AN ACCOUNT OF THE STRUCTURES CONCERNED IN THE PRODUCTION OF THE JUGULAR PULSE. By ARTHUR KEITH, M.D., Lecturer on Anatomy, London Hospital Medical College.

A study of the pulse in the jugular vein has now become established as a routine method of examining disordered hearts—an advance due to the labours of Dr James Mackenzie and of those who have adopted his method. With the introduction of a new clinical method, as is also the case with a new operative procedure, certain structures and relationships assume an increased importance and require a fresh description. In this paper I propose to recast our description of the structures which seem to me to be directly concerned in the production of the venous pulse—my account having reference only to the arrangement as found in the human body. I propose to deal not only with the normal but also with the disordered heart, using for this purpose the series of specimens sent to me for examination by Dr James Mackenzie. These hearts are of special value for the purpose of study, because Dr Mackenzie had kept accurate records of their action during many years prior to the death of the patient.

The Position of the Jugular Bulb.—The right jugular bulb, from which a tracing of the venous pulse is usually taken, is situated farther from the sternal end of the clavicle than one expects. Its position is best indicated

1 James Mackenzie, The Study of the Pulse (1902), and numerous papers in the British Medical Journal during 1905, 1906. See also Professor Wenckebach's Arrhythmia of the Heart, translated by Snowball, 1904, and especially this author's article in the Archiv für Anat. und Physiol., 1906, p. 297; papers by Dr G. A. Gibson, Edin. Medical Journal, 1905, N.S. vol. xviii., p. 9; British Medical Journal, 1906, vol. ii. p. 1113; by Dr John Hay, British Medical Journal, 1905, vol. ii. p. 1034; Lancet, 1906, vol. i. p. 139. A full list of papers dealing with records of the jugular pulse is given by Dr John Cowan, Practitioner, April 1907.
by a point—the jugular point—on the upper border of the clavicle, 25–30 mm. from the sternal end (fig. 1). With the patient in the supine position, the jugular valves which demarcate the bulb from the rest of the vein are situated about 20 mm. above the jugular point, and deep to the sternal head of the sterno-mastoid (fig. 1). If, however, the patient's head be rotated somewhat to the right, rendering the sterno-mastoid lax, then the bulb may be reached in the interval between the sternal and clavicular heads of the muscle. The distance of the bulb from the end of the clavicle is increased if the thyroid body be large or if the neck be short; if the neck is long or the thyroid small, the distance is decreased. The bulb lies directly over the first stage of the subclavian artery (fig. 1), and hence the constant appearance of the arterial pulse in the tracing of the jugular pulse. Mackenzie regards the arterial wave in the jugular tracing as derived from the carotid artery; this may be the case, for above the jugular bulb the vein and carotid artery lie side by side in close contact. Or it may be, as Belski has pointed out, that the arterial pulse wave seen in the jugular pulse is conveyed from the ascending aorta, which lies in contact with the superior vena cava (fig. 2).

The Venous Cistern from which the Heart is filled.—The jugular bulb is part of a large venous cistern represented in fig. 2, and consequently such tracings represent the fluctuations in the pressure of blood contained within this cistern. The cistern is formed by the superior and inferior vena cava,
the innominate, iliac, hepatic and renal veins; it is shut off from the venous system of the lower extremities by strong valves situated in the common femoral veins from 10 to 25 mm. below Poupart's ligament (fig. 2); from the venous system of the upper extremity by equally strong valves in the terminal part of the subclavian vein; from the venous system of the head and neck by the valves above the jugular bulb. The jugular valves are evidently the weakest of the three pairs, for when this cistern is subjected...
to sudden compression, as in shunting and lift accidents, it is they that give way and lead to the characteristic venous discoloration of the head and neck, which not uncommonly attends such accidents. Non-functional valves may occur in the external iliac or renal veins. To estimate the capacity of the cistern, I selected a male adult subject in which there was an effusion of nearly 600 cc. of fluid within the pericardium, and in which there was, consequently, a great distension of the veins, a condition always present when the jugular pulse is well marked. The veins were emptied of blood and filled with fluid through the right renal vein at a pressure varying from 6 to 8 mm. Hg.; the cistern, as above defined, had a capacity of 430 cc. The weight of the liver, by compressing the inferior vena cava, offered a considerable resistance to the flow of fluid from the abdominal to the thoracic part of the cistern. I estimated that the thoracic part of the cistern contained about 30 cc.; the abdominal part, 400 cc. Taking the output of the heart at 50 cc. for each beat, one may infer that the cistern contains blood to serve for rather more than eight beats.

The Action of the Musculature of the Body-Wall on the Venous Cistern.—Since the greater part of the venous cistern lies within the abdominal cavity it is to be expected, from the experimental results of Hill and Barnard,¹ that active or passive compression of the abdominal cavity will increase the pressure of the blood within the cistern and also within the right side of the heart, and thus alter the amplitude of the waves seen in a tracing of the jugular pulse. This result Dr James Mackenzie has shown to me in his tracings. Dr Leonard Hill found that blood could be squeezed from the liver of the living animal as from a sponge, and in this way the cistern may be quickly filled and distended. I estimated, from injections made on five adult subjects, that the portal system—including in this system all the vessels that lie between the capillaries of the alimentary canal and the capillaries of the liver—contains 500 cc. of blood when moderately distended; probably an amount equal to this could be pressed easily out from the human liver and thrown within the venous cistern, as above defined. The extent to which the abdominal part of the venous cistern is compressed by the tone and contraction of the muscles of the belly-wall may be estimated by observations on the intra-abdominal pressure as measured within the rectum and within the stomach. In the upright posture the intra-rectal pressure, in a position of rest, varies from 14 to 24 mm. Hg., fluctuating with the respiratory movement; if the body be bent or if a weight is lifted, the pressure may mount up to 80 or even 100 mm. Hg. Within the stomach, the pressure varies from 3 to 6 mm. Hg. when standing at rest; a negative pressure can be made to appear if a forced

¹ Journ. of Physiology, vol. xxi., 1897, p. 325.
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thoracic breath be taken; if the trunk is flexed or if a weight be lifted, a pressure of 40 to 60 mm. Hg. can be obtained.

When the venous cistern is compressed by such movements of the body-wall, its contents can escape only into the right side of the heart. Mr. Barnard found, on squeezing the abdomen, that the right side of the heart became distended, and that it was possible in this way to force blood through the passive right heart and lungs into the left auricle. In this experiment the wall of the right auricle, being less resistant than that of either the venous cistern or of the right ventricle, became the most distended; as long as the pericardium was intact, great over-distension or rupture of the right auricle was prevented. In many of the hearts sent to me by Dr. Mackenzie, the right auricle was found to be greatly and permanently distended and the right ventricle compressed, a result probably due to a long-continued high pressure within the venous cistern and right side of the heart. In brief, the distension of the right auricle is caused by the contraction of the musculature of the belly-wall, acting through the venous cistern as above defined.

Attachments of the Heart and of the Auricular Musculature.—Before discussing the arrangement of the auricular and ventricular musculatures and the functional significance of that arrangement, it is necessary to mention certain neglected facts connected with the fixation of the heart within the thorax, and the fulcrum or fixed points from which the cardiac musculature acts. When the heart, while still attached within the pericardium, is pulled forwards, as is diagrammatically represented in fig. 3, it is seen to have two attachments—(1) by the venous mesocardium (from e to e in fig. 3), by which the commencement of the cardiac tube is attached to the pericardium, through which the veins enter the auricles; (2) the arterial mesocardium (from d to d in fig. 3), by which the termination of the cardiac tube is fixed, through which the systemic and pulmonary aortae leave the pericardial sac. Save at these two mesocardial areas the heart is free. That part of the pericardium to which the auricles are attached is bound to three structures—(1) to the roots of the lungs and by the lungs to the wall of the thorax; (2) to the diaphragm, especially to the crura of that muscle; (3) to the structures in the root of the neck through the superior vena cava and the fibrous tissue surrounding that vessel. The longitudinal (antagonistic) musculature of the auricles has its fulcrum or attachments in the venous mesocardium; if the chest be opened, the normal auricular fulcrum are lost. The auricular musculature, when freed from its natural attachments, can no more perform its normal action than can a skeletal muscle when separated from its attachments.

1 See Lancet, 5th March 1904, p. 629.
The Base of the Heart and of the Ventricles.—There is great need for a stricter use of the word “base” when applied to the heart as a whole and also when applied to the ventricles. As used clinically, the term “base” is applied to the attached part of the heart, and includes the commencement and end of the heart. At least one ought to distinguish the two parts—the commencement or venous base and the terminal or arterial base (see fig. 3).

As applied to the ventricles the term “base” is still more misleading; in it are included the commencement and end of the ventricular part of the cardiac tube. It would be equally correct to apply a common term to the two orifices of the stomach. The two parts of the base of the ventricles are shown in fig. 3; the commencement of the ventricular tube may be defined as the auricular base (a, a, in fig. 3); the termination of the ventricle, the aortic base (c, c, in fig. 3). I pointed out some years ago that the wave of negative variation which commenced and terminated in the base...
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of the ventricle was easily explicable when one remembered that the base contained the commencement and end of the ventricular tube (Lancet, 5th March 1904, p. 631). Lately, Professor Gotch, who was unaware of my surmise, has demonstrated in the frog’s heart that the negative wave commences at the auricular base and ends at the aortic.

From tracings which Dr Leonard Hill took of the turtle’s heart, it is clear that the apical part of the ventricle is in a state of contraction before the part of the heart at the aortic base.

The Characters of the Jugular Pulse.—A study of the jugular pulse provides the anatomist with a master-key to the architecture of the heart. It cannot be said that our present description of the cardiac musculature helps us to understand either the movements or action of the heart. This defect is due, I believe, to two circumstances—(1) because we do not study its structure while the heart is still fixed by its normal attachments in the thorax; (2) because we have concentrated our attention on the relationship of the ventricles to the arteries and neglected their relationship to the auricles and to the venous cistern. A study of the jugular pulse is concerned with the structural relationship of the ventricles to the auricles, and of the auricles to the venous cisterns from which the two auricles are filled. The main purpose of this paper is to show that each auricle and ventricle contains two sets of muscular fibres: (1) circular or “driving” fibres—for compressing the chamber and expelling the blood; (2) longitudinal or “antagonistic” fibres, the longitudinal of the right auricle (the auricle concerned in the jugular pulse) being the opponents or antagonists of the longitudinal of the right ventricle, and stand to each other in the same functional relationship as the biceps and triceps of the arm. The doctrine is not a new one; it has been taught by many physiologists, but, so far as I know, no one has ever applied the conception to a study of the structure of the heart. The experimental observations of Porter¹ and of Burton-Opitz,² the clinical observations of Mackenzie and Wenckebach, and the exact account of the structure of the heart given by Bruce MacCallum,³ with my own dissections, provide ample material for the correlation of the movements and structure of the heart. The observations of Haycraft⁴ on the movements of the heart within the chest have also been of great service to me.

¹ W. T. Porter, “Researches on the Filling of the Heart,” Journ. of Physiol., vol. xiii. p. 513, 1892.
² R. Burton-Opitz, “The Flow of Blood in the External Jugular Vein,” Amer. Journ. of Physiol., vol. vii. p. 435, 1902.
³ J. Bruce MacCallum, “On the Muscular Architecture and Growth of the Ventricles of the Heart,” Johns Hopkins Hosp. Reports, vol. ix. p. 307, 1900.
⁴ P. B. Haycraft, Journ. of Physiol., vol. xii. p. 438, 1891.
In fig. 4 is reproduced tracings of four types of the jugular pulse (3, 4, 5, 6), with their time relationships to the apex beat (1) and radial pulse (2), given by Professor Wenckebach in his article in the Archiv für Anatomie und Physiologie, 1906, p. 317. Tracing No. 3 is that of the jugular pulse in a condition of health; in the period of auricular systole, the jugular bulb is seen to fill; in the period of ventricular systole, the bulb is emptying; in the period of diastole, the bulb at first fills and then suddenly empties and again begins to fill preparatory to the next auricular systole. I propose now to discuss the cardiac musculature which is in action during each of these three periods.

The Musculature in Action at the Commencement of Auricular Systole.

—As shown by the tracings in fig. 4, there is an expansion of the jugular bulb during the contraction of the auricle. Are the orifices of the superior and inferior vena cava in the right auricle then closed—or are they then open so that the wave caused by the contraction of the auricle may pass unhindered to the jugular bulb? At the present time it is taught that these orifices are then closed by circular muscle fibres—a musculature derived from the sinus venosus and contracting before that of the auricle. There are no circular muscle fibres round the inferior caval orifice of the human heart, and those which surround the termination of the superior vena cava (see A, fig. 7) are not strong enough to quite occlude the superior caval orifice and act as a sphincter. In cases where the venous eistern is well filled and the jugular pulse well marked, Mackenzie could hear the jugular valves close with a click during auricular systole; in such cases there is evidently a direct spread of the auricular wave to the jugular bulb. The absence of a mechanism for preventing the regurgitation of blood from the auricles of birds and mammals is remarkable; for in fishes, amphibia, and reptiles this is effectively prevented by the two membrano-muscular venous valves which guard the sino-auricular orifice. In the warm-blooded vertebrates the sinus venosus no longer exists as a separate chamber; with the appearance of the diaphragm the greater part of the cavity of the sinus becomes overgrown by the musculature of the right auricle. The venous valves become broken up; but out of the right venous valve is evolved a very remarkable band of musculature—the right tænia terminalis—shown in figs. 5, 6, and 8. When the right auricle is thrown into an artificial state of contraction by the injection of a hot liquid mass, the tænia falls within the right auricle, across the mouth of the superior vena cava, occluding that orifice, and in former papers 1 I inferred that it

1 "The Evolution and Action of Certain Muscular Structures of the Heart," Lancet, 27th February, 5th March 1904; Proc. Anat. Soc. of Great Britain and Ireland, November 1902.
was the only effective means in the mammalian heart for preventing regurgitation of the blood from the right auricle. When the resuscitated heart is fixed in a manner similar to that which obtains in the unopened thorax, the tænia terminalis is seen to inflect the auricle in front of the caval orifices but not to an extent sufficient to completely occlude these orifices, and I conclude, therefore, that there is no muscular or valvular mechanism in the avian or mammalian heart which can completely prevent regurgitation of the blood from the right auricle if that chamber be dis-

![Diagram of a heart](image)

Fig. 5.—Drawing of a heart, from a case recorded by Dr Mackenzie. The jugular pulse was of the type shown in 6, fig. 4. The auricle is greatly distended. (One-half natural size.)

The venous cistern, described at the commencement of this article, has evidently taken the functional place of the sinus venosus, and the six pairs of valves which prevent regurgitation of blood from that cistern have evidently taken the place of the venous valves at the sino-auricular junction. Regurgitation from the right auricle during systole can only occur when the diastolic pressure in the right ventricle is greater than that in the venous cistern. The pressure within the abdominal part of that cistern is always positive, and hence the inferior caval orifice is guarded neither by sphincter nor competent valve; and in the thoracic part of the cistern the pressure may be negative, and hence the superior caval orifice
is furnished with a muscular mechanism which may be competent at low pressures. I conclude, therefore, that Mackenzie is right in regarding the expansion of the jugular bulb during auricular systole, in cases where the right auricle is distended, as directly due to the contraction of the auricle; but in conditions of health it is probably due to the arrest of the venous outflow.

**Fig. 6.**—Right wall of the heart viewed on its inner aspect. From a specimen obtained from a subject in which there was evidence of a long-standing venous back pressure—from arterial sclerosis of the coronary arteries, with consequent great dilatation of the auricle. The heart was hardened _in situ_ by the injection of formalin. (One-half natural size.)

1, superior vena cava; 2, inferior vena cava; 3, right tenia terminalis; 4, musculi pectinati; 5, auricular canal (annular fibres); 6, marginal and infundibular cusps of tricuspid; 7, musculi papillares; 8, trabecular network at apex of right ventricle; 9, internal longitudinal system running from apex to pulmonary artery; 10, pulmonary artery; 11, sub-Eustachian sinus, between Eustachian valve and base of right ventricle; 12, auriculo-ventricular groove; 13, appendix of right auricle.

_The Pectinate Musculature of the Right Auricle._—Although the right tenia terminalis and musculi pectinati make up the chief mass of the musculature of the right auricle, the part they play in auricular systole is neglected at present. In fig. 6, the right wall of the heart is represented—similar to that which has been removed to make the drawing shown in fig. 5. The right tenia terminalis and pectinate musculature are shown as they appear on the inner wall of the heart. The musculi pectinati, fifteen to eighteen in number, each from 1 to 2 mm. in diameter, take their
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origin in the right tænia terminalis (figs. 5 and 6) and end in the circular musculature of the auricular canal (5 in fig. 6). Their relationship to the heart as a whole is shown in figs. 8 (horizontal section) and 7 (heart viewed on its right side). They have their origin or fulcrum in the tænia terminalis; when they contract, the auricular canal, auriculo-ventricular groove, and base of the right ventricle are drawn towards the tænia terminalis (towards the venous mesocardium), as is shown diagrammatically in fig. 7. The musculi pectinati not only expel the blood from the auricle but also draw the base of the ventricle on to its load of blood. The musculi pectinati in the normal diastolic auricle are from 20 to 25 mm. long; in the greatly distended auricles obtained from cases of long-standing venous back pressure, such as the specimen shown in fig. 6, they measure from 30 to 40 mm. In the auricle, artificially thrown into a state of contraction by the injection of a hot mass, the musculi pectinati shorten to half their diastolic length. I conclude, therefore, that in the normal heart the
musculi pectinati draw the auricular base of the right ventricle backwards to the extent of about 6 to 8 mm.

The Antagonistic Musculature of the Right Ventricle.—Every muscle in the body has its opponent, and to this law the pectinate musculature of the right auricle is no exception. It is opposed by two groups of musculature in the right ventricle—the outer spiral layer, shown diagrammatically in fig. 7, and the inner longitudinal musculature—musculi papillares and longitudinal columnæ—shown in fig. 6. Both these groups of musculature commence in the apex of the heart, which, during systole of the ventricle, certainly does not retreat towards the base. The apex of the heart is the fixed point from which this musculature acts as the opponents of the musculi pectinati; how the apex becomes a fixed point will be discussed later. All physiologists agree that in ventricular systole, the auricular base of the ventricle moves towards the apex. The minute one grasps this conception of the action of the musculature of the heart, the apparent complicated arrangement of the superficial spiral fibres, which take their origin in the vortex at the apex of the heart and turn with a spiral twist to reach an insertion in the membranous tissue at the auricular base of the right ventricle, becomes plain; so does the arrangement of muscular trabeculae within the heart. They are so arranged as to draw the auricular base of the ventricle towards the apex, and thus elongate the musculi pectinati and expand the auricle. There is nothing new in the statement that the auricle expands to occupy the space vacated by the ventricle, but somehow it has escaped the attention of anatomists that the musculature of the auricle and ventricle is specially arranged to accomplish this purpose. As long as the ventricle contracts, the more and more must its auricular base approach the apex of the heart and the more must the auricle be expanded.

Various Forms of Jugular Pulse, and their Relationship to Distension of the Auricle.—From his observations on the normal heart, Professor Wenckebach concludes that the jugular bulb is emptying during the whole period of ventricular systole (tracing 3, fig. 4), because the auricle is being expanded as long as the ventricle is contracting. Burton-Opitz estimated, from experiments made on dogs, that 90 per cent. of the venous outflow in the veins of the neck took place during the period of ventricular systole, showing the importance of this movement in the filling of the heart. Certainly contraction of the ventricle is not necessary for an expansion of the auricle, for in many cases of jugular pulse analysed by Mackenzie and by Wenckebach, the auricle was found to contract without the ventricle; yet the auricular systole is followed by a certain degree of collapse of the jugular bulb, showing that the auricle had dilated without
any active co-operation on the part of the ventricle. Such observations are made only in cases of heart-block—partial or complete—and in such cases the venous cistern and auricle are over-distended. It must be remembered, however, that in such cases, although systole of the auricle is not followed by a systole of the ventricle, yet it is followed by a reposition of the base of the ventricle, for during the auricular systole the base of the ventricle is drawn into the position that marks the commencement of a ventricular systole; when the auricular systole is over and its diastole has commenced, the auricular base of the ventricle, under pressure of the venous blood, returns to its position of rest, and this movement is accompanied by collapse of the jugular bulb. It is anatomically impossible that there can be a contraction of the pectinate musculature without a corresponding movement of that part of the ventricle on which this musculature acts.

In tracing 6, fig. 4, Wenckebach represents a very different type of jugular pulse, and one that Mackenzie has regarded all along as of the greatest significance. In the cases from which this type of tracing is obtained, the jugular bulb is expanding or filling instead of emptying during the period of ventricular systole. Now, in every one of the hearts sent to me by Mackenzie and from which he had obtained this type of jugular tracing, there was one absolutely constant feature—there was great dilatation of the auricle with a certain degree, sometimes more, sometimes less, of compression of the ventricle. In these hearts the auriculo-ventricular groove occupied the position corresponding to that of ventricular systole in the normal heart (see B, in fig. 7). Figs. 5 and 6 are from hearts in which the + instead of the — jugular wave occurred during ventricular systole. In all cases where this type of jugular pulse occurs there is great distension of the venous cistern and of the auricle; the auricular base of the heart is pushed forwards so far in diastole that during ventricular systole it cannot move forwards more, and therefore there can be no expansion or dilatation of the auricle and no emptying of the jugular bulb during ventricular systole. The permanent distension of the auricle under a high venous pressure has destroyed the antagonistic action between the auricular and ventricular musculature and suction action of the heart.

In fig. 4, Wenckebach represents two tracings (4, 5) which are intermediate to the negative type (tracing 3) and positive type (tracing 6) of jugular pulse. In these intermediate types the jugular bulb commences to expand during ventricular systole; in tracing 4, the bulb expands during the last third of ventricular systole—in 5, during the latter half of that period. The explanation which Wenckebach offers is that the appearance of the expansion of the bulb during ventricular systole depends on the degree to
which the venous cistern and auricle are distended. The greater the head of pressure the quicker will the auricle become distended; or, putting the same explanation into anatomical terms—the more the auricle is distended by the head of pressure in the venous system the more is the auriculo-ventricular groove pushed towards its forward limit (see fig. 7), and hence, with the forward swing of the base of the ventricle in systole, there is only a limited positive expansion of the auricle and, consequently, only a shortened period in which the jugular bulb collapses. That is to say, the pressure of blood in the venous cistern not only alters the amplitude but also the type of jugular pulsation.

Mackenzie, however, has accumulated a great deal of evidence to show that when the positive type of jugular pulse appears (tracing 6, fig. 4), there is much more than merely a distension of the great veins and auricles. He finds that this type of pulsation appears suddenly; that all signs of an auricular contraction disappear from his tracings; or if they are present they occur subsequent to, or at the same time as, the contraction of the ventricle. In his opinion the inception of the heart-rhythm has been altered, and, instead of commencing at the great veins (sino-auricular node described by Flack and the writer?), begins at the auriculo-ventricular junction (auriculo-ventricular node—Knotten of Tawara?). (See K and R, fig. 5.) In such hearts I have been unable to detect any positive microscopic lesion in either the sino-auricular or auriculo-ventricular node. The one feature always present is great dilatation of the auricle (fig. 5); hypertrophy of the tænia terminalis and musculi pectinati (fig. 6). It is possible that, in such cases, the venous pressure within the auricle has become so great that conduction and contraction of the auricular musculature is so depressed that for all practical purpose the auricle is paralysed, as Mackenzie originally supposed.

The Diastolic Movement of the Heart.—In Professor Wenckebach's tracings (fig. 4) it will be seen that the jugular bulb still continues to expand or fill for a brief interval after the diastole of the ventricles have commenced; this brief diastolic expansion is followed by a fall. Everyone is agreed as to the meaning of the diastolic fall—it is the result of the opening out and filling of the ventricles; but what explanation is to be given of the brief expansion of the bulb which precedes the fall? Wenckebach's explanation is that it is due to reposition of the base of the heart, and this, on anatomical grounds, I believe to be the right one. In fig. 7 (page 11) only the extreme positions of the auriculo-ventricular groove are represented; between A, its position in auricular systole, and B, its position in ventricular systole, there is an intermediate or diastolic position—not represented in the figure. When ventricular systole is ended,
the auriculo-ventricular groove and the bases of the ventricles fall back immediately into the diastolic position; this movement evidently causing a temporary compression of the auricles, and the expansion seen in the jugular bulb at the commencement of diastole.

The Manner in which the Apex of the Heart becomes a Fixed Point to serve as a Fulcrum for the Spiral and Longitudinal Musculature of the Ventricles.—It is not my purpose now to discuss the meaning and cause of the apex beat; I merely wish to show that the theory I am now advancing of the heart’s movements gives a full and satisfactory explanation of the peculiar arrangement of the musculature of the ventricles, especially in the region of the apex. At the present time no explanation is offered of the muscular vortex which occurs at the apex of the left ventricle (see figs. 6, 7, 8, 9), of the remarkable thinness of the ventricular wall at the apex (that of the left ventricle is only 1 to 2 mm. thick), of the superficial spiral fibres of the heart (which, commencing at the apex, end on the auricular bases of the ventricles), or of the peculiar and constant arrangement of the trabeculae and columnæ carneæ within the heart. When it is realised that the apex of the heart in systole becomes a fixed point or fulcrum from which the longitudinal and spiral fibres of the ventricles may act and thus expand the auricles, these structures, previously obscure and meaningless, become significant and easily understood.

I have already mentioned the superficial spiral fibres of the heart; their arrangement is shown in figs. 7 and 10. The arrangement of the longitudinal system within the right ventricle is represented in figs. 5 and 6; that of the left in figs. 8, 9, 11. In both ventricles the arrangement is the same; in both there are two systems of internal longitudinal fibres—(1) those which pass in the form of papillary muscles and fleshy columns to the auricular base of the ventricles; (2) those which pass from the apex to the aortic base of the ventricles. The significance of the system passing to the auricular base of the ventricles is clear, namely, to draw them towards the apex and thus expand the auricles; but what is the meaning of those passing from the apex to the aortic base? (See e, n, in fig. 5; 9 in fig. 6; k in fig. 9, and m in fig. 11.) These apical-aortic fibres lie parallel to the column of blood expelled by the ventricles in systole; they certainly do not draw the apex of the heart towards the aorta. If anything, the apex of the heart moves forward and upwards in systole. Nor do they draw the aortic base towards the apex, for all physiologists agree that the distance between the apex and aortic base of the ventricles is not diminished, or only slightly diminished, during systole. Were the ventricle made up of purely circular or driving fibres, then the distance from apex to base would increase during systole; for a tube composed of purely circular fibres must increase in
length as it contracts, for as the fibres diminish in length they gain in thickness. These longitudinal fibres of the heart, passing from apex to aortic base, seem to me to stand in the same relationship to the circular or driving fibres of the ventricle as the longitudinal muscular coat of the bowel stands to the circular. That is to say, the fibres passing from apex to aortic base act as antagonists to the circular or driving fibres; the one tends to shorten the apex-base diameter of the heart, the other to increase it; by the balance between these two systems the apex of the heart is maintained as a fixed point from which the other longitudinal systems may act on the auricular bases of the ventricles.

The Attachments and Relationships of the left Auricle.—The manner
in which the left auricle empties its contents into the left ventricle, when
the heart is *in situ*, is not easily understood, and is scarcely alluded to by
any who have made a special study of the heart. A horizontal section
of the heart gives the clearest picture of its relationships. It is situated
between the roots of the lungs, being attached very firmly to each; through
the lungs, in the unopened thorax, it is bound to the walls of the thorax.
Behind it lies the unyielding structures of the posterior mediastinum. A
coronal section (fig. 9) shows that the upper border of the auricle is also
in contact with unyielding structures—the pulmonary arteries and bronchi.
To the trachea and bronchi the upper border of the left auricle is extremely
firmly bound by an expansion of the venous mesocardium (see fig. 9, b, and
fig. 10, xxx). Thus the posterior, upper, and lateral aspects of the left
auricle are in contact with structures which are more or less unyielding,
and we cannot suppose that these walls approximate or move towards
the centre of the auricle during systole. Only two surfaces of the left
auricle are in contact with structures which are freely movable—the
floor, which is in contact with the base of the left ventricle; and the anterior
or aortic wall, which is in contact with the ascending aorta (fig. 9). On
the anatomical evidence, which is the only evidence at present available,
one must infer that in systole of the left auricle its floor and anterior wall
are drawn towards its posterior and upper wall. That is to say, in systole
of the left auricle the auricular base of the left ventricle is drawn upwards
and the aorta drawn backwards in the manner represented diagrammatically
in fig. 9.

*Systolic Movements of the Aorta.*—In figs. 7 and 9, representing
profiles of the heart, viewed from the right and from the left, the systolic
movements of the ascending aorta are represented. In systole of the
auricles the commencement of the aorta swings backwards to the right,
in systole of the ventricle it moves forwards and to the left. The final
proof that such movements occur must be obtained by experiment on the
living heart naturally attached within the unopened thorax—an experiment
by no means easy of performance. The anatomical evidence that such
movements must occur seems to me convincing. It is as follows: (1)
When the left auricle (while the heart is still *in situ*) is filled with
injection, the aorta is pushed forwards as the auricle fills; it retrocedes
towards the posterior wall of the auricle as that cavity is emptied; (2) in
mitral stenosis or cases where the left auricle becomes greatly dilated, that
dilatation is attended by a forwards displacement of the aorta (see fig. 11);
(3) for the reasons already given, it is impossible to conceive a contraction
of the left auricle except by an upward movement of the auricular
base of the left ventricle, and a backward movement of the aorta; (4) an
extension of the pericardium (the sinus obliquus, fig. 8) passes up behind the left auricle to act as a bursa in this movement; (5) the musculature of the interauricular septum is apparently without purpose unless one grants—as a working hypothesis—that this aortic movement occurs. The position and arrangement of the interauricular septum is indicated by the number 13 in fig. 8. The greater part of the musculature of this septum is attached to the central fibrous body at the root of the aorta (14 in fig. 8);
from that attachment the fibres run along the septum to end in the right and left auricles near the root of the right lung and in the inferior vena cava. They terminate in those parts of the auricle which are fixed by the venous mesocardium. It is impossible to conceive that these fibres can draw inwards the mesocardium: on the other hand, the root of the aorta is movable; the functional significance of that movement is apparent from figs. 7 and 9. Were the interauricular septum merely a passive partition between the auricles—as it is usually supposed to be—there would be no need for the definite and constant arrangement of muscular bundles of which it is composed. On the other hand, the theory of the heart movements which I advance gives a satisfactory explanation of the musculature of the interauricular septum.

The Antagonistic Arrangement of the Musculature of the Left Auricle and Ventricle.—In the arrangement of its musculature and manner of contraction the left auricle differs totally from the right. Here there is no pectinate musculature, for the greater part of the left auricle in mammalian and avian hearts is formed by an expansion derived from the pulmonary veins. The arrangement of the musculature, as seen in a left auricle in the condition of systole, is shown in fig. 10. It will be seen, in the first place, that many of the muscular bands of the left auricle end in the termination of the inferior vena cava, which, in turn, is fixed to the pericardium and diaphragm. One of the bands which ends thus is shown in fig. 10 (b); it is the left tænia terminalis—a band of muscle which, taking its origin in front of the superior vena cava in common with the right tænia, sweeps to the left in the anterior wall of the left auricle and then turns down between the left auricular appendix and left pulmonary veins to end as above described. It is also shown in the horizontal section of the heart (fig. 8, a); the arrow in that figure indicates the direction of its movement in systole of the left auricle.

The upper and lateral borders of the vestibule of the left auricle are fixed to the roots of the lungs by the pulmonary veins, and by strong fibrous tissue of the venous mesocardium (the line of attachment is shown in fig. 10 by a series of x’s). When the musculature of the left auricle contracts—the tænia terminalis and muscular laminae which end in the auricular canal—its collective effect is to draw upwards the auricular base of the left ventricle into the position indicated by A’ in fig. 10. On this part of the base of the ventricle end (1) the superficial spiral fibres which commence in the apex and in the posterior interventricular sulcus (fig. 10); (2) the internal longitudinal system—papillary and columnar musculature (figs. 8, 9, 11). The apex of the heart serves as the fulcrum for these systems of musculature, and hence in ventricular systole the base is drawn towards
the apex (fig. 10a) with a consequent expansion of the left auricle to occupy the space vacated by the ventricle. With this movement one would expect a rapid flow of blood to the auricle from the veins of the lungs. Is there any evidence of such a flow?

The Cardio-Pneumatic Movements.—If the tracing of these movements obtained by Mosso, and reproduced by Hill in his article on the circulation in Schäfer's *Text-Book of Physiology*, be examined, it will be seen to agree in every detail with the tracing obtained from the jugular pulse. At the commence ment of ventricular systole there is an inspiratory movement of the air; just before the end of the systole there is a slight expiratory movement corresponding to the terminal systolic rise seen in tracings 4 and 5 given by Wenckebach of the venous pulse (see fig. 4). Soon after the commencement of diastole, there is an inspiratory movement, corresponding to the diastolic emptying of the jugular bulb. Those who have worked at the
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Microscopic structure of the lung know how difficult it is to differentiate sections of the smaller pulmonary veins from sections of infundibula and air-cells, so intimately are the walls of the veins fused in the general structure of the lung. One would therefore expect that the fluctuations of blood-pressure in the left auricle and pulmonary veins would be reflected in the air-content of the lung. The tracings of these movements taken by Haycraft¹ and by Harris,² however, differ very materially from that given by Mosso. At the commencement of ventricular systole they find an expiratory and not an inspiratory movement. The inspiratory movement sets in and continues during the last two-thirds of the ventricular systole. I cannot account for the initial expiratory movement observed by Haycraft and Harris during ventricular systole, but it seems to me that the inspiratory movement which follows it can be accounted for by an emptying of the pulmonary veins quite as satisfactorily as by a direct action of the contracting ventricle on the lungs.

¹ J. B. Haycraft and R. Edie, Journ. of Physiol., vol. xii., 1891, p. 426.
² D. Fraser Harris, Journ. of Physiol., vol. xxvi., 1905, p. 495.
The Effect of Dilatation of the Left Auricle on the Left Ventricle.—In dealing with dilatation of the right auricle, I showed that, as the auricular chamber became distended, the base of the ventricle became pushed forwards until it occupied permanently a systolic position. With dilatation of the left auricle, the base of the left ventricle comes to occupy a similar position. The auricular base is pushed downwards and forwards (see fig. 11, ii-v). The chordae tendineae and musculi papillares become permanently shortened. In such a heart as is shown in fig. 11, the auricle becomes practically a passive and over-distended chamber, constantly in a condition of diastole; when the ventricle contracts, its base is already in the systolic position; hence there can be no positive expansion of the auricle due to ventricular systole. If the cardio-pneumatic movements are really due to the expansion of the left auricle by the systole of the ventricle, then the inspiratory movement in such cases should occur only during diastole of the heart—as is the case in over-distension of the right auricle.

The Auriculo-Ventricular Index.—In fig. 12 is reproduced a drawing (half natural size) of another of the hearts sent to me by Dr Mackenzie. It is that of a man in whom the ventricles are enlarged, a consequence of arterio-sclerosis; but the auricles, compared to the ventricles, are relatively small. The drawing is reproduced for two reasons: (1) because the jugular pulse was of the normal type (see tracing 4, fig. 4); and (2) because it

Fig. 12.—Right chambers of a heart in which the jugular pulse was found to be of the normal type. (One-half natural size.) (To be compared with heart shown in fig. 5, p. 9.)

a, superior vena cava; b, inferior vena cava; c, diaphragmatic wall of right ventricle; d, interventricular septum; e, moderator band; f, infundibulo-aortic wall; g, pulmonary artery; h, ascending aorta; i, septal cusp of tricuspid; k, sinus of right ventricle; n, infundibulum of right ventricle; o, septum ovale; s, right pulmonary veins.
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illustrates the method which I have found most useful in making a record of pathological hearts. If the heart shown in fig. 12 is compared with that represented in fig. 5 (p. 9), in which the jugular pulse was of the type shown in tracing 6, fig. 4 (p. 6), a striking difference will be observed in the proportion of auricle to ventricle. In the heart of fig. 5 the auricle is greatly dilated, the ventricle compressed; in the other (fig. 12), although both chambers are hypertrophied and dilated yet the proportion between auricle and ventricle is approximately normal. If I am right in regarding the change in the jugular pulsation as due to the dilation of the auricle and compression of the ventricle, then it is important to obtain an accurate method of expressing the relationship of auricle to ventricle. To estimate their relative proportions I take the following measurements:

(1) Of the lateral wall of the right auricle and ventricle.—The points from which measurements are taken are shown in fig. 8 (p. 16); the auricular wall is measured from 3 to 5; the ventricular from 5 to 1. In the heart with the dilated auricle (fig. 5) the auricular measurement is 95 mm., the ventricular 90; that is, the lateral auricular wall stands to the ventricular wall as 105 : 100 (auricular index = 105). In the heart shown in fig. 12 the auricular measurement is 85 mm., the ventricular 105 mm., the auricular index = 80. In normal hearts the lateral auricular index varies from 60 to 80; in the dog, cat, kangaroo, bear, horse, calf, ox, I found that this index varied from 30 to 60. The lower the auricular index, then the greater should be the expansion of the auricle during ventricular systole and the more marked the systolic collapse of the jugular bulb.

(2) Of the septal wall of the right auricle and ventricle.—The measurements were taken from the points shown in figs. 5 and 12. The auricular septal wall was measured between 1 and 2 (fig. 12), the ventricular from 2 to 3 (fig. 12). In the heart with the dilated auricle (fig. 5) the auricular measurement was 55 mm., the ventricular 72 mm., the septal auricular index being thus 76. In the heart shown in fig. 12 the auricular measurement was 50, the ventricular 90 mm.; the septal auricular index being 55. In normal human hearts the septal index varies from 45 to 55.

(3) I found that with dilatation of the auricle the diaphragmatic wall of the right ventricle (c, fig. 12) became reduced in extent, while the sternal wall (d in fig. 12) was scarcely affected. In the heart with the dilated auricle (fig. 5) the diaphragmatic wall is 83 per cent. of the sternal wall; in the other heart (fig. 12) the proportions are similar, but this result is due, not to a reduction of the diaphragmatic wall, but an elongation of the sternal wall of the heart shown in fig. 12.

(4) Of the left chambers of the heart.—The points from which measurements were taken are indicated in fig. 11 (p. 21): the auricular height was
measured from I to II; the ventricular from II to III. In normal hearts the auricular height varies from 50 to 60 per cent. of the ventricular measurement; in hearts where the left auricle is dilated, the auricular measurement varies from 70 to 100 per cent. of the ventricular.

(5) Measurements were also taken of the diaphragmatic and septal walls of the left ventricle between the points shown in fig. 11. In dilatation of the left auricle, the diaphragmatic wall becomes reduced; the sternal wall is reduced to a less extent.

Method of Preparing Hearts for Examination.—The method at present employed in the post-mortem examination of the heart are too crude to yield accurate information concerning cardiac lesions. For its proper examination the heart must be specially prepared and systematically examined—not roughly measured, and cut in pieces as removed from the body. In examining Dr Mackenzie's hearts I have used the following method: (1) The heart is washed for twelve hours in running tap water, all blood being squeezed out from its chambers; (2) the heart is then hardened and preserved by the well-known Kaiserling process, being floated in an ample bath of the solution with the chambers dilated to their normal extent by the injection of fluid or by the insertion of cotton-wool; (3) after they are thus fixed the arteries are systematically examined; (4) the lateral walls of the heart are removed, as shown in figs. 5, 6, 11, and 12, each heart being thus divided into three pieces; (5) serial sections were made of the termination of the superior vena cava at the position of the sino-auricular node (see fig. 5); (6) serial sections are made of the a.v. node, a.v. bundle, and several sections of the a.v. ramifications in the apex of the left ventricle; (7) measurements and drawings were made of the valves, orifices, thickness of the walls and of the chambers of the heart, as indicated in the paragraph dealing with the auriculo-ventricular index.

Summary.

(1) The jugular bulb from which records of the venous pulse are usually taken is situated deep to the clavicular head of the sterno-mastoid, 25 to 30 mm. outwards from the sternal end of the clavicle.

(2) The jugular bulb is part of a venous cistern from which the right side of the heart is filled.

(3) The greater part of this cistern lies within the abdominal cavity and is, consequently, compressed by the musculature of the wall of that cavity.

(4) That it is necessary to recognise two parts in the base of the ventricle—the auricular base and the aortic base (see fig. 5). The one is the commencement of the ventricular tube; the other is its termination.
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(5) In the heart there are two systems of musculature—one circular in arrangement and expelling in function, the other longitudinal and concerned in systolic movements of the auricle and ventricle. The longitudinal system of the ventricles is antagonistic in action to that of the auricles. The longitudinal system is concerned in the production of the venous pulse.

(6) The longitudinal musculature acts from three fulcrums: (1) the apex of the heart; (2) the venous mesocardium; (3) the arterial mesocardium (see fig. 3).

(7) When the auricles become greatly dilated the antagonistic action between their longitudinal musculature and that of the ventricles is lost, and with this loss the characters of the jugular pulse are altered.

(8) In systole of the heart the ascending aorta must undergo a pendulum swing (see figs. 7 and 9).

(9) The cardio-pneumatic movements probably arise from the expansion of the left auricle caused by the contraction of the left ventricle, and thus correspond to the pulsations of the jugular vein.

(10) The theory of the heart movement here advanced gives a satisfactory explanation of the arrangement of the cardiac musculature.

(11) Description of the method used in the examination of pathological hearts, in place of the cursory methods commonly employed (p. 24).