Harveian Lecture

ON

THE FUNCTIONAL ANATOMY OF THE HEART.*

BY

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ABOUT the middle of last century, when physiologists broke away from anatomists, they stole our patron saint—Harvey. Yet Harvey was an anatomist; from 1615, when he was 37 years of age until 1656, when he was 78, he was the leading lecturer on anatomy in London. It was the application of a right method to the study of the structure of the human body which led him to see that the heart was a double pump forcing the blood to circulate throughout the body.

To understand how Harvey became an anatomist we must follow him to the University of Padua in the last year of the sixteenth century, when he was in his twenty-second year. It was a fortunate circumstance for Harvey that Fabricius, Professor of Anatomy at Padua, was then reinvestigating the occurrence and use of valves in veins. He explained to his students that valves did not occur in arteries because in them the blood ebbed and flowed; but they were absolutely essential for veins in order that the venous blood, which was designed for the nourishment of the tissues, might be evenly distributed to all parts of the body. Were the veins of the arms and legs destitute of valves, it was quite clear, he maintained, that blood would gravitate to the hands and feet and so rob other parts of the body of their just share. We see, then, that Fabricius was studying the anatomy of the various parts of the human body in order to find out the purpose which they served; he was a functional anatomist. We may smile at his conclusions, but we could not make a greater mistake than to condemn his methods, for it was by following Fabricius's example that Harvey was led to his great discovery.

We have no exact information relating to Harvey's investigations between the time of his return to England in 1602 and his appointment as Lumleian lecturer at the College of Physicians in 1615. During those thirteen years he dissected many kinds of animals,² for Harvey was not only a functional anatomist, but a comparative anatomist and embryologist as well. We have only to turn to his introduction to his book on the motion of the heart and blood in animals to discover the manner in which he proceeded to work. He used anatomy as a touchstone on which to test the physiological theories of his day—the theories which Fabricius could expound so convincingly to his students. It was impossible to gainsay the then dominant theory relating to the use of veins. From an anatomical point of view the theory was apparently sound. The products of digestion certainly passed into the radicles of the portal vein and were "concocted" in the liver before being passed into the systemic venous system. The theory explained the existence of the liver and the distribution of veins to the most distant parts of the body. Fabricius had given the reason for the presence of valves in veins—except those in the jugular veins at the root of the neck. Harvey was quick to note that they pointed the wrong way, if Fabricius's theory were true. His real difficulties began when he sought to explain the parts connected with the right side of the heart. The blood entered that side of the heart, so he had been taught, for two reasons: (1) To supply the lungs with nourishment; (2) to send a supply to the left ventricle through the interventricular septum. "Why, then," asked Harvey, "is the vein which carries the blood from the right ventricle to the lungs given the coats of an artery and made as large as the aorta which has to supply 'vital' blood to the whole body?"

To men of Harvey's time the explanation of air passages to the lungs and of venous passages leading from the lungs to the left chambers of the heart were perfectly satisfying.

They were the means by which air reached the left ventricle of the heart. In that chamber the air mixed with the transuded venous blood, and so vital blood was brewed—the blood which gave life and heat to all parts of the body. That the heart was the centre of life and heat had been proved beyond all dispute. Cut out the heart of an animal, and what happens? It died and turned cold; that was plain proof of the truth of the thesis. That air was necessary for the brewing of vital spirits in the left ventricle was a matter of common knowledge. Occlude the windpipe and an animal died, because the element necessary for the manufacture of "vital spirits" no longer reached the left ventricle. The left ventricle and arteries were clearly designed for the distribution of life-giving blood to all parts of the body. The heart could be felt to expand and suck the blood in, and then in turn the arteries could be felt to swell and suck the blood out. The blood ebbed and flowed in the arterial channels. It was a law of nature to ebb and flow. The sea ebbed and flowed; so did the breath.

To this physiological theory Harvey applied the critical judgement of the anatomist. No theory of the function of an organ could be true that did not explain every detail of its structure. To trace the direction of the blood current he took the valves as his guide. The venous valves pointed in every case towards the heart. The valves in the right side of the heart directed him towards the lungs; the valves on the left side of the heart directed him away from the lungs and towards the arteries. There was only one theory which accounts for all of those facts—namely, that the heart acted as a "water-bellows," a double pump, and in order that it could so act he had to presume that the blood moved in a circle. Such a theory of the heart gave a complete and absolutely satisfying explanation of all points in its structure; Harvey could conceive no other theory that would account for all the details of the heart's structure.

Harvey's theory was originally an anatomical hypothesis, but being a man who knew how deceitful hypotheses may prove to be, he put it to the test of experiment. He examined the movements of the living heart; he tested the flow of blood in arteries; he noted the flow of blood in veins. He found the flow to be such as his anatomical reasonings had led him to expect. But to the day of his death his conception of a blood circulation was still a theory; three years after his death in 1657, Malpighi saw with his eye those passages which lead from arteries to veins—passages which Harvey had pictured only in the eye of his imagination.

It might be said that the anatomical methods applied by Harvey at the commencement of the seventeenth century are not applicable to the conditions which prevail at the beginning of the twentieth century. I will give an example to show that they are—that they will be applicable as a basal principle in biological research for all time. Soon after the introduction of Roentgen rays in 1895 I used the method of transillumination to study the action of the crura of the diaphragm. I could not see how it was possible for the crural parts of the diaphragm to contract without acting directly on the heart and roots of the lungs, because the pericardium links the middle part of the diaphragm to both of these structures. I found that it did act directly on them. In the course of my investigations I was led to study the exact attachment of the musculature of the auricles to the pericardium, and thus indirectly to the diaphragm. That led me on to investigate other points in the musculature of the heart. In the course of these investigations I had noted the fine tendon-like structures in the left and also in the right ventricle. I never investigated them; I supposed them to be, as other anatomists had supposed them to be, means for preventing over-dilatation of the ventricles.

In 1906 Tawara, a Japanese, working in the laboratory of Professor Aschoff, discovered that these tendon-like structures were the arborescences of a muscular trunk which commenced in the region of the auricles and descended on each side of the interventricular septum towards the apex of the heart. Tawara explained the presence of the bundle and its branches by supposing that they formed a system for conducting and distributing impulses from the auricles to the ventricles of the heart. Erlanger and others proved by experiment that his guess was right. Tawara noted that the bundle at its

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commencement in the auricle was made up of a peculiar muscular (nodal) tissue, in which he supposed the inception of the contractile impulse took place. In the following year Major Martin Flack and I, while investigating hearts on which Sir James Mackenzie had made his classical polygraphic records, discovered tissue of a nodal nature at the junction of the right auricle and superior vena cava. We supposed, because of its position and structure, that this node was the centre at which the heart-beat commenced. In 1910 Dr. Thomas Lewis and Dr. Wybau proved by electrical means, and independently of each other, that our guess was right. You can see that Tawara, Flack and I were applying Harvey's anatomical methods; Erlanger, Lewis, and Wybau applied his experimental methods. Harvey realized more fully than any anatomist that structure is a sure guide to function; that no physiological theory can be true unless it gives a complete and final explanation of all points of structure.

Taking Harvey as our guide, then, let us see how far our modern functional conception of the heart falls short of giving a full and satisfactory explanation of its structural features. We shall take the apical region first. Why are the ventricles of the mammalian and avian heart shaped like a cone? Why is it that the wall of the ventricles in the region of the apex is so thin that even in a cart-horse it is only 2 mm. in thickness, while the rest of the ventricular wall ranges from 10 mm. to 25 mm. in thickness? Why do the spiral fibres of the ventricles form the well known apical vortex? Why do the main arborescences of the A.V. bundle terminate in the apical region so that, as Dr. Thomas Lewis has demonstrated, the contraction wave is first manifested there? The arrangement of the musculature of the heart, both of auricles and of ventricles, is so complex that not any one of us has succeeded in giving a satisfactory explanation, yet we cannot claim to have mastered the mechanism of the human heart until we can give a functional explanation of its architecture.

In searching for an answer to some of the questions I have placed before you, we have to remember that the heart is a pump of a peculiar kind. In all forms of pump invented by man only one part of the wall is movable (the piston), and it is moved by a power which lies outside the pump. In the cardiac pump the whole wall is movable and the power is resident in every part of the pump wall. The expelling energy is manufactured in the wall of the pump—not in an adjacent boiler. Further, we must remember that the human heart is made up of a central or principal pump—the left ventricle, to which is attached three subsidiary pumps—the right ventricle for the maintenance of a pulmonary circulation, and the right and left auricles—loading pumps for the right and left ventricles. I brush aside a theory which is prevalent at the present time, a theory that defines the auricles as mere reservoirs. No one who has given attention to the elaborate architecture of the auricular musculature can countenance such a theory.³

As practical engineers we must look into the manner in which the cardiac pump is fixed. Each chamber of the heart must have its fulcrum—the point from which its musculature obtains a fixed point—before it can exert its power. The auricular pumps are fixed to the dorsal wall of the pericardium, and through extensions of that sac, and by means of the pulmonary vessels and the lungs, they are fixed to the walls of the thoracic cavity—both costal and diaphragmatic. When we open the thorax we at once undo the fixation of the auricles. Professor Berry Haycraft⁴ was, I believe, the first to recognize that fact. There are two points of fixation—two fulcra—from which the musculature of the ventricular pumps act. There is, in the first place, the ascending aortic stem fixed within the cupular part of the pericardium and the extensions of that membrane to the neck and to the roots of the lungs. There is, in the second place, the apex of the heart itself. By a most cunning mechanism—one of the most marvellous in the body—nature has converted the apical region of the heart into a movable fulcrum from which its ventricular musculature can and does act. In lower vertebrates, such as the tortoise, the mechanism of apical fixation is supplied by a ligament which anchors the blunt curvature of the ventricular chamber to the pericardial sac.

We have been discussing the fixation of the complex four-chambered cardiac pump; we must now look into a

more important matter—the manner in which the ventricular chambers of the heart are fixed. For that purpose we must appeal to comparative anatomy and embryology for help. From these sources we learn that the primitive tubular heart undergoes an extraordinary transformation in the human embryo—a transformation not unlike that which takes place in the stomach. In the stomach one border undergoes a rapid and extensive development to form the greater curvature, while the other is retarded in growth and becomes the lesser curvature. In some animals the lesser curvature is so short, so suppressed, that the oesophageal and pyloric orifices are almost in contact. In the ventricular part of the cardiac tube the lesser curvature undergoes so great a degree of retrograde development that the auricular or proximal orifice comes to be situated side by side with the aortic or distal orifice, with only the anterior cusp of the mitral valve between them. The greater curvature has grown out as evaginations to form the ventricular chambers, leaving an untouched part between them to form a septum. The beginning and end of the ventricular tube have come to rest side by side on the lesser curvature, and form what we call the "base" of the ventricles.

It is quite clear that the anterior cusp of the mitral is a most important landmark on the ventricular base; it separates the auricular commencement from the aortic termination of the ventricular tube. The distinction between auricular and aortic bases is one of the utmost practical importance. When the ventricles contract it is the auricular base, surrounding the mitral and tricuspid valves, which becomes greatly reduced in size; the aortic base is, from a functional point of view, scarcely altered. When the ventricles contract the aortic base becomes a fulcrum from which the expelling musculature acts, while the auricular base descends towards the apex,⁵ drawn by a musculature which acts from the apical fulcrum. The auricular and aortic bases are contrasted in both a morphological and a physiological sense. The descent of the auricular base necessarily enlarges the auricles; the movements of the auricular part of the ventricular base provide a key to the venous pulse. They do more than that, they give us a clue to the muscular architecture of the ventricles.

The complex architecture of the ventricular musculature was, in Harvey's time, a well-worn theme. A century and a half after Harvey, Hunter dismissed the matter by saying: "Much more pains than were necessary have been taken to dissect and describe the course and arrangement of the muscular fibres of the heart." The principle, however, which Hunter steadfastly applied to the elucidation of muscular action does prove of the utmost assistance. For Hunter it was a law that no muscle acted alone; every muscle acted in co-operation with an antagonist. His supreme example was the circular muscular coat of an artery. In the bowel the circular fibres have longitudinal fibres as their antagonists, for the effect of contraction in a circular muscular coat is to diminish the calibre of a tube, and at the same time to increase its length. Hunter saw that arteries were elongated by the contraction of their muscular coat, and regained their normal length by the contraction of their elastic coat, the muscular and elastic coats being antagonistic.

When we apply Hunter's principle to the study of the muscular coats of the left ventricle we see that we have to deal with a co-ordinated antagonism between a very massive circular "expelling" coat set between an outer and inner spiral coat. That principle will not help us unless we also recognize the two fulcra or fixed points of the left ventricle—the aortic fulcrum and the apical fulcrum. The fixed axis of the left ventricle passes from the mouth of the aorta to the apex; all the muscular fibres of the left ventricle are so set that in contraction they approach that axis. Besides the principle of antagonism and of fulcra, there is a third principle involved in the architecture of the ventricular musculature. The principle of the iris diaphragm is utilized. All the muscular coats or fasciculi of the heart are so set that they ultimately end in the internal spiral coat of the left ventricle, just as every segment of an iris diaphragm takes a share in forming the margin of its pupil. Without doubt the left ventricle represents one of nature's greatest mechanical triumphs.⁶

When we apply the principles just enunciated to elucidate the muscular architecture of the heart we are at once

impressed by the functional importance of the region of the apex. The chief terminal arborescences of the A.V. bundle end in the trabecular network of the apical region. Dr. Thomas Lewis⁷ has demonstrated that the apical region is the first to pass into contraction with the onset of ventricular systole. When we open the ventricles we see that their internal musculature—columnae carnaeae and muscoli papillares—commence in the apical region and divide into two sets. The larger set terminates in the auricular or movable base, the smaller or septal set in the fixed or aortic base. When we examine the outside of the ventricles we find the same arrangement in the spiral fibres. They commence in the vortex of the apex and divide into two sets—an extensive one which ends in the auricular movable base, and a less extensive, which ends in the fixed aortic base. Between these outer and inner sets is placed the great middle driving muscle of the left ventricle; its spirals are so closely pressed together that they give the appearance of being purely circular; we may speak of them as the circular set. The circular musculature, acting by itself, would diminish the circumference and at the same time lengthen the lumen of the ventricle the elongation is antagonized by the internal and external apico-basal musculature. We know that, at least in the earlier phase of ventricular systole, the auricular base approaches the apex and therefore the circular fibres are more than antagonized; in the later stages of ventricular systole the opposite is the case; the circular fibres become dominant and press again on the auricle, raising the intra-auricular pressure. The apico-aortic fibres are purely sustaining in function; they neither shorten nor lengthen in systole.

In several respects the structure and mechanism of the right ventricle is peculiar. There is incorporated in the infundibulum of the right ventricle a chamber—the pylorus of the primitive cardiac tube—an element which has completely disappeared in the left ventricle. The pulmonary orifice does not serve as a fixed point for the ventricular musculature; the infundibular septal bands of the right ventricle act from the aortic base. Further, the right ventricle has only one wall—the lateral; its septal wall—the interventricular septum—is part of the left ventricle; it takes only a passive share in expelling blood from the right ventricle. On the other hand, the right ventricle is provided with a highly developed internal musculature passing from its apex to the auricular base. The systolic movement of that base is more marked on the right side than on the left side of the heart. Hence we find in the lateral wall of the right auricle a well-developed opponent set of muscles—the muscoli pectinati. In auricular systole the muscoli pectinati elongate the apico-basal fibres of the right ventricle; in ventricular systole the opposite occurs.

I noted, when investigating those hearts in which Sir James Mackenzie first observed that the auricles had ceased to functionate—from auricular fibrillation, as was afterwards proved—that a condition was present similar to that which occurs in a limb when a set of muscles undergoes contracture from paralysis of the opponent group. In such cases the lateral wall of the right auricle had become elongated and stretched, while in their opponents—the apico-basal fibres of the right ventricle—an extreme degree of shortening had occurred.

I have merely touched on some of the unsolved problems relating to the structure and mechanism of the heart. I am content if I have succeeded in showing that Harvey's methods of investigating anatomical problems are still the best that we anatomists can adopt.

REFERENCES.

- ¹ Sir Thomas Barlow, *BRITISH MEDICAL JOURNAL*, 1916, II, p. 577.
² See D'Arcy Power's *William Harvey*, in the *Masters of Medicine* series, 1897.
³ See Proceedings of the Anatomical Society of Great Britain and Ireland, November, 1902 (appended to *Journal of Anatomy and Physiology*).
⁴ *Journ. of Physiol.*, 1891, vol. xii, p. 438.
⁵ See Chauveau and Marey, *Mém. de l'Acad. de Médecine*, 1863, vol. xxvi, p. 313; Haycraft, *Journ. of Physiol.*, 1891, vol. xii, p. 438.
⁶ The best account of the arrangement of the muscular fibres of the heart is that given by the late Professor Bell Pettigrew (*Phil. Trans.*, 1864, p. 445). The late Dr. John Bruce MacCallum also gave an excellent account in *Johns Hopkins Hospital Reports*, 1900, vol. ix, p. 307.
⁷ Professor Franklin Mall added very important embryological facts (*American Journ. of Anatomy*, 1912, vol. xiii, p. 249). For an introduction to the older literature see the chapter on the heart in Poirier's *Traité d'anatomie humaine*, 1899, and Quain's *Elements of Anatomy*, 1892. My statements are based on dissections carried out between 1901 and 1907, and will be published in full at some future date.
⁸ Croonian Lecture, *Proc. Roy. Soc.*, 1917, S. B, vol. lxxxix, p. 560; *Lectures on the Heart*, 1916.

THE TOLERANCE OF PHYSICAL EXERTION, AS SHOWN BY SOLDIERS SUFFERING FROM SO-CALLED "IRRITABLE HEART."

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It is now two years since we introduced at the Military Heart Hospital, Hampstead, a system of graded drills, arranged from exercises in the army exercise book, and employed these both remedially and as means of grading soldiers returned to us for the condition known as "disorderly action of the heart," "irritable heart," etc. We have repeatedly contended that the surest means of gauging capacity for physical endurance is to test the men upon drill, the highest grades of which should approach in their severity the tasks which will be set to these men when they return to their dépôts. The test of capacity for work should be the observed reaction to work. That this thesis has been justified fully is shown clearly in an article published recently elsewhere,¹ in which the after-histories of 239 graded out to duty categories by this system are compared with the recommended categories of discharge. This comparison is reviewed in the subjoined table:

Recommendations.	Disposition within 11 Months.
Fit for general service 72	Full duty overseas, 79: Known to reach firing line (of whom 26 make good) 35 Not known if in firing line 23 Known not to have been in firing line 21
Likely to be fit for general service within 3 months 47	In provisional units 30 Full duty home service 8
Light duty; unlikely to be fit for overseas within 3 months 20	Light duty overseas 7 Labour companies (H.S.) 23
Light duty, but unlikely ever to be fit for service overseas 68	Light duty (H.S.) 33 Sedentary duty 16
Sedentary work at home 32	Under treatment 5 Discharged permanently unfit 38
239	239

This system and its results have aroused a good deal of interest, and a large number of military hospitals both at home and abroad have adopted it; others are following suit. Since the recent removal of the heart hospital to Colchester we have continued to receive numerous inquiries as to the details of our method. In part these have been described in previous publications.² In the present article the work of the medical officer's examination room is described, his method of prescribing exercises, and his method of judging the toleration of exercises so prescribed.

The drills now in use are termed B 15, C 15, BC 30, C 30, and D 30,* the letter indicating the stiffness of the exercises, the number the duration of the drill in minutes. B 15 consists of simple movements, and calls for no considerable expenditure of energy; D 30 includes many of the stiffest exercises of the army exercise book, and entails thirty minutes' hard work.

Seeing that most of our patients are recently from France, all those cases to whom drills are prescribed start on the easiest drill, and progress from this to those of higher grades, according to tolerance. A few days or a week upon the two 15-minute drills suffices; a week is usually spent on each of the three 30-minute drills. Men who promise well may be kept a week or so longer on the highest grades of drill to harden them. It is a rule of the hospital that patients upon 15-minute drills are to be considered unfit to leave the hospital premises except under escort; those on 30-minute drills are given afternoon passes freely. This rule has the advantage of stimulating the men to accomplish the 30-minute drills. All men on exercise C 15 and BC 30 go regularly for route marches in the early afternoon; these are short marches of one or two miles in the immediate neighbourhood of the hospital, and at slow time. Men in classes C 30 and D 30 are taken for longer marches of four to five miles in the

* Two of our original drills, A 15 and AB 30, have been discarded.