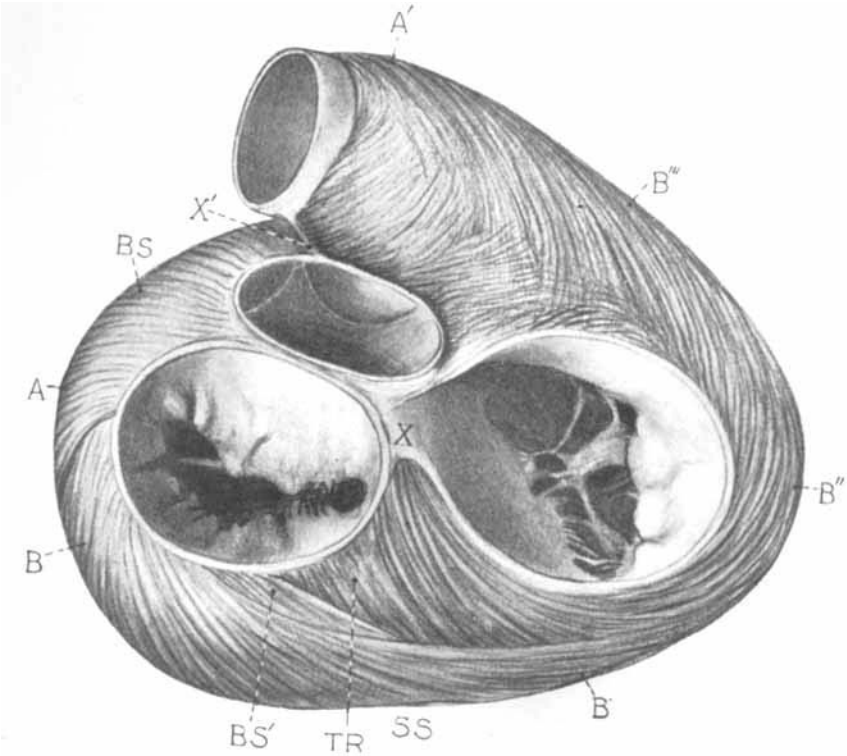


Fig. 1 Base of a well developed heart showing the course of the superficial muscle fibers. *A*, *A'* (*BS*), origin of the superficial bulbo-spiral muscle; *B*, *B'*, (*SS*) origin of the superficial sino-spiral muscle. From *X* to *X'* around the front of the aorta indicates the course of the aortic septum. *TR*, posterior triangular field. With the exception of figs. 13 and 15 the figures are natural size.

bundles of the ventricles of the heart. Throughout this paper I shall speak of a vortex of the right ventricle, and the vortex, or vortex of the left ventricle, to designate the vortex of the B N A.

That the main superficial muscle bundles enter the heart at its apex to spread out on the inside of the ventricle has been known to anatomists since the time of Borelli, whose account of the contracting mechanism of the heart muscle is the one my study strives to revive. E. H. Weber has given us the most satisfactory account of the arrangement of the muscle bundles of the ventricle and his description should be studied by all who wish to become familiar with the subject. It is one of the most satisfactory accounts that has yet appeared.[19] Weber pointed out clearly that the superficial and inner muscle bundles radiated spirally from the apex towards the base of the heart, but in opposite directions. In viewing the heart as an object it is found that they pass from left to right towards the apex on the outside of the heart, and from right to left on the inside. Between these two layers there is a middle layer which according to Wolff can be broken into an outer sheet with fibers more nearly parallel to the outer layer of muscle bundles and an inner sheet in which the direction of muscle bundles corresponds more nearly with those of the inner layer. So the statement made by Ludwig that any cube of heart wall extending from the pericardium to the endocardium is composed of fibers on the outside which are at right angles to those on the inside, rests upon a sound anatomical basis. When such a block is torn to pieces it is further found that the fibers on one side gradually rotate in position as they are followed to the other.

Weber's studies of the musculature of the heart, especially that of the left ventricle, do not deal with the course of the fibers in the septum in a satisfactory manner, and he expressly states that this portion of the heart must be unraveled before a comprehensive view of the whole system of muscle bundles will be obtained. In this region the many studies of Casper Friedrich

[19] The large modern textbooks with the exception of Quain's Anatomy ignore the musculature of the heart altogether or give but a meager account of this subject.

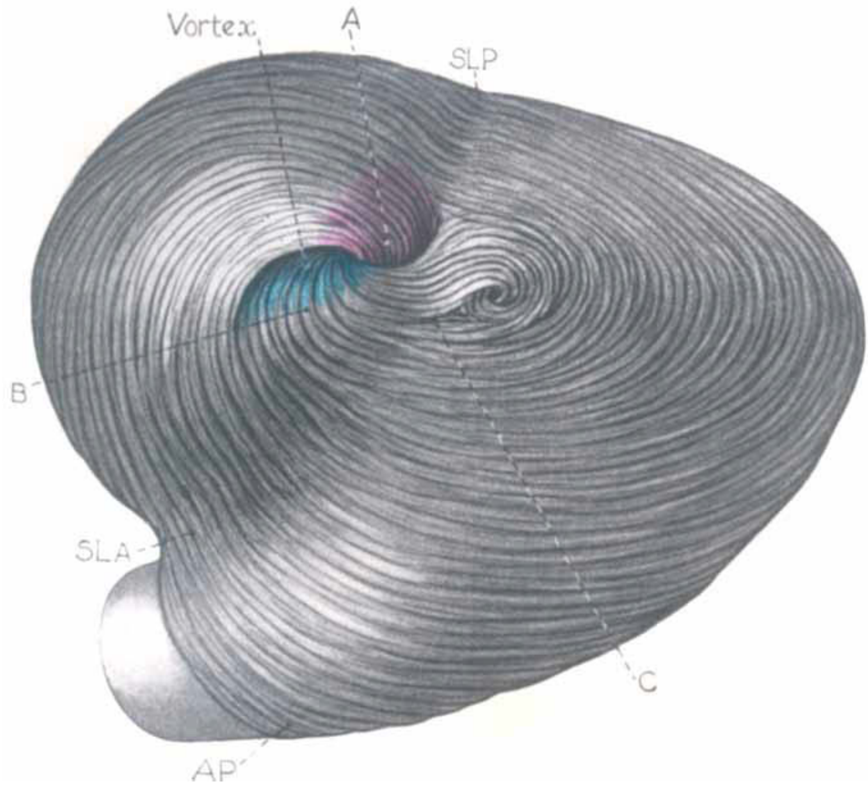


Fig. 2 Apex of the heart to show the two vortices. *A*, superficial bulbo-spiral bundle forming the posterior horn of the vortex, which then enters the septum; *B*, superficial sino-spiral bundle forming the anterior horn of the vortex. This bundle encircles the right ventricle, including its vortex, in its course to the anterior horn of the left vortex, *SLA* and *SLB*, anterior and posterior longitudinal sulci.

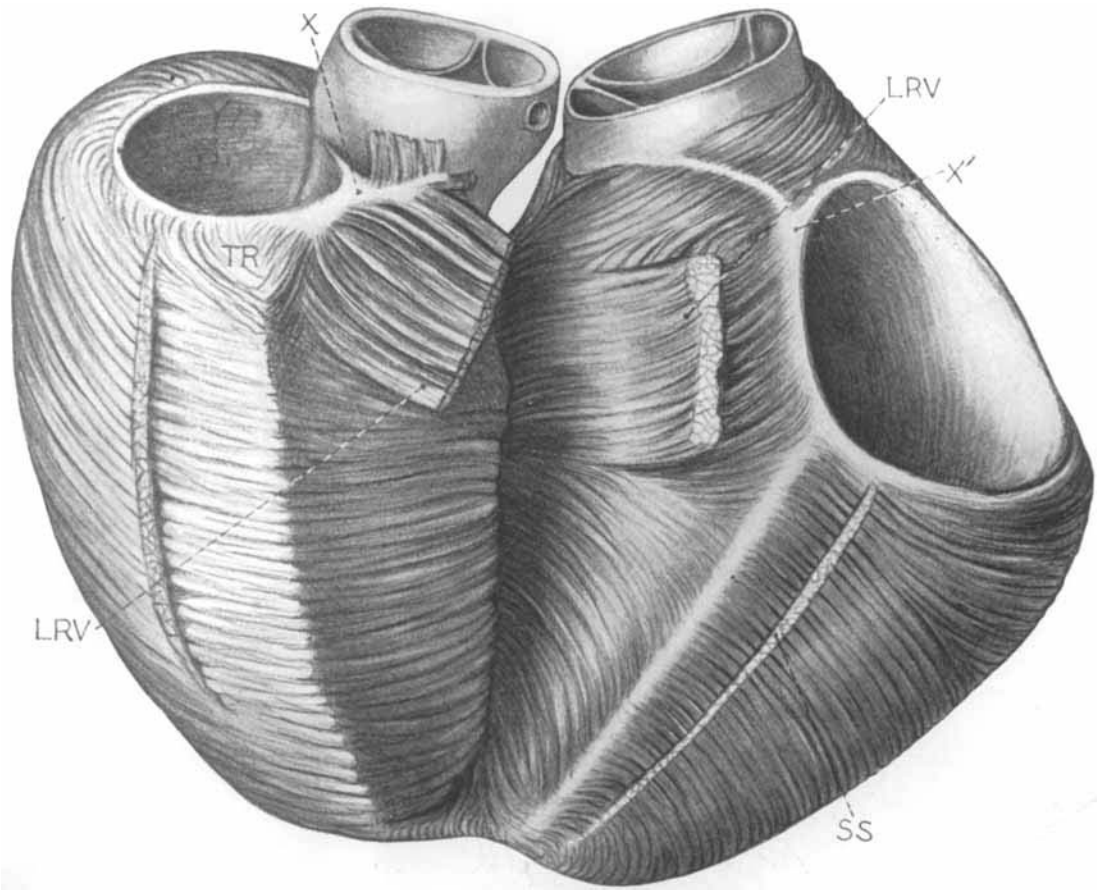


Fig. 3 Heart shown in fig. 2 broken open from behind according to MacCallum's method. *SS*, superficial and deep sino-spiral sheet cut transversely; *LRV*, the muscle band from the membranous septum to the right ventricle cut transversely. The tendon of the conus, conus part of the aortic septum, is shown on the medial side of the conus, *X'*. On the posterior side of the aorta the atrio-ventricular bundle is seen. *TR*, posterior triangular field extending downward into the raphé.

Wolff fail, as well as those of the earlier anatomists. However, it appears that Gerdy's study interpreted this portion of the heart wall in a very satisfactory manner, although his work was not accepted by Weber. Weber states expressly that Gerdy's work was so poorly presented that it was impossible for him to separate the theoretical from the observations in it. Although Weber could not confirm the fleshy fibers which connect the papillary muscles of the right and left ventricles they really do exist, as has been shown by MacCallum and as I have also frequently observed. Furthermore, Gerdy described and pictured nearly correctly the strand of muscle fibers which I have called the superficial bulbo-spiral bundle.[20] This he describes as a bundle which crosses upon itself to form a figure 8 a comparison which has been applied quite differently by later investigators. Subsequently the ventricle wall including the septum was carefully investigated by Ludwig and than by Krehl, whose work comes from Ludwig's laboratory. They constantly kept before their minds the heart as a whole, and the function it has to perform in contracting.

A good account of the middle muscular layer of the left ventricle is given by Krehl who describes it as a cylindrical band of fibers which form loops and do not end at the atrio-ventricular ring. Although this circular muscle was recognized by Weber[21] it is here described anew and is known in the literature as Krehl's *Triebwerk.* That the fibers of the *Triebwerk* arise also from the atrio-ventricular ring my own studies show. Below a bundle extends from it to the apex, as was noted by Krehl.[22]

The cylindrical muscular band described by E. H. Weber and by Krehl is nothing but the transverse fibers of the left ventricle repeatedly described by anatomists during the past two centuries.[23] That this layer of fibers can be shelled out of the wall

[20] Although this bundle is not quite correctly given in Gerdy's fig. 12, it is easily seen that he observed it in his specimens.

[21] Weber, *l.c.*, p. 148. Also Ried, Todd's Cyclopædia of Anatomy and Physiology, London, 1836, vol. 2, page 592.

[22] Krehl, *l.c.*, p. 348.

[23] These are the spiral fibers of the middle layer according to Borelli and Lower. Haller, *l.c.*, states that the transverse fibers of the middle layer go to form the septum.

of the left ventricle as a basket, or better as a cylinder, for it is open at both ends, was first emphasized by Krehl, and just this point is what has caused so much difficulty in our laboratory, for according to MacCallum the cylinder easily resolves itself into a single sheet or scroll in the foetal pig as well as in the adult heart. To explain this apparent contradiction is one of the objects of this communication. Before taking up this main point it will be necessary to consider briefly the arrangement of the muscle fibers at the base of the heart, at the apex, the membranous septum and, incidentally, the atrio-ventricular bundle.

Fig. 2 is given to show the arrangement of the superficial bundles at the apex of the heart, which shows a vortex under each ventricle. A satisfactory analysis of the vortex of the left ventricle, showing its two horns, is given by Pettigrew.[24] He showed that it is easy to separate the two bundles of muscle entering the apex, into anterior and posterior horns, as Haller did, and judging by his illustration, one passes to the septum and the other to the interior of the left ventricle. This I have been able to confirm fully in numerous specimens of human hearts. It is not so easily confirmed in the pig's heart.

An excellent illustration of the arrangement of the muscle fibers at the base of the heart is given by Bonamy, Broca and Beau.[25] My fig. 1 differs from theirs inasmuch as it includes the tendinous connection between the pulmonary artery and the aorta with the fibers arising from it. Also on the posterior side I show the fibers coming out of the septum and passing under those that arise from the left fibrous ring; these two sheets are pictured as a single sheet in their figure.

Since the chief muscle bundles of the heart are connected either directly or indirectly with the fibrous bands at its base it is necessary to have a clear understanding of them. These include the membranous septum of the ventricles, which is continued into the aortic septum. E. H. Weber made it clear that the architecture

[24] Pettigrew, Phil. Trans. London, 1864. This figure is copied in Quain's Anatomy, Tenth Edition, 1892, vol. 2, Fig. 322.

[25] Bonamy, Broca and Beau, Atlas d'Anatomie descriptive, Paris, gives an excellent illustration of the apex of the human heart. Toldt (Atlas, Berlin und Wien, 1901, Fig. 931) also gives a satisfactory figure.

of the musculature of the heart would not be fully understood until the muscle bundles of the septum are included in the problem. Since Weber's time the problem has shifted from the study of the muscular septem to that of the membraneous septum. The English anatomists have been familiar with the membranous septum for some time but it was not known to anatomists generally until it was rediscovered in Hyrtl's laboratory.[26] This membrane marks the place at which abnormal openings between the two ventricles are most likely to occur, that is, persistence of the interventricular foramen of the embryo. However, for a proper understanding of the membranous septum it must be extended to include the aortic septum.

That the muscle bundles of the conus form relatively simple rings which attach themselves to the root of the aorta has been long known. In fact, they arise and end in a raphé or tendon at the point of juncture of the pulmonary artery and the aorta, as is well shown in figs. 3, 8 and 13.[27] When the conus is carefully separated from the aorta in a heart which has been boiled for several hours in dilute acetic acid or in a heart (preserved in carbolic acid) from which the connective tissue and fat have been removed, it is found that these two vessels are firmly blended along this tendinous line which when followed enters the membranous septum. By replacing the right ventricle in figs. 3 and 8 it is easy to see the connection between the tendon of the conus and the membranous septum. It takes but little imagination to realize that these two structures are derived from the aortic septum of the embryo as has been clearly pointed out by His.[28] Attention may be called at this point to the muscle bundles which end in the membranous septum in figs. 3 and 8. Undoubtedly they belong to the atrio-ventricular bundle which passes through the membranous septum, for in early stages of development this bundle passes through the interventricular foramen and becomes

[26] See Hope, A treatise on diseases of the heart, 1849, p. 302; Huschka, Wiener med. Wochenschrift, 1855; Reinhard, Virchow's Archiv, Bd. 12, 1857; and Virchow, Ibid, Bd. 13, 1858.

[27] Krehl, *l.c.*, Fig. 1. He has also given a good description of this tendon as the tendon of the conus. See also MacCallum.

[28] His, Beiträge zur Anatomie des mensch. Herzens, Leipzig, 1886, p. 8.

tied up in the membranous septum as the aortic septum closes the foramen.

A clear understanding of this region of the heart was not obtained until the subject was investigated embryologically. Then the relation of the tendon of the conus became clear, and the membranous septum received a new meaning, in the study of anomalies in the understanding of the atrio-ventricula bundle, as well as of the muscle bundles of the ventricles in general. This septum is in the center of the heart to which important structures pass; the aorta is firmly tied to it and the contracting muscle of the ventricle acts towards it.

A brief review of the history of our knowledge of the development of the membranous septum is given by His.[29] In order to explain an anomalous heart Lindes[30] studied the development of the chick's heart and discovered that in its separation into right and left hearts the single heart tube was divided by three independent septa, namely the septum of the atrium, the septum of the ventricle, and the septum of the aorta. Subsequently these united as is now well known. The work of Lindes was extended by His in a study of the human heart and he found that the aortic septum grows from above downward to reach the septum of the ventricle and finally closes the interventricular foramen through the formation of membranous septum. As Lindes pointed out, correctly, the aorta arises in the embryo from the *right* ventricle and through the formation of the membranous septum its communication with the right side is cut off. All this may be seen easily in fig. 3 when it is recalled that the points marked *X*, *X*.′ were in apposition. The figures of His are needed to make this point clear.[31]

According to His,[32] the heart muscle, which extends over the bulb of the aorta in the embryo, must degenerate in part for it does not extend correspondingly high in the adult. He divides the septum aorticum into three parts: (1) The inter-arterial region or

[29] His, Anatomie mensch. Embryonen, Pt. 3, 1885, S. 178.

[30] Lindes, Inaug. Diss., Dorpat, 1865.

[31] His, Anat. mensch. Embryonen, Figs. 101, sa; 106, sa; 111, sa; and 118, sm.

[32] His, Beiträge, etc.

the septum aorticum superius; it consists chiefly of two layers of elastic plates with connective tissue between them. (2) A region between the aorta and the right ventricle or the septum aorticum inferius; it consists of the elastic wall of the aorta, a thin layer of the muscle of the conus and a layer of connective tissue. (3) The region between the ventricles or the septum membranaceum.[33]

Before considering the arrangement of the deeper layers of the muscle bundles of the left ventricle it is necessary to describe briefly a few of the peculiarities of the superficial bundles. These, as has been stated, arise at the base and converge spirally toward the apex; those over the right ventricle are in a more transverse direction, while those over the left ventricle are more perpendicular This is well shown in figs. 5 and 6, and has been well illustrated by Wolff in his various papers.[34] But in addition to the spiral fibers which cross the anterior longitudinal sulcus quite transversely there is often seen in the posterior longitudinal sulcus a bundle which runs perpendicularly towards the apex and appears to be better marked in the heart of the new-born child than in the adult. This bundle is well pictured in Wolff's paper [35] as well as in Henle's Anatomy,[36] and as it is constant, it need not be considered a variation but should be included in the description of the superficial bundles of the posterior side of the heart, which here have a downward tendency often forming bundles as they approach the apex.[37]

In addition to the bundle just described a small thin superficial sheet is occasionally seen over the middle of the right ventricle near the base of the heart. This is also better seen in the hearts of

[33] Figures illustrating the membranous septum may be found in His, *l.c.;* Quain's Anatomy, figs. 310 and 317; Toldt's Atlas, fig. 929; Spalteholz's Atlas, fig. 420; and Piersol's Anatomy, fig. 660.

[34] See also Bourgery, Traité Complet de l'Anatomie de l'Homme, Paris, 1836, Tome 4, Pl. 10; Bonamy, Broca et Beau, *l.c.*, Tome 2, Pl. 4; Quain's Anatomy, *l.c.*, vol. 2, fig. 320; Toldt's Atlas, *l.c.*, figs. 929 and 930; Henle, *l.c.*, vol. 3, fig. 39; as well as elsewhere.

[35] Wolff, *l.c.*, Tome 2, Tab. 6.

[36] Henle, *l.c.*, fig. 39. Also Toldt, fig. 930.

[37] Weber, *l.c.*, p. 145, denies the existence of a fasciculus in the posterior longitudinal sulcus.

young children as is pictured by Henle.[38] I mention this as a variation in the human heart, but it is certainly constant in the pig's heart and caused MacCallum much difficulty in studying the heart musculature. It may be that more careful examination of this sheet will show that it is present on all hearts, for our present method of cleaning off the epicardium might easily destroy it.

The longitudinal bundle of Wolff lying in the posterior longitudinal sulcus is certainly present in most young hearts and it does not interfere materially with the study of the outer spiral muscle bundles for it lies upon them. However, Weber observed that although superifical bundles entered the septum both through the anterior and the posterior longitudinal sulci, the penetrating fibers were much more marked along the former than the latter. It is quite easy to strip off the superficial bundles over the posterior sulcus but not over the anterior, for here the sperficial bundles enter the septum while behind they pass over it. This arrangement was encountered by MacCallum in dissecting the macerated heart of the foetal pig when he attempted to strip off the superficial bundles with a blunt probe. He then found that it was easy to lift off the superficial layer of muscle bundles over the back of the heart but not over the front. These bundles having been cut, he further found that the deeper fibers all entered the septum which when broken open permitted him to unroll the musculature of the left ventricle as a scroll. Through MacCallum's method of dissection, which Bourgery[39] had almost invented, it is possible to unravel the musculature of both ventricles in a satisfactory manner, that is, the same result is obtained in all specimens.[40]

The chief bundles of the superficial fibers all arise from the tendinous rings and membranes at the base of the heart, especially those around the aorta, as may be seen in fig. 1. After the superficial layers have been removed it is seen that the deeper bundles stream towards the aorta more markedly than the super-

[38] Henle, *l.c.*, fig. 39, B.*

[39] Bourgery, *l.c.*, Tome 4, Pl. 10 b, fig. 5.

[40] Searle, Todd's Cyclopædia of Anatomy, vol. 2, describes a similar unrolling and gives excellent illustrations of specimens made in this way in his figs. 278 to 282. The chief circular band he calls the rope, for when unrolled it appears like a twisted rope.

ficial. The ligaments that attach themselves to the aorta are the aortic septum, the valves as well as two fibrous rings, one of which encircles the right ostium venosum and the other the left. The bicuspid and tricuspid valves are attached partly to the fibrous rings and partly to the septum aorticum. Through them the papillary muscles are attached to the tendinous structure in the base of the heart. These all tend to the tie firmly the muscle bundles to the aorta, towards which they force the blood in contracting, and were it not so the force of contraction might "shoot the aorta out of the heart." The two rings encircling the ostia venosa unite over the septum of the ventricle into a single band and continue into the membranous septum. Here they form the posterior fibrous triangle, which is very pronounced in the pig. So it may be seen that the aorta is held in place by three ligaments all of which are extensions of the septum aorticum. They correspond to the three semilunar valves of the aorta and also mark the trigona fibrosa of the B N A.

I shall describe them (1) as the posterior one which is an extension of the membranous septum backward between the venous ostia.[41] It forms the posterior fibrous triangle and to it are attached the medial cusp of the tricuspid valve and the anterior cusp of the bicuspid valve.[42] At the point of attachment of this ligament to the aorta the atrio-ventricular bundle of His perforates the membranous septum to enter the left ventricle. This ligament expands into that portion of the wall of the aorta which lies opposite the posterior semilunar valve.[43] (2) The left ligament[44] marks the fibrous triangle to the left of the aorta opposite the left leaflet of the semilunar valve immediately below the left coronoary artery. The left ligament appears to have nothing to do with the aortic septum. The left fibrous ring to which the bicuspid valve is attached arises from left and the posterior ligaments of the aorta. (3) The right ligament encircles the right side of the aorta opposite the right cusp of the aortic valve below the right coronary artery.

[41] Poirier and Charpy, Tome 2, fig. 360, nodule droit.

[42] See Spalteholz's Atlas, 1896, fig. 419.

[43] Note that the *B N A* as used for this valve, improperly called the right semilunar value by English anatomists.

[44] Nodule gauche.

It is formed largely by His' septum aorticum superius or Krehl's tendon of the conus. It is shown in fig. 3, *X*, *X′*, and fig. 8. The muscle bundles of the conus as well as the bulbo-spiral band arise from this ligament. The right ligament which is much better marked in the pig and dog than in man sends a delicate lateral branch around the right venous ostium to form the anterior segment of the right fibrous ring.[45] To sum up, the aorta is tied to the heart muscle by three ligaments, as well as through the valves to the papillary muscles. Two of these ligaments, the right and the posterior, are derived directly from the membranous and aortic septa, while the third, the left, seems to be independent of them, encircles the heart to the left, and marks the line of separation between the origin of the bulbo-spiral and sino-spiral muscular bands.

The superficial fibers of the heart, all of which arise from the tendinous structures at the base (septum aorticum and its extensions), pass spirally towards the apex of the heart to form the great vortex there. Above they form a thinner layer than below; as they approach the apex the fibers must either diminish in number or they must form a thicker layer. Probably both conditions prevail for fiber bundles are constantly leaving the superficial layer to pass into the depth, but transverse sections as well as dissections show that the main superficial fiber bundles gradually become piled upon one another as the apex is approached until they finally form the whole thickness of the heart wall at this point In other words there are no circular fibers in the apex.

At the vortex all of the fibers penetrate the heart to form the inner layer of the heart muscle of the left ventricle, as is well known. Here they spread upward and finally are attached again at the fibrous bands from which they arise. However, in general a bundle which arises at a given portion of the heart on the outside returns to the opposite side of the ventricle on the inside. Thus, bundles arising from the septum aorticum in front of the heart on the outside, the bulbo-spiral bundle, and posterior to the aorta on

[45] The tendinous bands just described are well illustrated in Toldt's Atlas, fig. 932.

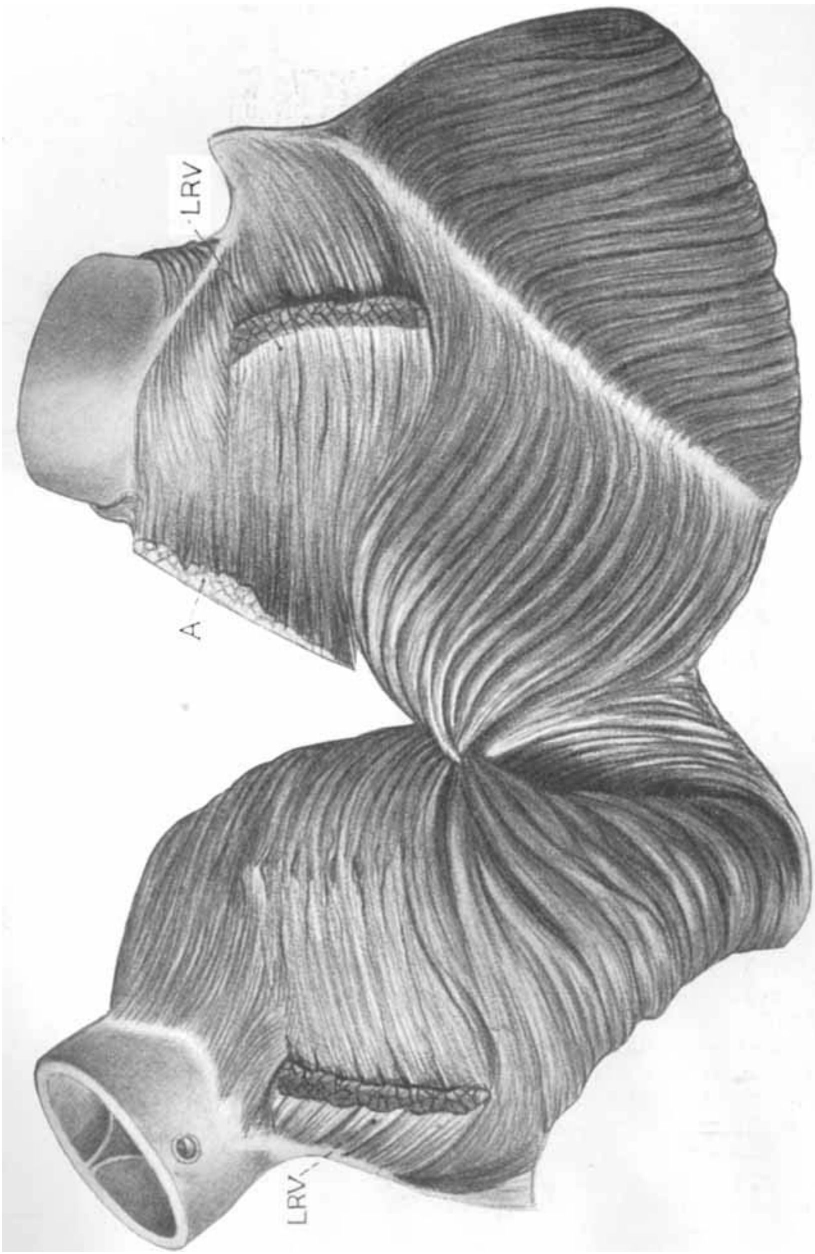


Fig. 4. Same as fig. 3 only separated more to show the opening into the left ventricle and the interlocking of the sino-spiral and bulbo-spiral muscle bands. *A*, cut end of the beginning of the bulbo-spiral muscle band. Part of it arises in common with the longitudinal bundle of the right ventricle, *LRV*.

the inside. The sino-spiral bundle arises on the posterior surface of the heart on the outside forms the anterior horn of the vortex and ends largely on the anterior side of the heart on the inside.

The two horns of the vortex are constant in human hearts and through them it is possible to divide all of the superficial fibers into two distinct groups, for all of the fibers stream either to one horn or to the other. By cutting the superficial fibers which cross the posterior longitudinal sulcus it is seen that the right ventricle is easily broken from the left. It is clear, by comparing figs. 2 and 3, that all of the fibers that encircle the right ventricle help to make its vortex and then enter the anterior horn of the vortex of the left ventricle.[46] In separating the right heart from the left it is well to keep the break as near to the right ventricle as possible and in so doing it is soon observed that a large bundle crosses the septum passing from the aorta to the median wall of the right ventricle. This bundle is shown in fig. 3, *L R V*, and is the one described and pictured by MacCallum as "a band of muscle from the right ventricle ending in the left atrio-ventricular ring." According to MacCallum it must be cut in order to unroll completely the left ventricular wall of the foetal pig. This bundle has also been observed by MacCallum in the heart of a child and repeatedly by Knower [47] in the adult heart. No doubt it is this bundle that Senac[48] described a century and a half ago and which has been identified repeatedly since. According to E. H. Weber[49] the medial wall of the right ventricle is thinner than that of the left ventricle at the same point. The fibers are parallel to the long axis of the heart, and immediately below them are the circular fibers of the

[46] Although this point is brought out by MacCallum's method of dissection, MacCallum did not demonstrate it because he studied the hearts of fœtal pigs which had been well macerated in a nitric acid and glycerine solution. This treatment injures the delicate arrangement of the muscle bundles and only the coarser bands remain. Moreover in the pig's heart the muscle bundles at the apex are more intimately blended than in man, which explains why my description of the apex of the human heart does not correspond with MacCallum's. See MacCallum's diagrams.

[47] Knower, Anatom. Record, vol. 2, p. 204.

[48] Senac, Tratié du Coeur, Paris, 1849.

[49] Weber, *l.c.*, p. 150.

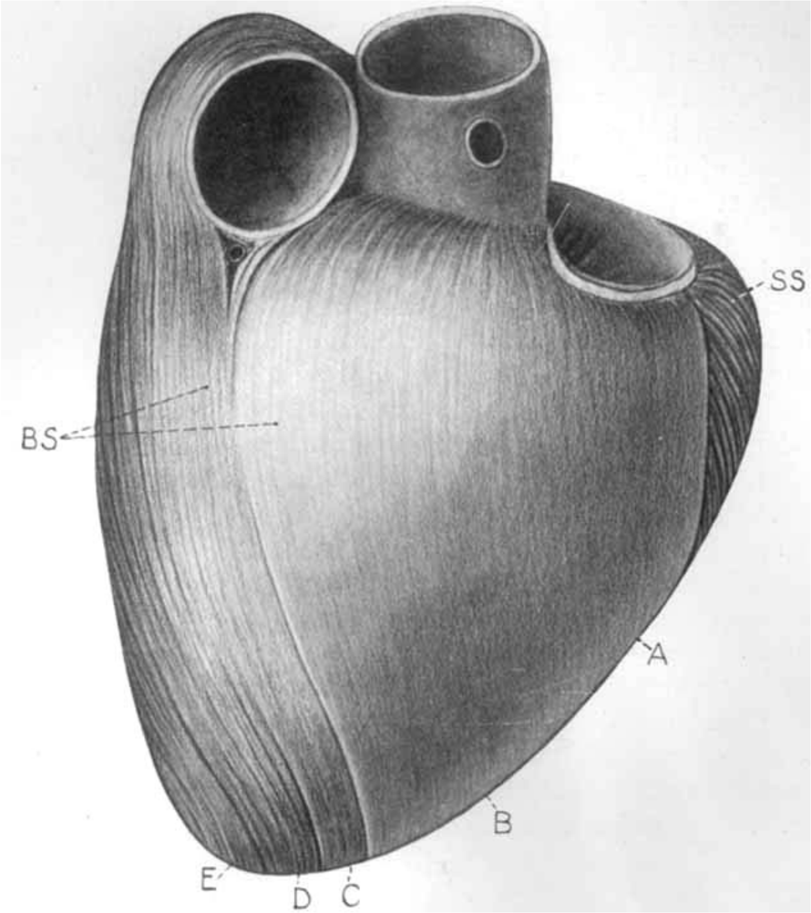


Fig. 5 Right side of a large hypertrophied heart. Figs. 5 to 12 are from the same specimen. *BS*, superficial bulbo-spiral band; *SS*, superficial sino-spiral band. Corresponding bundles in the figures of this heart are marked *A*, *B*, *C*, *D*, and *E*, respectively. For the sake of clearness bundles *A*, *B*, and *C*, are drawn with a smooth surface.

left ventricle.[50] It is this bundle which Ludwig[51] describes as arising from the border between the septum and aorta and from the free border of the papillary muscle of the right ventricle. It continues forward and downward to the anterior surface of the apex of the heart where it enters the septum along the anterior longitudinal sulcus by the way of the vortex. Probably the best description is by MacCallum, who isolated this bundle by his method of dissection. It is clearly shown in fig. 3 and its distribution over the inner wall of the right ventricle is shown in fig. 15. Here it is seen to blend with the sino-spiral bundle in the anterior horn of the vortex and is ultimately lost in the papillary muscles of the left ventricle. It therefore belongs to the interventricular bands of Gerdy and MacCallum.

By cutting this bundle the septum may be split completely as fig. 3 shows. The conus is next separated from the aorta and its tendon, to demonstrate the septum aorticum. From here superficial fibers encircle the heart; these are indicated by the cut surface in fig. 4, *A*. In fig. 3 the fibers of the horns of the vortex have been separated which can easily be done with the fingers or with the handle of a scalpel. Those from the anterior horn of the vortex have an inward tendency, while those from the posterior horn course towards the septum and come to cross the others at right angles as shown in fig. 4. In separating the two horns of the vortex it is found that the cavity of the left ventricle is soon reached and in order to reach it most easily it is well to have a probe passed into the heart to its apex where it can easily be felt from the outside. At this point the walls of the left ventricle are thinnest, in proportion to the diameter of the lumen as Weber has pointed out.[52]

So far it is quite easy to unroll human hearts with constant results, but when it comes to a study of the deeper layers of the

[50] This bundle is shown in Gerdy's diagram, fig. 12.-

[51] Ludwig, *l.c.*, p. 199.

[52] Weber, *l.c.*, p. 144, says that this thin area is not remarkable because in different animals the heart thickness is in proportion to the diameter of the lumen, so as the lumen varies in different portions of the heart the wall varies correspondingly. Now we say "functional adaptation."

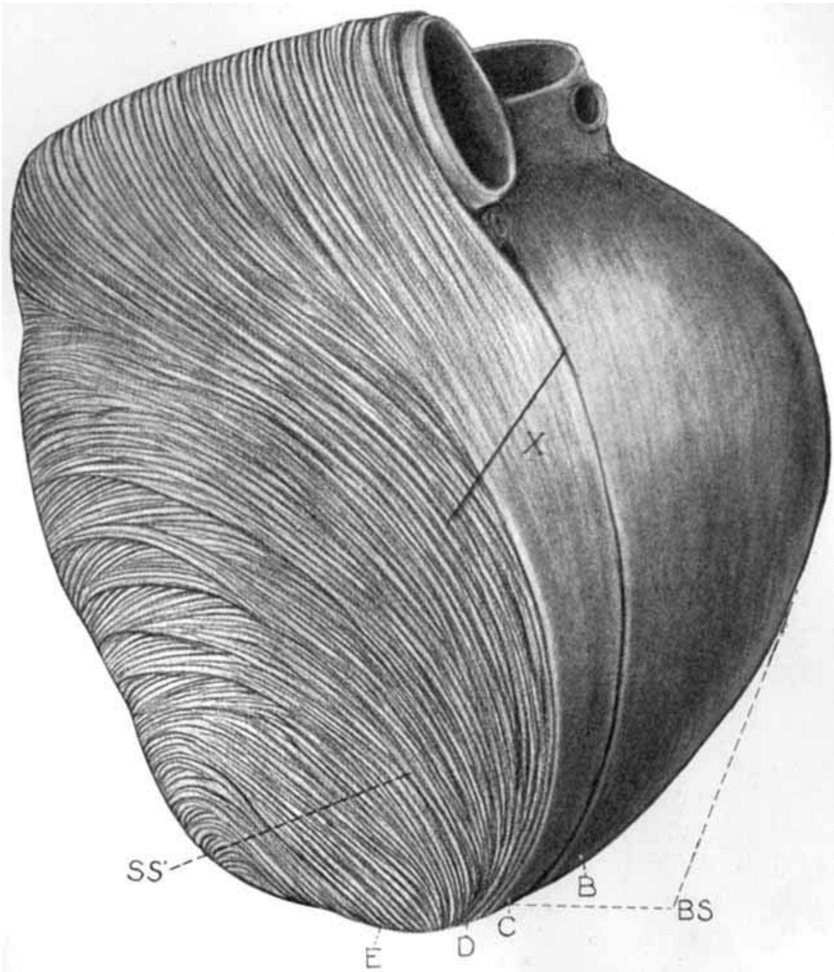


Fig. 6 Anterior surface of the heart, fig. 5, to show the arrangement of the fibers over the right ventricle. *BS*, bulbo-spiral band. *X*, the line across bundle *C* shows the position of the cut surface *X* in fig. 8.

left ventricle it is not so easy to convince one's self regarding a constant arrangement. Furthermore, it is difficult to describe the arrangement of the muscle bundles clearly, which in turn makes the literature difficult to understand.

The immediate connections of the two horns of the vortex of the left ventricle can be given with precision and in order to make them clear I have had a number of figures (5 to 12), drawn from the same heart. The views given in figs. 2, 3 and 4 have been omitted but in general they correspond so closely with them that it is unnecessary. In figs. 5, 6 and 7 the superficial muscle bundles which form the superficial bulbo-spiral band which enters the apex of the heart through the posterior horn of the vortex are drawn with a smooth surface and the several bundles in different drawings are marked with the same letters, *A*, *B* and *C*, in order that it is possible to identify them in the different figures. The most posterior sheet, that which arises from the tendinous ring around the left venous ostium, is marked *A*, that which arises from the side of the aorta, *B*, and that which arises from the septum aorticum (or the conus) *C*. Those marked *D* and *E* belong to the superficial sino-spiral band and enter the anterior horn of the vortex. It is seen by comparing figs. 2 and 7 that the apex is formed entirely by the anterior horn of the vortex and that the posterior horn encircles the apex. This is shown in an exaggerated way in MacCallum's account of the foetal pig's heart.[53] The locking of the two horns of the vortex is shown at *C* and *D* in fig. 7. Here they are blended completely but they may easily be separated by running a probe into the left ventricle. Specimens made in this way show a general tendency of all of the fibers of one horn to run at right angles to those of the other. The bundle marked *C* arises from the septum aorticum superior [54] which is much more pronounced in the dog and pig than in man. The line drawn on this bundle in fig. 6, *X*, shows the position of the cut surface, *X* in fig. 8.

[53] MacCallum, *l.c.*, fig. 16. Also in Piersol's Anatomy, fig. 665 and in Morris-McMurrich's Anatomy, fig. 383. Most of MacCallum's figures are reproduced in the latter work.

[54] Tendon of the conus, MacCallum; tendinous band between the pulmonary artery and aorta, Krehl.

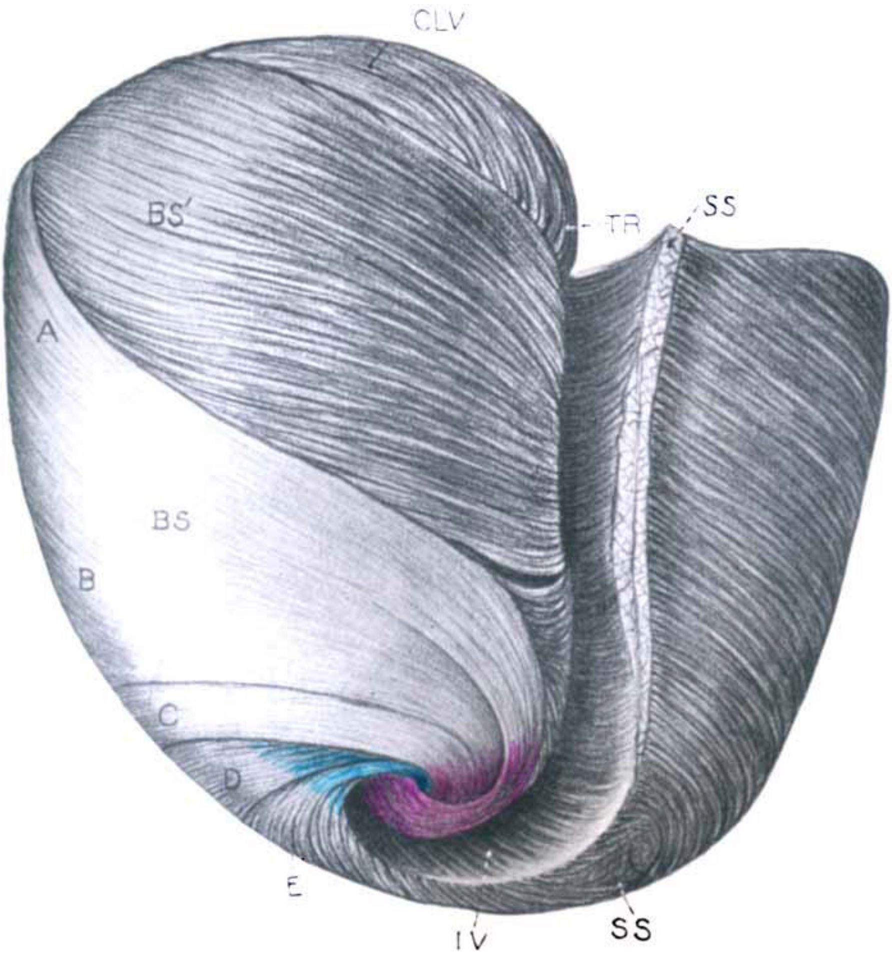


Fig. 7 Posterior view, somewhat to the left, after the superficial sino-spiral band has been removed to the posterior longitudinal sulcus. The deep bulbo-spiral band, *BS′*, enters the septum, above the superficial bulbo-spiral band, *BS; CLV,* circular muscle band of the left venous ostium; *TR,* posterior triangular field; *IV,* interventricular bands.

The remainder of the surface fibers, the sino-spiral band, arises from the posterior borders of the venous ostia, converge towards the apex to form the anterior horn of the vortex. In general, the fibers that arise from the arterial side of the heart, the bulbus of the embryo, pass to the posterior horn of the vortex, while those from the venous side of the heart form the anterior horn. It may be that this arrangement of the fibers is due to the bending of the heart in development; His thinks that it may be associated with the formation of the inferior septum. At any rate since all of the fibers that arise on one side of the heart enter the apex at the other, and vice versa, their course must be spirally around the heart which proves to be the case.

To follow the bundles which arise from the septum aorticum around the heart through the posterior limb of the vortex into the apex and through the septum to their ends is not altogether easy. This has been the great difficulty in the study of the architecture of the musculature of the heart, and it will not be solved to the satisfaction of all anatomists until the development of the bundles is known. At present it is difficult to rest what I have found upon an embryological basis for the main part of the story is run through by the time the embryo is 12 to 15 mm. long, and such hearts can not be dissected. Nor can the course of the muscle fibers be followed with any degree of certainty through the study of serial sections.[55]

It is apparent that the bulbo-spiral was well known to Gerdy who attempted to picture it.[56] Gerdy also observed that the walls of both ventricles are formed by a series of loops which are attached to the tendinous rings at the base of the heart; they become larger as they extend towards the apex of the heart, and successively fall into one another. The loop which reaches to the apex, the bulbo-spiral, forms a double loop in passing through the septum, and thereby is converted from a single loop into an 8-like figure. Although Gerdy's illustrations are crude and his description is

[55] His says, *l.c.*, p. 177, that the fibers must develop from left to right along the anterior longitudinal sulcus and from right to left along the posterior longitudinal sulcus.

[56] Gerdy, *l.c.*, fig. 12.

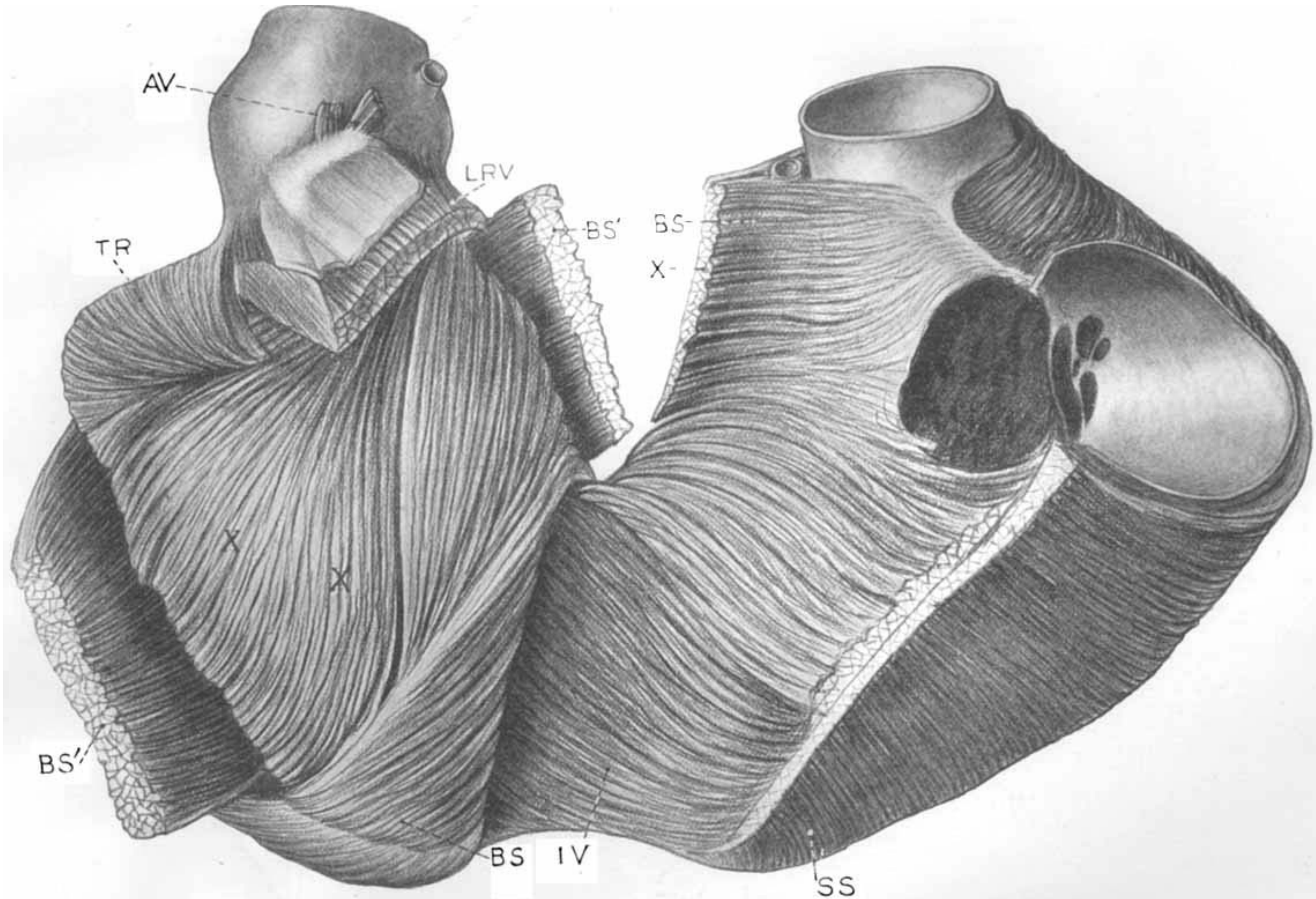


Fig. 8 The septum is completely divided. *BS* and *BS'*, superficial and deep bulbo-spiral bands; *SS*, sino-spiral fibers; *IV*, interpapillary band; *LRV*, origin of the longitudinal bundle of the right ventricle which entered the hole torn in the right ventricle; *TR*, posterior triangular field; *X*, termination of the bulbo-spiral band.

by no means clear, it is evident, that he recognized the main groups of muscle bundles of the heart, for he studied the muscle bundles of the whole heart, including those of the septum.

The long muscle bundles around the left ventricle, those forming the figure 8 according to Gerdy, were better described and illustrated by Ludwig in his well-known study. However, Ludwig's figure 8 is not open above like Gerdy's, who connected one limb of the double loop with the tendinous structures at the base of the left ventricle and the other to the base of the right. According to Ludwig,[57] the loops forming a figure 8 are confined to one ventricle. The course of the fibers which arise externally at the base of the ventricle encircles the apex and returns on the inside of the heart to be attached at the base again. Those that arise deeper encircle the heart midway between the apex and the base and end again at the base; they form a complete figure 8. In general, I find this description of the main muscle bundles of the walls of the ventricles the most nearly correct, although his schema is not accepted by Krehl.[58] In Krehl's publication a band of muscle is described which is not attached to the tendinous structure at the base of the heart, but instead makes a complete circle and ends in itself. That this cannot be correct is evident from Krehl's own description[59] when he says that the direction of the course of the fibers of this layer is practically the same as the rest of the fibers of the wall of the ventricle. In the circular layers (*Triebwerk*) the fibers on the outside run from above downward from left to right and on the inside in the opposite direction. While many may see in Krehl's description a contradiction to Ludwig's original description, I see in it only a confirmation. Where Krehl erred was in saying that the fibers in his circular layer do not arise nor end in tendons as do the outer and inner muscle layers of the heart. Since MacCallum succeeded in unrolling the wall of the left ventricle into a single sheet of muscle showing that it must form a scroll, it has been difficult for us to account for Krehl's statement regarding a middle muscle band in the wall of the left

[57] Ludwig, *l.c.*, fig. 8.

[58] The work of Krehl was done in Ludwig's laboratory and received his approval.

[59] Krehl, *l.c.*, pp. 347, 349, and figs. 9, 10.

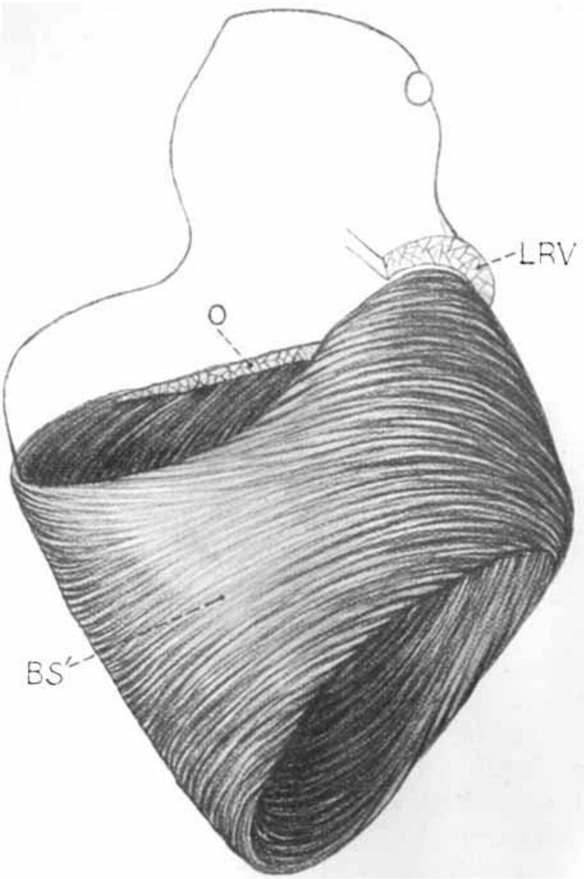


Fig. 9 Deep bulbo-spiral band drawn in the outline of fig. 8. *O*, origin of the fibers on the opposite side of the ventricle.

ventricle, which ends in itself. My own dissections of the muscle wall of the left ventricle, as well as MacCallum's, show that all of the muscle bands arise in tendons either at the base of the heart or in the papillary muscles which in turn are attached to the tendon of the base through the valves.

Returning now to the two main muscle bands which form the horns of the vortex, it is found by separating them that the cavity of the left ventricle is opened, as shown in fig. 4. This figure shows that where the two main bundles lock there is a third bundle—the so-called circular fibers of the heart. In order to separate the bundles at this point it is necessary to remove this third layer which is shown in fig. 7, *BS′*, as arising from the left side of the left ostium and then passes into the septum through the posterior longitudinal sulcus. It forms the deep bulbo-spiral band. In fig. 8 a piece of the deep bulbo-spiral band, *BS″*, is cut out to show the course of the superficial bulbo-spiral band, *BS*, as it passes through the septum. In studying this figure it is to be remembered that the cut edge of the bundle marked *X* does not belong to the deep bulbo-spiral bundle but to the superficial bulbo-spiral which passes around the heart and enters at the apex. The position of this cut is shown by the straight line *X* in fig. 6. It is also to be observed that the deep bulbo-spiral band passes under the longitudinal bundle of the right ventricle (figs. 8 and 9, *LRV*, which arises from the aortic septum just below the medial cusp of the tricuspid valve.

The superficial layer of the deep bulbo-spiral band is shown in fig. 9. The view is exactly the same as in fig. 8 with part of the origin of the longitudinal bundle, *LRV*, from the aorta to the right ventricle removed. It is also noticed in fig. 9 that the bundle arises on the opposite side of the aorta marked as a cut end, *O*, in the figure (See also fig. 10, *BS′*). The course of the fibers is also given which reminds us somewhat of Krehl's figures.

In fig. 10 the large flap of muscle which is turned back is the portion of the bulbo-spiral band marked *A* and *B* in figs. 5–7. It encircles the apex in fig. 10, enters the septum, fig. 8, and passes below the deep bulbo-spiral band, figs. 8, 10 and 12.

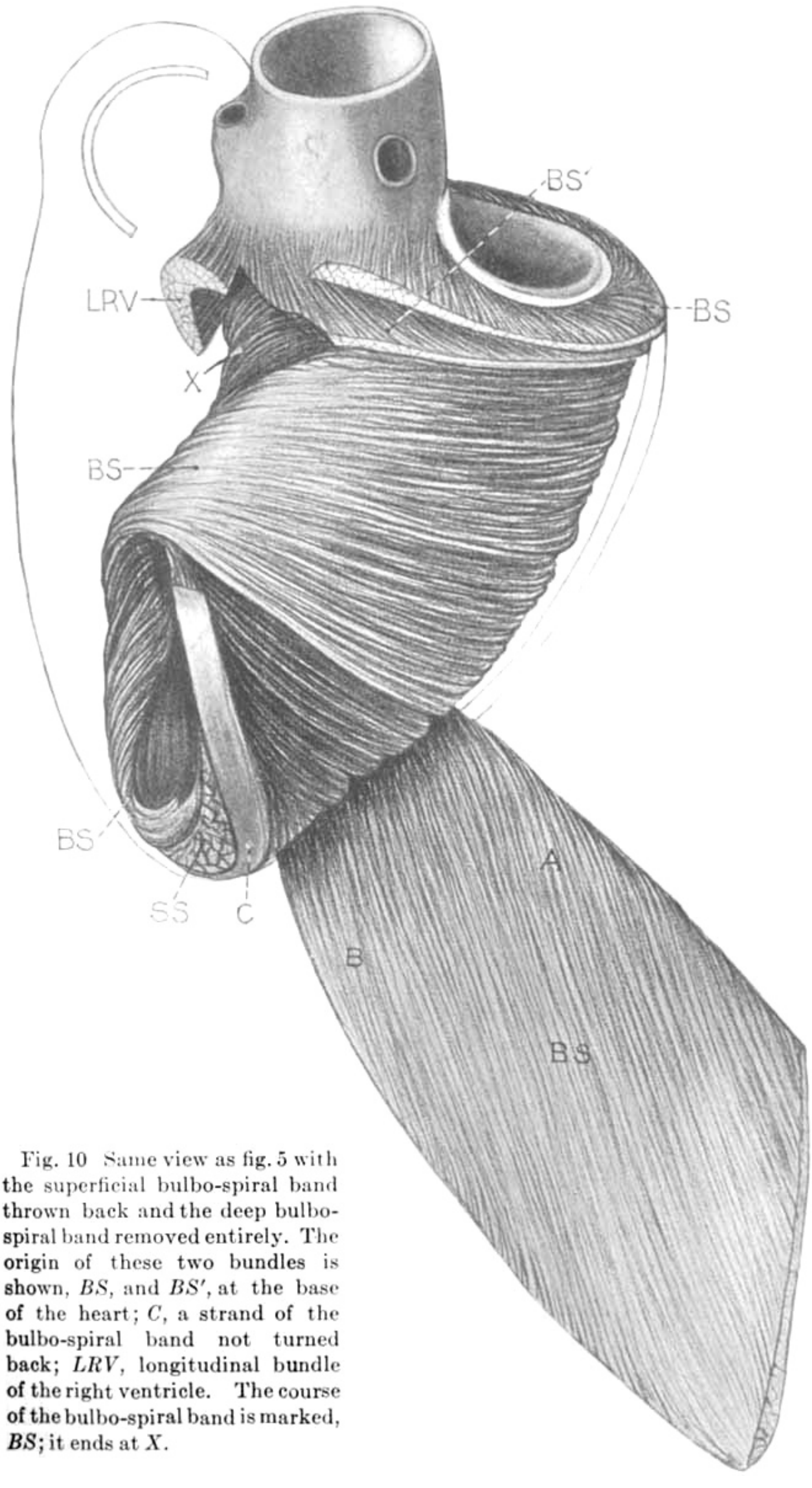


Fig. 10 Same view as fig. 5 with the superficial bulbo-spiral band thrown back and the deep bulbo-spiral band removed entirely. The origin of these two bundles is shown, *BS*, and *BS'*, at the base of the heart; *C*, a strand of the bulbo-spiral band not turned back; *LRV*, longitudinal bundle of the right ventricle. The course of the bulbo-spiral band is marked, *BS*; it ends at *X*.

The deep bulbo-spiral band having been removed the continuation of the superficial band below is revealed. This now encircles the heart and ends below and behind the aorta in the aortic septum as shown in figs. 8, 10, 12, *X*. Fig. 11 shows the deep bulbo-spiral band drawn upon the outline of fig. 10.[60] The older authors recognized this cylinder of circular fibers around which the superficial and deep fibers are wrapped to form the vortex. This arrangement may be seen by superposing figs. 10 and 11 as well as in fig. 12. Krehl also recognized that the deep bulbo-spiral band was intimately connected with fibers from the apex, for he states expressly that not only fibers from the outer and inner layers but also numerous fibers from the circular layer pass to the apex of the heart. His description of the circular bands is by no means consistent for he describes it as a cylinder, as a cylinder with fibers going to the apex, and pictures it as a basket entirely closed below. These variations are due entirely to the thickness he gives to this layer.

Coming back now to the superficial bulbo-spiral band, it is seen that it enters the apex and passes below the deep bulbo-spiral band, blends with it to encircle the left ventricle and with a general upward tendency ends in the septum aorticum below and behind the aorta. That is these fibers make nearly a double circle around the heart to form the figure 8 of Gerdy and Ludwig. The lower loop of the 8 encircles the apex and the upper loop lies within the deep bulbo-spiral band. It is also clear that my figure 8 is not closed above, just as Gerdy described it, and that its two free ends are attached to the septum aorticum on the two sides of the aorta.

In my description I have included with the deep bulbo-spiral band those circular fibers which pass through the septum as a single bundle, fig. 12, *BS'*, between the superficial bulbo-spiral bundle *BS*, the sino-spiral bundle, *SS*, and the longitudinal bundle of the right ventricle, *LRV*. Two views of the deep bulbo-spiral band are shown in figs. 9 and 11. It is noticed at once that the course of the

[60] This cylinder of fibers was well known to Winslow, Wolff and Weber (Weber, *l.c.*, pp. 151, 152) and had recently been described anew by Krehl.

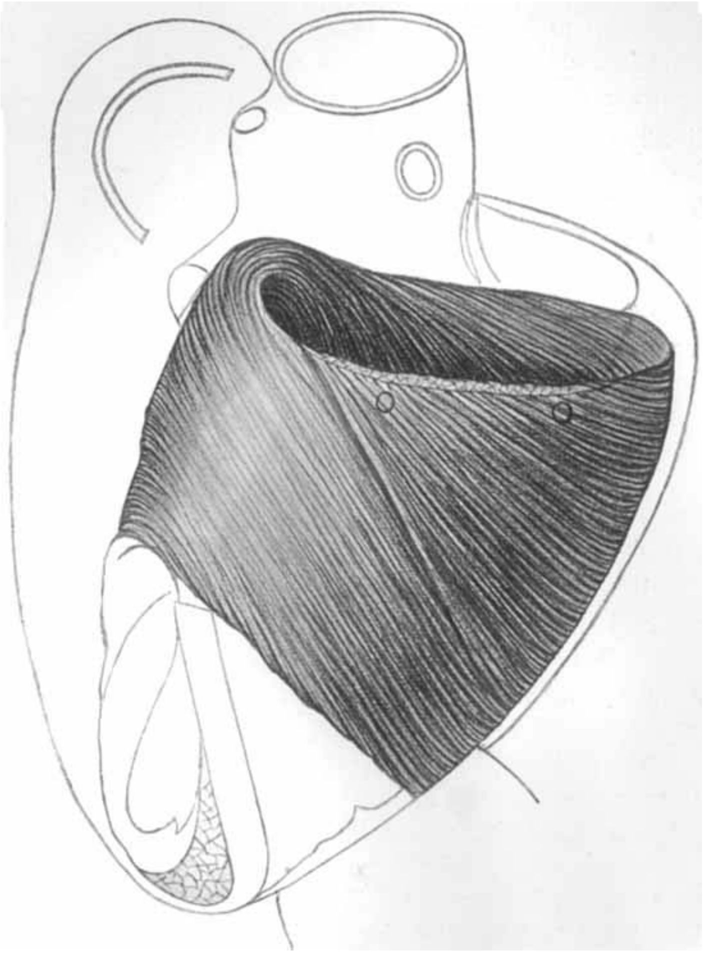


Fig. 11 The deep bulbo-spiral band which was removed from the specimen shown in fig. 10. The view is the same. *O*, origin of the fibers which are shown out in fig. 10, *BS'*.

fibers is not circular but in general inclines externally towards the superficial fibers of the heart and internally towards those under the endocardium.[61] Within the septum they have a transverse direction on the outside and within they have a general upward tendency as shown in figs. 9 and 11. It is further observed that the fibers of the deep bulbo-spiral band arise at the base of the heart immediately below the origin of the superficial band which passes from the same point to the vortex. This is shown in fig. 10, *BS*, and *BS'*, which gives this band as an extension of the longitudinal band of the right ventricle, *LRV*. The entire course of the deep bulbo-spiral band is shown in fig. 11. The band as a whole shows the fibers turning upon themselves on the apical side, then becoming circular and blending with the superficial bulbo-spiral band as it comes up from the septum as shown in figs. 10 and 11. The point of separation between these two bands marks the place where the muscle fibers of the left ventricle are most nearly circular. Within the septum, fig. 12, *X*, this is not the case, as here the end of the superficial bulbo-spiral band passes toward the root of the aorta to which it is attached.

It is quite easy to see that Krehl's *Triebwerk,* as pictured in his figs. 9 and 10, includes not only the deep bulbo-spiral band but also many of the fibers of the superficial which enter the heart through its apex. His figures show that the fibers arise evenly all around the tendon of the venous ostium, a condition which I can not verify. They arise only on the left side of the aorta and the ostium venosum. fig. 10, and as they pass the septum are entirely free from tendinous connections with the base of the heart as fig. 11 shows. In fact this separation from the base is well marked in the embryo and can easily be seen in serial sections.

As figs. 8 and 9 show, the circular bands form quite a prominence below the opening of the aorta just above the septum. This prominence is much better marked in the heart of the pig and ox, so much so that it is very noticeable below the right semilunar

[61] The gradual change of the course of the fibers in passing through the heart wall is from longitudinal to transverse, then to longitudinal again. This is well shown in Gerdy's diagram which may be seen in Todd's Cyclopædia, vol. 2, fig. 271. See also my schema A.

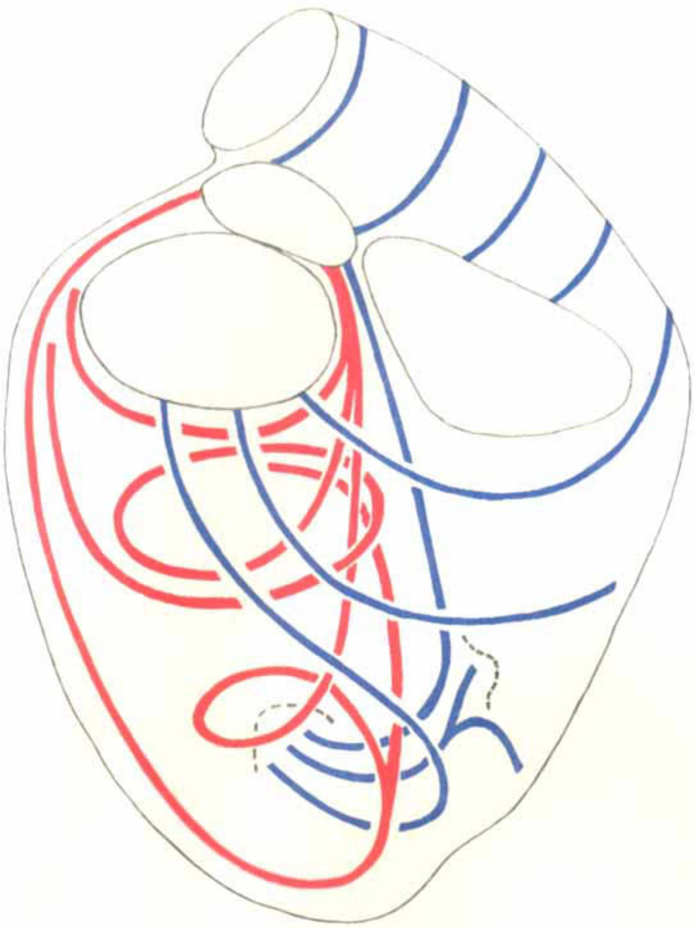
valve of the aorta. In fact the floor of this valve is fleshy, unlike that of the human.

It is also noticed in the pig's heart that many of the circular bands do not pass through the fleshy septum but are attached to the posterior ligament of the aorta and therefore do not make a complete circle. This bundle is shown cut off under the thumb of the left hand in fig. 19. In fact, there is a kind of raphé at this point in the pig's heart which reaches through the heart wall to the base of the posterior papillary muscle, and in a measure forms a break in the main circular bands. This is noted to call especial attention to a similar but much smaller group of muscle bundles around the left ostium in the human heart. Its attachment is to the posterior ligament of the aorta as shown in figs. 3, *TR*, and 8, *TR*. The circular bundles extending partly around the left ostium have been well pictured by MacCallum for the pig where they are very pronounced.[62]

The extent of the deep bulbo-spiral band varies very much in different hearts. In the new-born and in young children this band is very insignificant which indicates that during growth it must enlarge faster than the other heart muscle bundles. It also varies in size in the adult heart. Figs. 5 to 12 are taken from an hypertrophied heart which shows the circular bands markedly thickened. On the other hand in a dilated heart with thin walls it is barely present as fig. 13 shows. To show further variations I add an illustration of a well-developed small heart in fig. 14. Here the deep bulbo-spiral band is unusually well-developed, in fact as well as in the hypertrophied heart shown in figs. 5 to 12.

To show the course of the chief muscle strands of the ventricles of the heart, Schema B. is given. The bulbo-spiral bands are in red and the sino-spiral in blue. The superficial bulbo-spiral band reaches to the apex of the heart and there enters the septum; a layer somewhat deeper encircles the apex, while the middle layer, the deep bulbo-spiral, encircles the ventricle and ends with

[62] MacCallum, *l.c.*, fig. 20. MacCallum also finds that the deep bulbo-spiral band arises not only from the aortic septum but also from the tendon of the right ostium venosum. Such an extension of the origin of this bundle beyond the aortic septum does not exist either in the pig or in man.



Schema B. The chief muscle bundles which have been described are given. The bulbo-spiral group of fibers are in red and the sino-spiral in blue. The bundles immediately around the left ostium and the conus form single loops which attach themselves to the aortic septum. All other bundles may be considered modifications of these two simple loops.

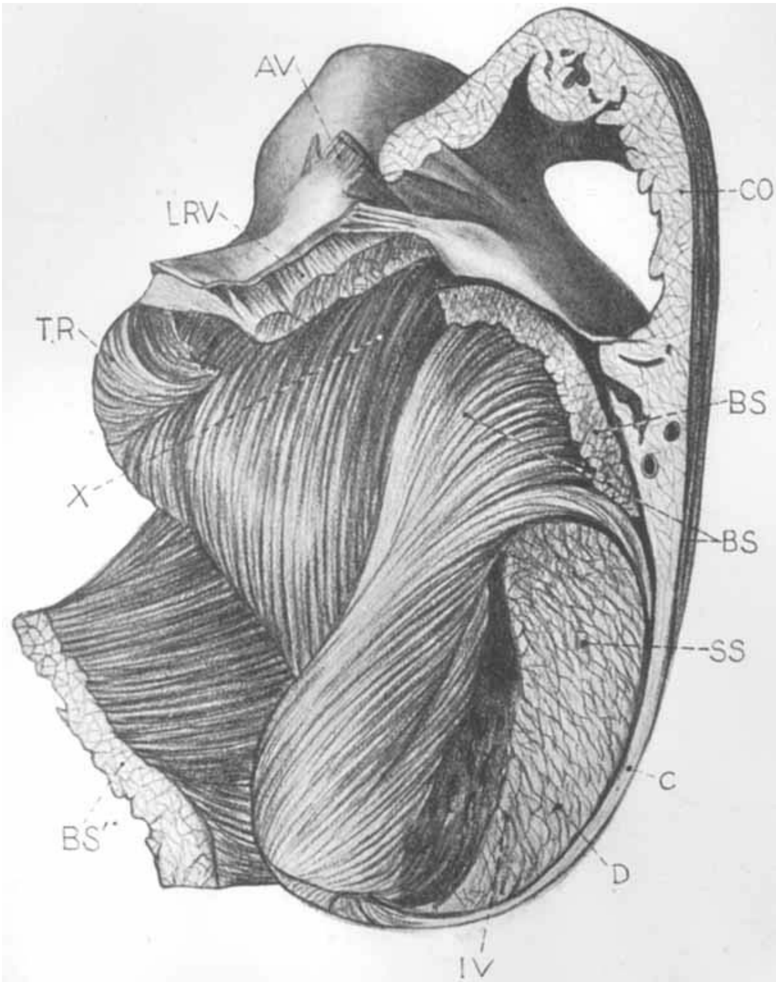


Fig. 12 Dissection of the septum viewed from the right side. *CO*, conus; *BS* and *BS'*, superficial and deep bulbo-spiral bands which end at *X*; *LRV*, longitudinal band of the right ventricle; *TR*, posterior triangular field; *SS*, sino-spiral band passing under fasciculus *C* of the superficial bulbo-spiral band; *D*, layer *D* of fig. 5 which is blended with the interpapillary layer, *IV*.

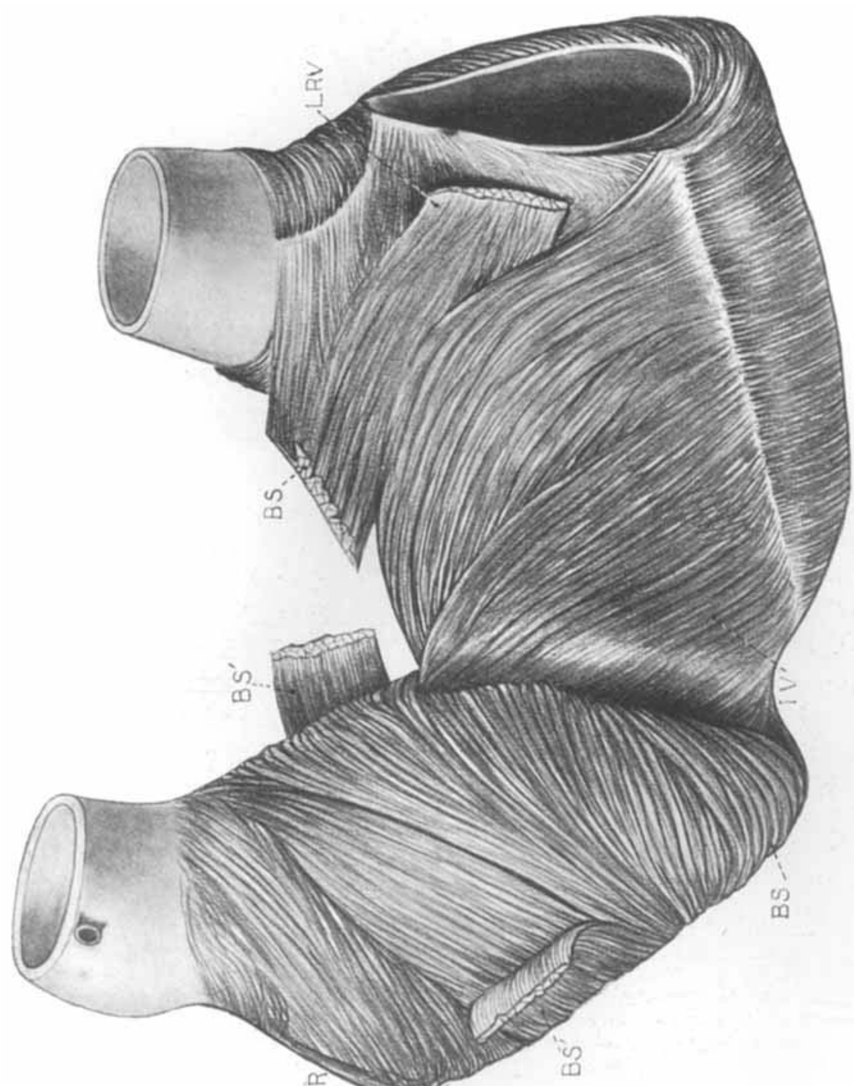


Fig. 13 A large dilated heart broken open from behind. The deep bulbo-spiral band, *BS′*, is very thin and delicate. *BS*, bulbospiral band; *LRV*, longitudinal band of the right ventricle; *TR*, posterior triangular field, with the point, raphé, extending towards *BS′*. Reduced one-fifth.

Fig. 14 A well developed heart of average size to show the very large deep bulbo-spiral band. The superficial bulbo-spiral band passes to the base of the heart and blends with *BS'*. *CLV*, circular band of the left venous ostium.

the superficial band on the dorsal side of the aorta. The small circular band ends in the posterior triangular field. The sino-spiral bundle encircles the right ventricle and blends with the longitudinal band of the right ventricle to form the anterior horn of the vortex before entering the left ventricle. Here they end partly in the papillary muscles. Other single loops encircle the conus and are attached to the aortic septum, or tendon of the conus.

While most anatomists state that all of the muscle bundles of the left ventricle form loops or V-shaped bundles which are attached to tendons at the base of the heart, this has been denied from time to time. Occasionally I have also found a bundle which seems to turn upon itself at the base of the heart as shown in fig. 14. It is noticed in this figure that a large bundle lies midway between the superficial bulbo-spiral and the deep bulbo-spiral band, passes diagonally through the septum to the base and then turns downward. It then encircles the base, blends with the deep bulbo-spiral band and ends at the dorsal side of the aorta in its posterior ligament. No such bundle is seen in figs. 8 nor 13. But it is quite easy by comparing figs. 8 and 10 to imagine a portion of the superficial bulbo-spiral band separated during part of its course to form the variation seen in fig. 14. Beside this one example I have not found any bundles which might be considered as forming V-shaped loops pointing away from the apex and towards the base in the left ventricle. But since the loops entering through the apex, as well as the main circular bands, pass nearly twice around the heart before they end, many variations must occur, and by a stretch of the imagination they may be found in every specimen.

The two muscle strands which cover almost the entire exterior of the heart and enter at the vortex are finally distributed over the interior of the left ventricle as well as to the papillary muscles. All ultimately end at the atrio-ventricular ring. A complete separation of these bands under the endocardium as they are separated under the epicardium is hardly possible. However, with some reserve a statement may be made regarding their distribution within the left ventricle.

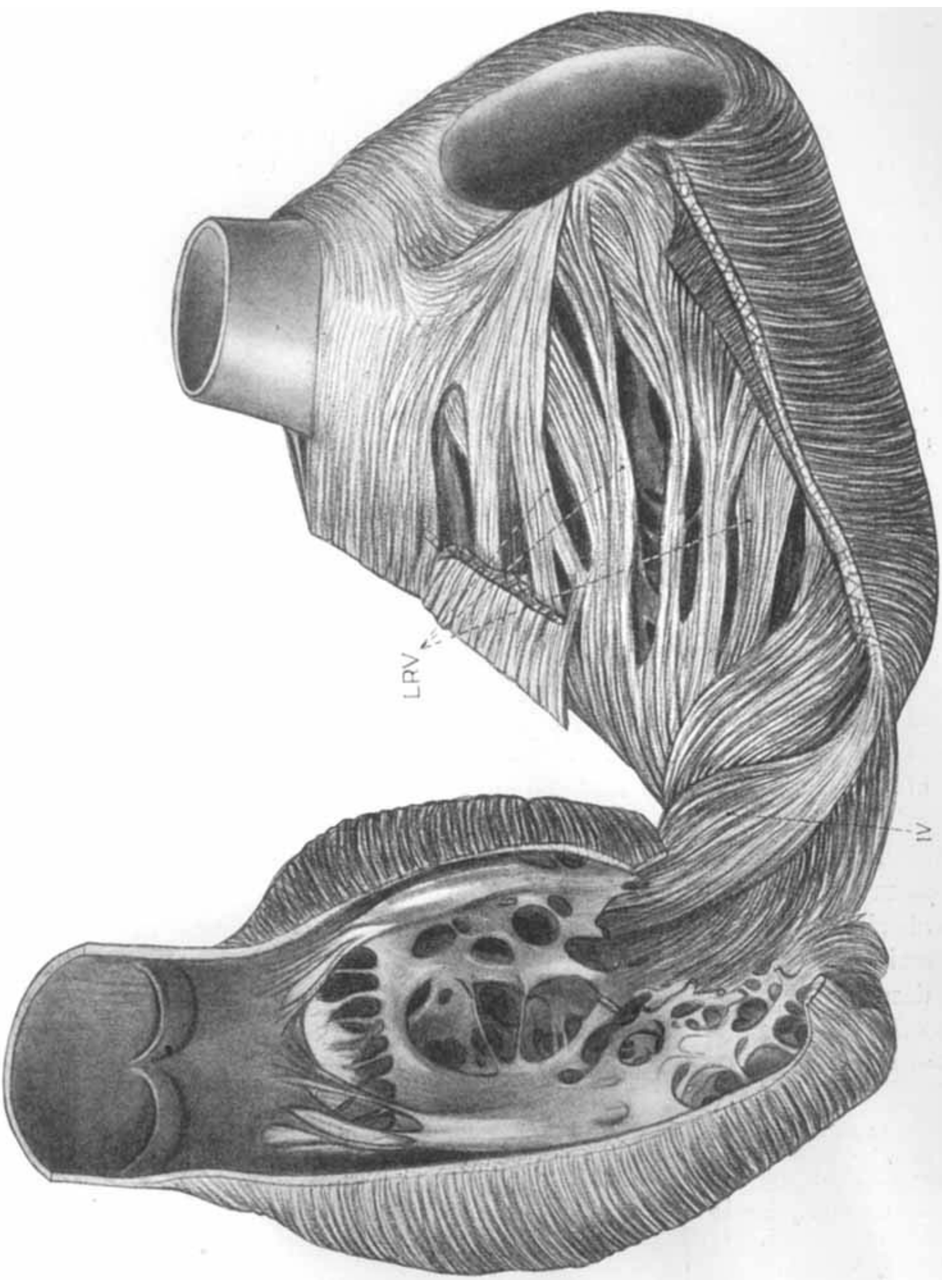


Fig. 15 Large heart from which most of the septum has been removed to show the interpapillary bands which pass as the longitudinal layer of the right ventricle to the membranous septum. *LRV*, *longitudinal bands of the right ventricle*; *IV*, interpapillary muscle band. Reduced one-fifth.

The superficial bulbo-spiral band, arising from the conus and entering through the posterior horn of the vortex, passes up the septum and blends with the deep bulbo-spiral band. In some specimens they attach themselves at once to the aorta, as shown in fig. 13. In this specimen the circular bundle around the left venous ostium is unusually poorly developed. In other hearts, as in figs. 8 and 14, practically no attachment to the aorta is made at once but all of the bands encircle the ventricle again and are finally attached to the posterior ligament of the aorta. This is shown in figs. 8 and 10 as well as in fig. 14. From this description it follows that the bulbo-spiral band distributes itself within the left ventricle chiefly on its posterior side. That is, it arises on the anterior side of the heart, externally passes once-and-a-half times around the heart and ends on its posterior side internally.

The sino-spiral bundles, arising at the ostium behind and passing over the right ventricle to enter the left vortex through its anterior horn, are reënforced by a thick band of muscles from the interior of the right ventricle and pass at once to both papillary muscles of the left ventricle which seem to be composed almost entirely by them. Many fibers pass the bases of these muscles and extend upward to end in the anterior side of the fibrous ring of the left venous ostium. In general, they line the anterior side of the left ventricle and also end in both papillary muscles.[63]

This brings us to the interventricular bands. They were already known to Gerdy whose description of the heart musculature has stood the test of time. Since E. H. Weber denied absolutely the existence of these bundles[64] they were not taken seriously by anatomists until they were rediscovered and well described by MacCallum.

Fig. 2 shows a strand of muscle fibers, *C*, passing from the vortex of the right ventricle to the apex of the left ventricle where

[63] In the pig MacCallum associated the sino-spiral bundle exclusively with the anterior papillary muscles and the bulbo-spiral with the posterior papillary muscle. However, this is correct only to a certain extent, for in man the posterior papillary muscle is associated with both spiral bands. This arrangement is necessary in order to unroll the ventricle of the pig into a sheet, as MacCallum did.

[64] Weber, *l.c.*, p. 153.

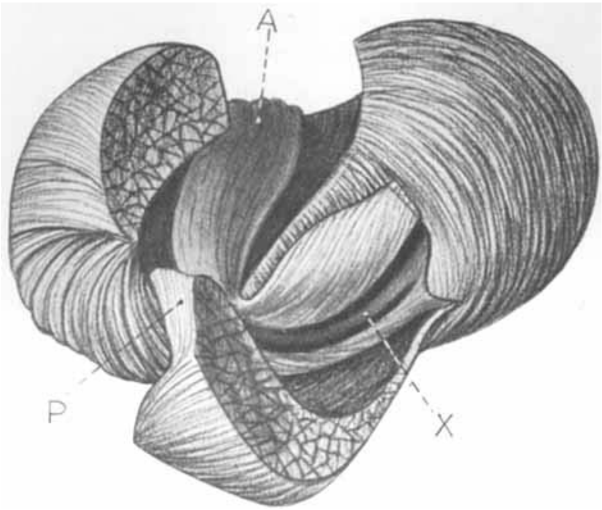


Fig. 16 Pig's heart cut open on its left side and then boiled after which the papillary muscles were torn out. *A* and *P*, anterior and posterior papillary muscles. A muscle band from the right ventricle passes between them. The bundle *X* belongs to the anterior papillary muscle.

it enters at the locking point of the two horns of its vortex. If now the strands of the anterior horn of the vortex of the left ventricle are cut as they pass over the posterior longitudinal sulcus, *SLP*, the interventricular strands are brought to light deep in the septum as is well shown in figs. 3 and 8. By cutting through all the muscle which connects the two ventricles in fig. 8, fig. 12 is obtained. Here it is clearly seen that the interventricular bands, *IV*, lie nearest the lumen of the ventricle, while the bulbo-spiral bundle, *C*, and that forming the anterior horn of the vortex, *D*, lie more superficially. The connection of the interventricular strands is shown in fig. 15; this is from a distended heart which has been macerated and fully dissected. It is seen that the interpapillary bands also extend upward in the right ventricle to end in the membranous septum.

Although the muscle strands are more intimately blended with one another at the apex of the heart of the pig than in man, it has been easier for me to follow the attachments of the papillary muscles in the former than in the latter. Possibly this has been the case on account of an abundance of pig's hearts. It is seen by unrolling the left ventricle of the pig's heart that the chief circular bands which arise from the bulbus fall into three distinct bands which are easily separated from one another. The first is the single circular band around the left ostium, and the second and third are the spiral bands which enter the septum. The superficial bulbo-spiral band instead of encircling the left ventricle as it does in man divides into two bands (figs. 19 and 20); one is attached to the anterior tendon of the aorta, *BS, Post,* while the other encircles the anterior papillary muscle and is ultimately attached to the posterior ligament of the aorta, *BS, Ant,* In doing this the anterior superficial bulbo-spiral band, *BS, Ant,* passes within the walls of the ventricle, between the anterior and the posterior papillary muscles. In order to show this relation better fig. 16 is given. In the specimen from which this figure was made the left ventricle was cut open on its left side before the heart was boiled in dilute acetic acid. Then the papillary muscles were broken apart; the specimen shows clearly that the posterior muscle sends its fibers over the right ventricle, and the fibers from the anterior papillary muscles pass out of the apex of the heart on the medial side of the right ventricle. The strand marked *x* in fig 16 belongs to the anterior papillary muscle. Between the strands which enter the papillary muscles there is a third which passes from the right ventricle to the left and blends with the anterior bundle of the superficial bulbo-spiral band. By this arrangement it is easily seen that the anterior papillary muscle is intimately connected with the sino-spiral band and the posterior partly with the bulbo-spiral butmostly with the muscle bundles from the right ventricle both on its lateral and medial sides. This arrangement is well shown in figs. 16 and 18. In fig. 18 it is further seen that the roots of the posterior papillary muscle not only reach outside of the heart through the bulbo-spiral band to the aorta but also on the medial side of the right ventricle through the longitudinal bundles of the right ventricle to the membranous septum. On its posterior side it is intimately attached to the circular bands by the way of a raphé which is not

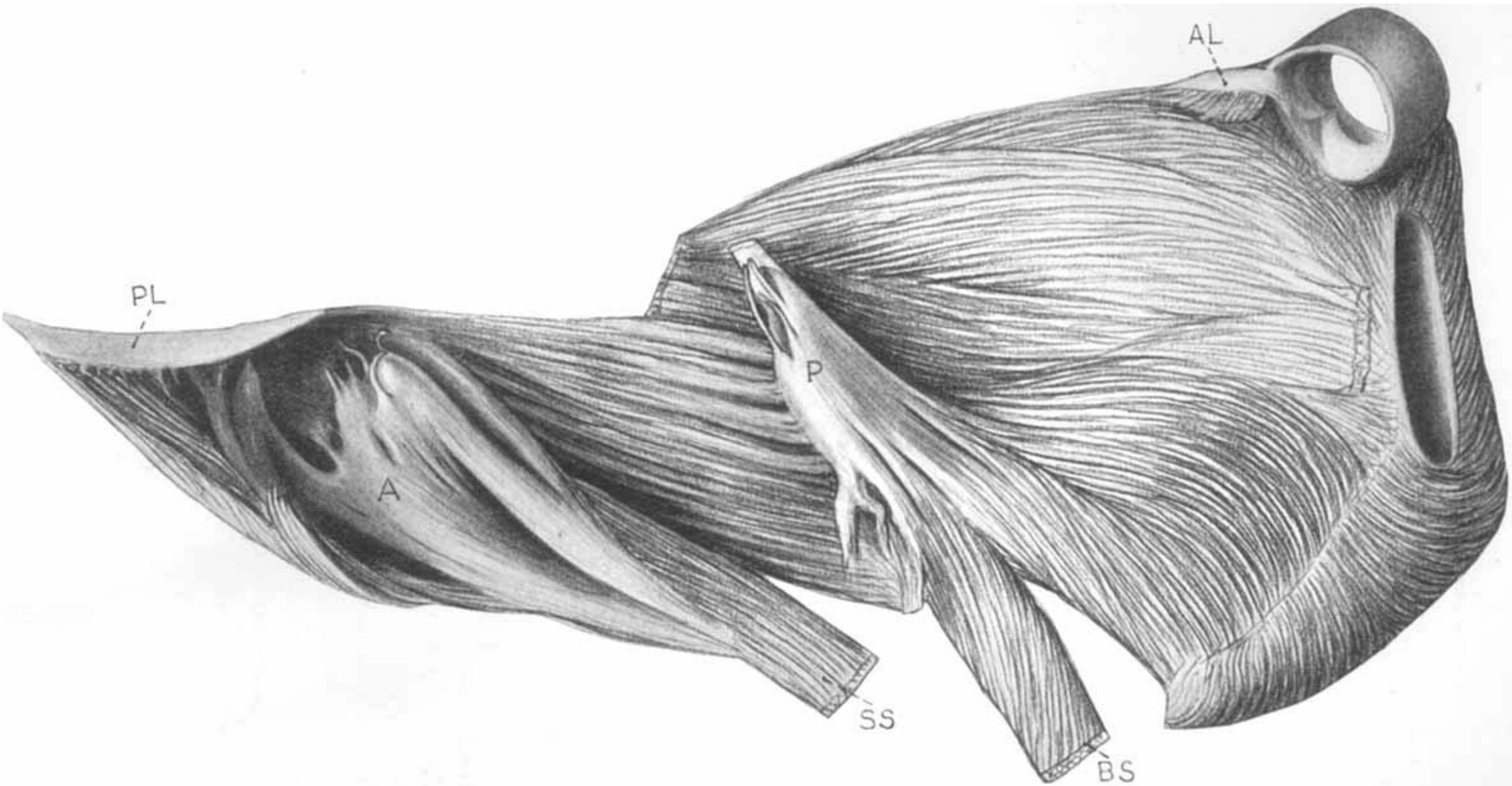


Fig. 17 Pig's heart unrolled according to MacCallum's method, *AL* and *PL*, anterior and posterior ligaments of the aorta. *A* and *B*, anterior and posterior papillary muscles; *SS* and *BS*, sino-spiral and bulbo-spiral muscle bands.

well marked in the human heart, but is indicated in figs. 3 and 8 (tip of *TR*) and is very pronounced in the pig. At this point the fibers from the posterior papillary muscles are so intimately blended with the deep bulbo-spiral band that often in peeling off this band it breaks at the raphé and leaves the large circular band around the left ostium as described by MacCallum and pictured in figs. 19 and 20, *BS'*. If this bundle, as shown in fig. 20, is pushed downward its cut end will come in contact with the base of the posterior papillary muscle to which it was intimately attached.

What has just been said shows that the papillary muscles are in direct continuation with all of the chief muscle bands of the heart and the attachment of the atrio-ventricular system to them gives meaning to this. An impulse or a wave coming through the bundle of His is at once communicated to the entire musculature of the ventricles.

In studying the musculature of the ventricles of the heart one's attention is directed mostly towards that of the left ventricle, and there is a tendency to neglect the right ventricle because it appears to be of simple construction. On the right side the inner muscle bundles are directed towards the conus as they are towards the aorta on the left side.

In tearing off the muscle bundles from any portion of the ventricle it is at once observed that the fibers always tend to pass upwards, towards the base, as they are stripped off. That is, they are constantly passing into the depth. Over the right ventricle this is so marked that when bundle after bundle is lifted up they are found to lie upon one another like the shingles of a roof with the deeper longitudinal muscle bands below serving as rafters (compare figs. 6 and 15).

The superficial muscle bundles, the superficial sino-spiral, come mostly from the left side of the heart, pass over the right ventricle quite freely and then back to the left ventricle. Just below this is a sheet which arises from the posterior part of the left ostium and enters the right ventricle to end there. This, the deep sino-spiral, is the sheet so well described by MacCallum. When these two sheets are examined together it is seen that fiber

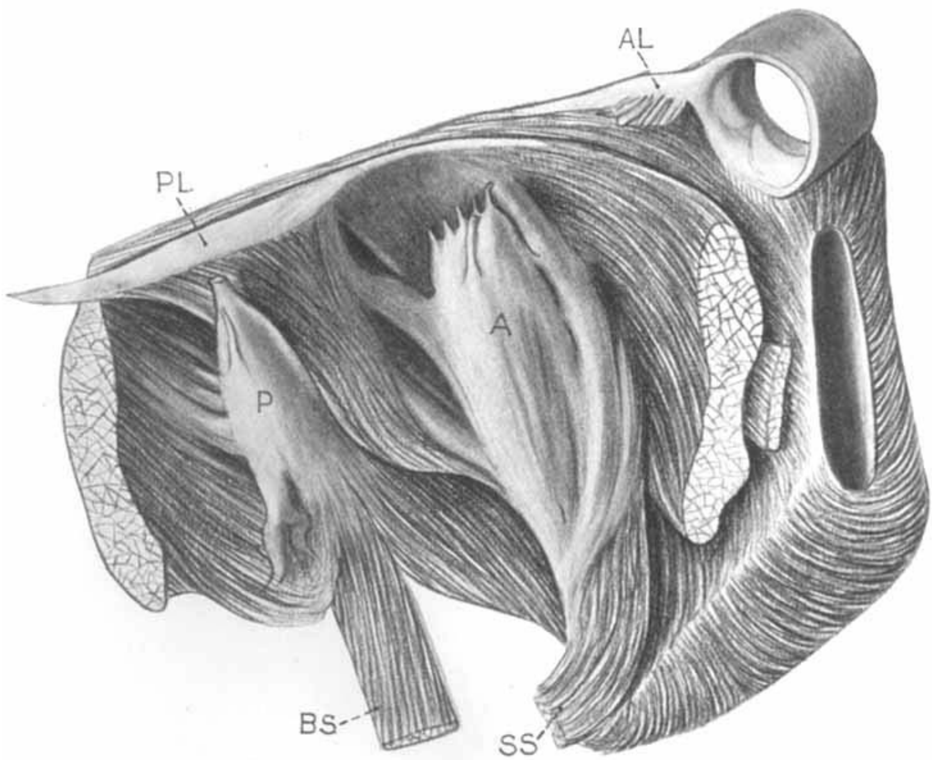


Fig. 18 Outer half of specimen shown in fig. 17 cut off and superposed upon the inner half to show proper relation of the papillary muscles. Letters as in fig. 17.

bundles are constantly passing into the depth whence they pass upward towards the conus. Especially is this true along the anterior longitudinal sulcus, as shown in fig. 6. This observation was first made by Wolff and has been repeatedly confirmed.[65] It is not difficult to see in this arrangement an extension upward of the vortex of the right ventricle. When these bundles once reach the inside of the right ventricle they all have an upward tendency, towards the conus. On the septal side the inner fibers pass towards the membranous septum, that is towards the ostium. These fibers communicate freely with the papillary muscles of

[65] Parchappe, Du Couer, Rouen, 1846, Pl. 5, fig. 1.

both ventricles as shown in fig. 15. The fibers from the conus cross the anterior longitudinal sulcus and pass to the apex as the bulbo-spiral band (fig. 6). Below these, the fibers encircle the right ventricle (fig. 1) and dip into the anterior longitudinal sulcus as indicated in fig. 6. At the apex of the right ventricle the fibers pierce the septum to pass into the left ventricle as shown in fig. 12.

At the base of the heart the fibers encircle largely the right venous ostium (fig. 1) to reach the conus where they blend intimately with the tendon of the conus (figs. 1, 3, 4, 8 and 13). At this point we also recognize the circular band of the conus as described by Ludwig, and subsequently by Krehl. This MacCallum could not verify in the pig. However it is present but by no means as marked as one would believe by reading Krehl's paper. It is seen in figs. 6 and 8 that a large loop encircles the conus which is broken by a tendon, the superior aortic septum. However, careful dissections of this region in man and in the pig reveal a small circular band of fibers which encircles the conus and is attached to the aortic septum only. So, as the aorta has its own simple circular band which includes the left venous ostium, there is a corresponding band in the right ventricle which includes the conus only. This arrangement is fundamental and may be described as the figure 8 of the base, one loop around the conus and the other around the aorta and the left ostium, with the cross piece as the septum aorticum. All the other loops of muscle bands may be considered as modifications of the two loops of the transverse figure 8, but they must all come back to the cross piece of the 8, or aortic septum. One loop encircles the main part of the bulbus and the other the main part of the sinus. (See Schema B).

The longitudinal bundles of the medial side of the right ventricle connects with the papillary muscles of the left ventricle and with the membranous septum on the right side of the heart (figs. 3, 8 and 15). A portion of it passes over the front of the heart to blend with the superficial bulbo-spiral band. This is shown in fig. 13 and in fig. 15 where its attachment to the membranous septum has been cut off, and in figs. 6 and 8 with the corresponding points marked by an *X*. In fact this bundle arises in common with the superficial bulbo-spiral band from the membranous septum and could be well considered with it (fig. 10, *LRV* and *BS*). If described with it it would be said to extend on the outside of the heart to the apex and thence through the septum, and on the inside of the right ventricle over the septum, finally ending in the papillary muscles of the left ventricle. It also ends in the large papillary muscles of the right ventricle.

MacCallum found that he could unroll foetal pigs' hearts which had been macerated in a solution of glycerine, water and nitric acid, into a single sheet or scroll of fibers. He was also able to unroll a number of foetal hearts as well as the heart of a child three or four years old. Subsequently Knower showed that hearts from cadavers which had been embalmed with carbolic acid could be unrolled by MacCallum's method with considerable ease. Since, however, my aim now is to interpret MacCallum's scroll, I shall use the adult pig's heart in my descriptions. I have extended his work by leaving the tendons at the base of the heart intact in order to show better the attachment of the fiber bundles at this point. The specimens were prepared by distending them with a three per cent solution of carbolic acid in water as already described.[66] They were then dissected, as shown in figs. 3 and 4. In doing so it is well to let the split be natural and not forced either to one side or to the other.[67] Soon the longitudinal muscle band from the membranous septum to the right ventricle comes into view and after it has been well isolated it is to be cut squarely. Next the aorta is to be torn from its root which takes with it the muscle bundles, superficial and deep bulbo-spiral, arising at this point. This may be understood by a glance at figs. 10 and 11. The splitting

[66] By this method hearts may be prepared in either the dilated or the contracted form. In order to make specimens rapidly and also quite satisfactorily hearts may be unrolled after boiling them in dilute acetic acid for half an hour. The specimen can then be cleaned easily, the muscle is not shrunken and the tendons at the base are still intact.

[67] Searle, Todd's Cyclopædia of Anatomy, 1836, vol. 2, evidently had this sheet before him when he described the "rope" of the heart. His fig. 278 is similar to my fig. 17.

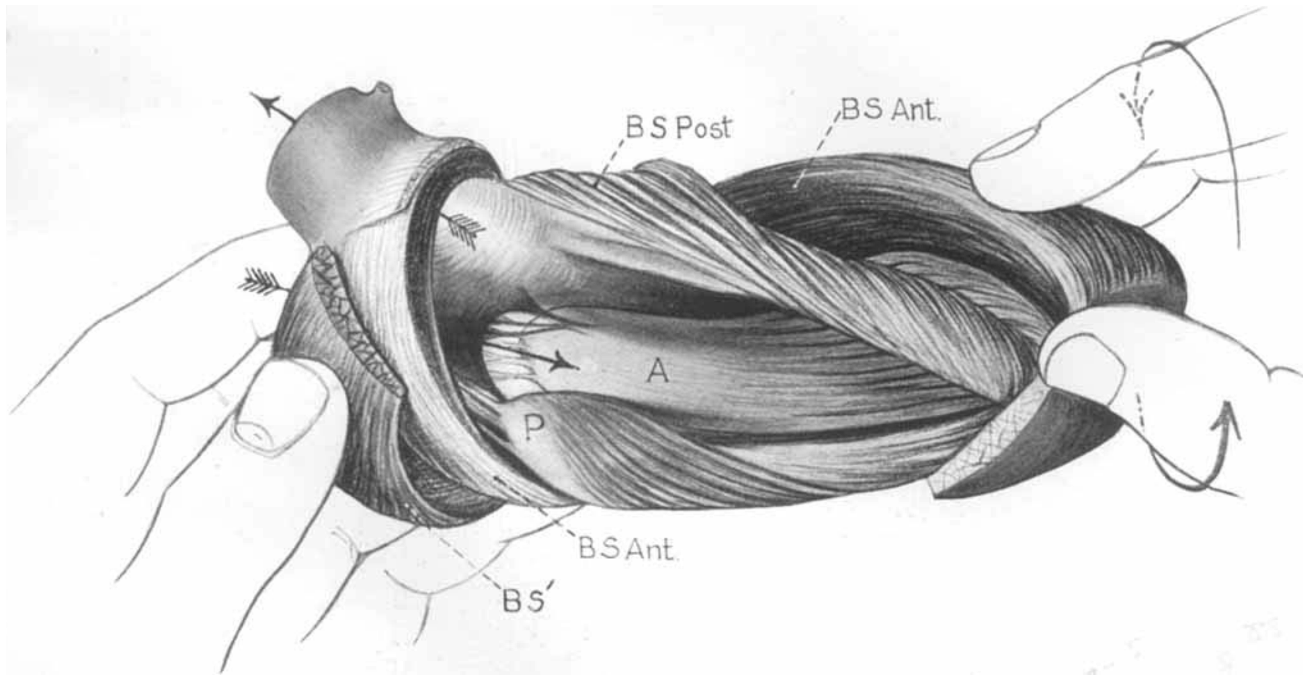


Fig. 19 Pig's heart with the outer fibers removed to show the bundles within the heart. *A* and *P*, anterior and posterior papillary muscles. *BS'*, portion of the bulbo-spiral band which encircles the left ostium; *BS*, *ant.*, portion of the superficial bulbo-spiral band which is attached directly to the root of the aorta; *BS*, *post.*, portion of the superficial bulbo-spiral band which encircles the heart in front and is finally inserted in the posterior ligament of the aorta. The heart is in diastole as the position of the left hand holding the apex indicates.

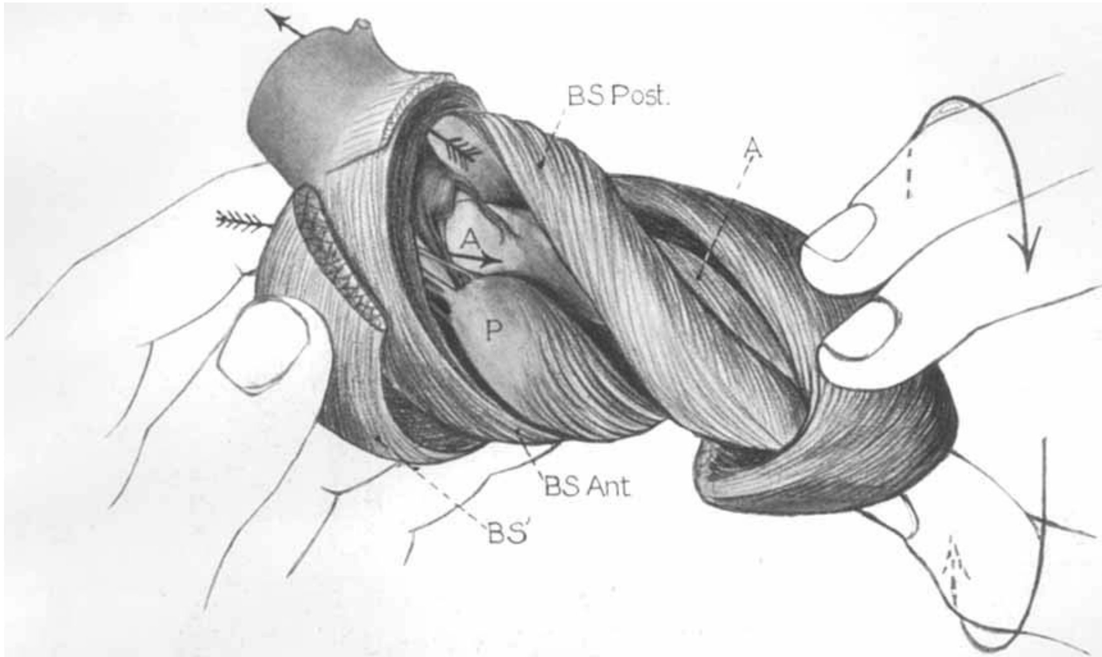


Fig. 20 Same as fig. 19 except the hand at the apex is twisting the heart to imitate the rotation which takes place when the ventricles contract. This action twists the inner muscle bundles and thus "wrings" the blood out of the heart.

of these bands is then extended around the heart to the posterior side much as is shown in fig. 8. As the aorta has been taken out (or macerated out in MacCallum's specimens) the first break into the cavity of the ventricle is immediately under the aorta, in fig. 8 which is also shown in fig. 18. Here it is clearly seen that the anterior papillary muscle is attached to the tip of the scroll as shown in fig. 17. That this split is natural and is easily made is shown by fig. 16, in which the two papillary muscles are shown with a strand of muscle tissue between them. This strand extends to the tip of the scroll and ends in the posterior ligament of the aorta (fig. 17, *PL*). This figure also shows the entire left ventricle unrolled with the two spiral strands hanging loosely below. The one associated with the posterior papillary muscle coming from the aorta is the bulbo-spiral band and the other which is attached to the anterior papillary muscle is the sino-spiral. Fig. 18 is made from the specimen shown in fig. 17, by cutting it in half and replacing the distal end within the proximal. In general it represents the left ventricle cut open from behind, and expresses clearly the course of the break when the wall of the left ventricle is unrolled.

What is here given only apparently contradicts what Krehl found when he isolated the *Triebwerk* of the left ventricle. My illustrations (figs. 10 and 11) show that this may also be unrolled if its point of origin is detached from the aortic septum. In so doing the entire circular bands which pass the septum, including the anterior papillary muscle, hold together, as shown in fig. 18. So Krehl's *Triebwerk* is not composed of muscle bundles which form complete rings but bundles which both arise and end in the tendinous structures at the base of the heart. In so doing the bundles turn upon themselves to form V-shaped loops just as do the bulbo-spiral and sino-spiral bundles as they enter the vortex. MacCallum's scroll again shows that all of the muscle fibers form V-shaped bundles which encircle the left ventricle. They are fitted into one another, those forming the circular bands making obtuse angles while the outer and inner bundles form acute angles at the apex. Between these two systems there are all intermediate gradations. (See Schema A.)

It is apparent that the arrangement of the superficial fibers of the heart is such that their contraction will cause the heart to rotate, as is well known to physiologists. In so doing the transverse diameter of the heart must diminish but it is not necessary that the long diameter should change as was pointed out by Hesse.[68] Since the rotation of the apex in contraction is accompanied by a straightening of the superficial spiral fibers, it must cause the inner spiral fibers to curve upon themselves for they run at right angles to the outer fibers. This is well illustrated in a diagram by Nicolai,[69] which shows that in contraction the outer fibers of the ventricle become straighter, while the inner ones become more spiral. According to my description of the heart muscle fasciculi such a contraction need not change the length of the heart, but it exaggerates to the utmost the folds which are formed within the heart during systole; in fact the lumen of the left ventricle is nearly obliterated. In fig. 19 the heart, which is held in both hands, is represented as it is in diastole. In order to imitate contraction of the heart as it takes place in systole it is necessary to rotate the apex as shown in fig. 20. In this change of position the inner bundles are twisted as one wrings out a wet rag. This was Borelli's[70] conception of the heart contraction which I do not believe can be improved on very much. Borelli gives an account of the arrangement of the muscle bundles of the heart in which it is pointed out that there is a general downward course of the fibers from the base to the apex where they form the vortex. He also gives a figure of two hands twisting a rope to illustrate the way the rotation of the contracting heart presses the blood out during systole. My dis-

[68] The statement to this effect by Hesse, His and Braune's Archiv, 1880, relates to the dog's heart. Krehl, *l.c.*, p. 349, thinks that it is equally applicable to the human heart, although evidence is wanting.

[69] Nicolai, Nagel's Handbuch der Physiologie, Braunenschweig, 1909, Bd. 1, fig. 74. Nicolai's description is entirely theoretical for he states that the architecture of the heart is by no means clear, and that the longer this subject is worked upon the more confused it becomes. Evidently Nicolai has neither studied suitable specimens, nor the literature upon the subject. It is becauc of the importance of Nagel's Handbuch that I call attention to Nicolai's dilemma.

[70] Borelli. De motu animalium, Romae, 1681.

sections support Borelli's conception of the mechanism of the heart beat. In order to make it clear to the reader two illustrations of the same heart, in diastole and in systole, are given. The curved arrows in figs. 19 and 20 indicate the necessary rotation of the heart at its apex to convert the one figure into the other. It is to be noted that this specimen is from a pig's heart in which the circular band at the base is much more pronounced and that of the septum much less marked than in man. Also the ending of the bulbo-spiral band within the heart divides into two distinct bands, one of which unites with the front side of the aorta and the other encircles the heart as in man and ends in the posterior ligament of the aorta. The external spiral bundles have been removed. In the dilated heart, fig. 19, the inner bundles are unwrapped and the outer ones, which have been cut off, were lengthened. In fig. 20 the opposite is the case, the inner bundles including the papillary muscles are wrapped upon themselves and fill the lumen of the ventricle. Specimens like the one from which figs. 19 and 20 are made are not so difficult to prepare and they show the mechanism of contraction much better than the illustrations do.

What has been said about the pig's heart can easily be read into the human, from the description I have given of it. Fig. 7 shows that contraction of the bulbo-spiral band will rotate the apex and wind up, or put under great stress, the chief deeper bundles of the left ventricle, as shown in fig. 8. Contraction of the deep bulbo-spiral band, the *Triebwerk* of Krehl, will then complete the contraction of the ventricle.

To obtain a proper understanding of the architecture of the heart the organ must be considered as a whole with a conception of the function it has to perform kept uppermost, as was done by Borelli and was emphasized by Weber and by Ludwig. Only from this standpoint is it possible to get a clear understanding of this intricate network of muscle bundles. Not only is this the case for the adult heart, but without it we cannot hope to unravel its development, for the arrangement of the fibers must be due to functional adaptation from the time the heart begins to beat.