less than one second, it will be appreciated that the most careful study is necessary in order to ascertain their exact relations to each other. When the heart is exposed in a living animal, the most prominent phenomenon is the alternate contraction and relaxation of the ventricles; but this is only one of the operations of the organ. In all the mammalia, the anatomy and action of the vascular system are practically the same as in the human subject; and although the exposure of the heart by opening the chest modifies somewhat the force and frequency of its pulsations, the various phenomena follow each other in their natural order and present essentially their normal characters. Having opened the chest, keeping up artificial respiration, the heart, enveloped in its pericardium, is observed, contracting regularly; and on slitting up and removing this covering, the various parts are completely exposed. The right ventricle and auricle and a portion of the left ventricle can be seen without disturbing the position of the parts; but the greater part of the left auricle is concealed. As both auricles and ventricles act together, the parts of the heart which are exposed are sufficient for purposes of study.

Action of the Auricles.—Except the short time occupied in the contraction of the auricles, these cavities are continually receiving blood, on the right side from the general system, by the venæ cavæ, and on the left side from the lungs, by the pulmonary veins. This continues until the cavities of the auricles are completely filled, the blood coming in by a steady current; and during the repose of the heart, the blood is also flowing through the auriculo-ventricular orifices into the ventricles. When the auricles have become fully distended, they contract quickly and with considerable power (the auricular systole), and force the blood into the ventricles, producing complete diastole of these cavities. During this contraction, the blood not only ceases to flow in from the veins, but some of it is regurgitated, as the orifices by which the vessels open into the auricles are not provided with valves. The size of the auriculo-ventricular orifices is one reason why the greater portion of the blood is made to pass into the ventricles; and farthermore, during the auricular systole, the muscular fibres which are arranged around the orifices of the veins constrict them to a certain extent, which tends to diminish the reflux of blood. There can be no doubt that some regurgitation takes place from the auricles into the veins, but this prevents the possibility of over-distention of the ventricles.

It has been shown that the systole of the auricles is not immediately necessary to the performance of the circulation; and the contractility of the auricles may be temporarily exhausted by repeated and prolonged stimulation, the ventricles continuing to act, keeping up the circulation of blood.

Action of the Ventricles.—Immediately following the contraction of the auricles, by which the ventricles are completely distended, there is contraction of the ventricles. This is the chief active operation performed by the heart and is generally spoken of as the systole. The contraction of the ventricles is very much more powerful than that of the auricles. By their action, the blood is forced from the right side to the lungs, by the pulmonary artery, and from the left side to the general system, by the aorta. Regurgitation into the auricles is prevented by the closure of the tricuspid and mitral valves. This act accomplished, the heart has a period of repose, the blood flowing into the auricles, and from them into the ventricles, until the auricles are filled and another contraction takes place.

Locomotion of the Heart.—The position of the heart after death or during the repose of the organ is with its base directed slightly to the right and its apex to the left side of the body. With each ventricular systole, the apex is sent forward and is moved slightly from left to right. The movement from left to right is a necessary consequence of the course of the superficial fibres. The fibres on the anterior surface of the organ are longer than those on the posterior surface, and pass from the base, which is comparatively fixed, to the apex, which is movable. As a consequence of this anatomical arrangement, the heart is moved upward and forward during its systole. The course of the fibres from the base to the apex is from right to left; and as they shorten, the apex is of necessity slightly moved from left to right.

The locomotion of the heart takes place in the direction of its axis and is due to the sudden distention of the great vessels at its base. These vessels are elastic, and as they receive the charge of blood from the ventricles, they become enlarged in every direction and consequently project the entire organ against the walls of the chest. This movement is aided by the recoil of the ventricles as they discharge their contents.

Twisting of the Heart.—The spiral course of the superficial fibres involves another phenomenon accompanying its contraction; namely, twisting. By attentively watching the apex, especially when the action of the heart is slow, there is observed a palpable twisting of the point upon itself from left to right with the systole, and an untwisting with the diastole.

Hardening of the Heart.—If the heart of a living animal be grasped by the hand, it will be observed that at each systole it becomes hardened. The fact that it is composed almost exclusively of fibres resembling very closely those of the voluntary muscles, explains this phenomonen. Like any other muscle, it is sensibly hardened during contraction.

Shortening of the Ventricles.—The point of the heart is protruded during the ventricular systole, but this protrusion is not due to elongation of the ventricles. By suddenly cutting the heart out of a warm-blooded animal and watching the phenomena which accompany the few regular movements which follow, it is seen that the ventricles invariably shorten as they contract. This can easily be appreciated by the eye, but more readily if the point of the organ be brought just in contact with a plane surface at a right angle, when, at each contraction, it is unmistakably observed to recede. During the intervals of contraction, the great vessels, particularly the aorta and pulmonary artery, which attach the base of the heart to the posterior wall of the thorax, are filled but not distended with blood; at each systole, however, these vessels are distended to their utmost capacity; their elastic coats admit of considerable enlargement, as can be seen in the living animal, and this enlargement, taking place in every direction, pushes the whole organ forward. It is for this reason that, in observing the heart *in situ*, the ventricles seem to elongate. It is only when the heart is firmly fixed or is contracting after it has been removed from the body, that the actual changes which occur in the length of the ventricles can be appreciated. During the systole, the ventricles are shortened and are narrowed in their transverse diameter, but their antero-posterior diameter is slightly increased.

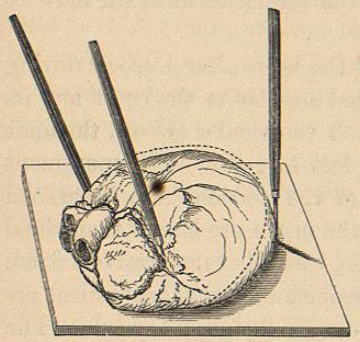

FIG. 19.—*Diagram of the shortening of the ventricles during systole.*
The dotted lines show the position of the heart during contraction.

In addition to the marked changes in form, position etc., which the heart undergoes during its action, on careful examination it is seen that the surface of the ventricles becomes marked with slight, longitudinal ridges during the systole.

Impulse of the Heart.—Each movement of the heart produces an impulse, which can be readily felt and sometimes seen in the fifth intercostal space a little to the right of the perpendicular line of the left nipple. This impulse is synchronous with the contraction of the ventricles. If the hand be introduced into the chest of a living animal and the finger be placed between the point of the heart and the walls of the thorax, every time that there is a hardening of the point, the finger will be pressed against the side. If the impulse of the heart be felt while the finger is on the pulse, it is evident that the heart strikes against the thorax at the time of the distention of the arterial system. The impulse is due to the locomotion of the ventricles. In the words of Harvey, "the heart is erected, and rises upward to a point so that at this time it strikes against the breast and the pulse is felt externally."

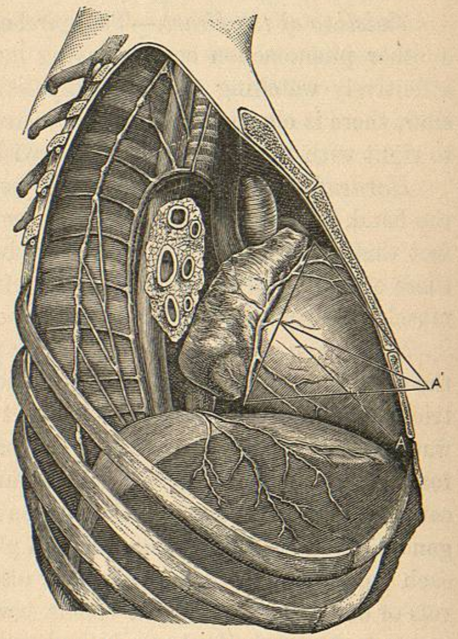

FIG. 20.—*Side view of the heart* (Landois).
A, apex during diastole; A', the same during systole. (Modified from Ludwig and Henke.)

Succession of the Movements of the Heart.—The main points in the succession of the movements of the heart are readily observed in cold-blooded animals, in which the pulsations are very slow. In examining the heart of the frog, turtle or alligator, the alternations of repose and activity are very strongly marked. During the intervals of contraction, the whole heart is flaccid and the ventricle is comparatively pale; the auricles then slowly fill with blood; when they have become fully distended, they contract and fill the ventricle, which

in these animals is single; the ventricle immediately contracts, its action following upon the contraction of the auricles as if it were propagated from them. When the heart is filled with blood, it has a dark-red color, which contrasts strongly with its appearance after the systole. These phenomena may occupy ten to twenty seconds, giving an abundance of time for observation. The case is different, however, with the warm-blooded animals, in which the anatomy of the heart is nearly the same as in man. Here a normal revolution may occupy less than a second; and it is evident that the varied phenomena just mentioned are followed with more difficulty. In spite of this rapidity of action, it can be seen that a rapid contraction of the auricles precedes the ventricular systole, and that the latter is synchronous with the cardiac impulse.

The experiments of Marey, with reference to the relations between the systole of the auricles, the systole of the ventricles and the impulse of the heart, were performed upon horses, in the following way:

A sound is introduced into the right side of the heart through the jugular vein. This sound is provided with two initial bags, one of which is lodged in the right auricle, while the other passes into the ventricle. The bags are connected with distinct tubes which pass one within the other and are connected by elastic tubing with the registering apparatus. At each systole of the heart, the bags in its cavities are compressed and produce corresponding movements of the levers, which may be registered simultaneously.

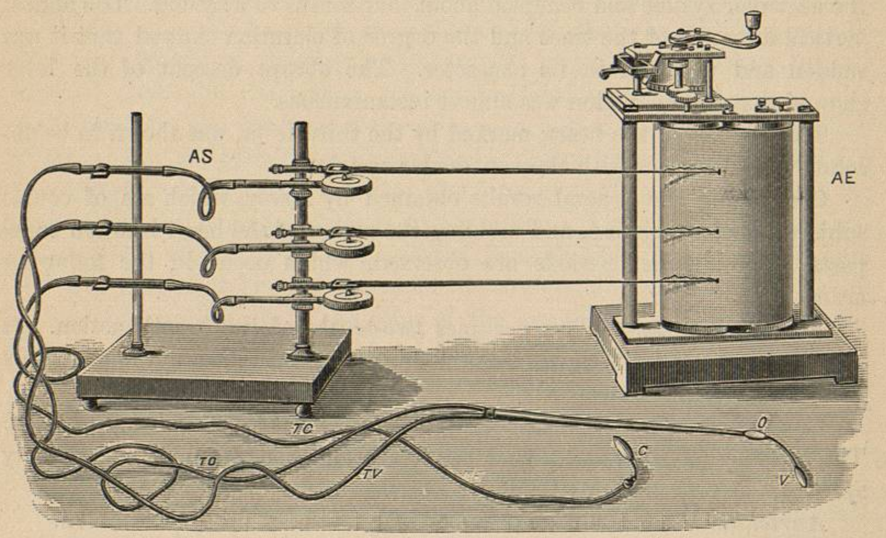

FIG. 21.—*Cardiograph* (Chauveau and Marey).
"The instrument is composed of two principal elements: A E, the registering apparatus, and A S, the sphygmographic apparatus, that is to say, which receives, transmits, and amplifies the movements which are to be studied." The compression exerted upon the bag *c*, which is placed over the apex of the heart, between the intercostal muscles, is conducted by the tube *t c*, which is filled with air, to the first lever. The compression exerted upon the bags *o* and *v*, in the double sound, is conducted by the tubes *t o* and *t v* to the two remaining levers. The movements of the levers are registered simultaneously by the cylinder A E.

To register the impulse of the heart, an incision is made through the skin and the external intercostal muscle over the point where the apex-beat is felt.

A little bag, stretched over two metallic buttons separated by a central rod, is then secured in the cavity thus formed and is connected by an elastic tube with the registering apparatus. All the tubes are provided with stop-cocks, so that each initial bag may be made to communicate with its lever at will. When the operation is completed and the sound is firmly secured in place by a ligature around the vein, the animal experiences no inconvenience, is able to walk about, eat etc., and there is every evidence that the circulation is not interfered with. The cylinder which carries the paper destined to receive the traces is arranged to move by clock-work at a given rate. The paper may also be ruled in lines, the distances between which represent certain fractions of a second. Fig. 21 represents the apparatus reduced to one-sixth of its actual size. Two of the levers are connected with the double sound for the right auricle and ventricle, and one is connected with the bag destined to receive the impulse of the heart. In an experiment upon a horse, the movements of the three levers produced traces upon the paper which were interpreted as follows:

The auricular systole, marked by the first lever, immediately preceded the ventricular systole and occupied about two-tenths of a second. The elevation of the lever indicated that it was much more feeble than the ventricular systole, and sudden in its character; the contraction, when it had arrived at the maximum, being immediately followed by relaxation.

The ventricular systole, marked by the second lever, immediately followed the auricular systole and occupied about four-tenths of a second. The almost vertical direction of the trace and the degree of elevation showed that it was sudden and powerful in its character. The abrupt descent of the lever showed that the relaxation was almost instantaneous.

The impulse of the heart, marked by the third lever, was shown to be absolutely synchronous with the ventricular systole.

Condensing the general results obtained by Marey, which are of course subject to some variation, and dividing the action of the heart into ten equal parts, three distinct periods are observed, which occur in the following order:

Auricular Systole.—This occupies two-tenths of the heart's action. It is feeble as compared with the ventricular systole, and relaxation immediately follows the contraction.

Ventricular Systole.—This occupies four-tenths of the heart's action. The contraction is powerful and the relaxation is sudden. It is absolutely synchronous with the impulse of the heart.

Auricular Diastole.—This occupies four-tenths of the heart's action.

Force of the Heart.—Hales (1733) was the first to investigate experimentally the question of the force exerted by the heart, by the application of the cardiometer. He showed that the pressure of blood in the aorta could be measured by the height to which the fluid would rise in a tube connected with that vessel, and estimated the force of the left ventricle by multiplying the pressure in the aorta by the area of the internal surface of the ventricle. The cardiometer has since undergone various improvements and modifications, but the above is the principle made use of at the present day in estimating the pressure of the blood in different parts of the circulatory system.

Hales estimated, from experiments upon living animals, the height to which the blood would rise in a tube connected with the aorta of the human subject, at 7 feet 6 inches (228·6 centimetres), and gave the area of the left ventricle as 15 square inches (96·67 square centimetres). From this he calculated the force of the left ventricle as equal to 51·5 pounds (about 23 kilos). This estimate, however, does not satisfy all the physical conditions, and it can not be accepted, even as an approximation.

The apparatus of Marey for registering the contractions of the different cavities of the heart enabled him to ascertain the comparative force of the two ventricles and the right auricle; the situation of the left auricle precluding the possibility of introducing a sound into its cavity. By first subjecting the bags to known degrees of pressure, the line of elevation of a lever may be graduated so as to represent the degrees of the cardiometer. In analyzing traces made by the left ventricle, the right ventricle and right auricle, in the horse, Marey found that as a general rule, the comparative force of the right and left ventricles is as one to three. The force of the right auricle is comparatively insignificant, being in one case, as compared with the right ventricle, only as one to ten.

Action of the Valves.—In man and the warm-blooded animals, there are no valves at the orifices by which the veins open into the auricles. As has already been seen, compared with the ventricles, the force of the auricles is insignificant; and it has farthermore been shown that the ventricles may be filled with blood and the circulation continue when the auricles are entirely passive. Although the orifices are not provided with valves, the circular arrangement of the fibres about the veins is such, that during the contraction of the auricles the openings are considerably narrowed and regurgitation can not take place to any great extent. The force of the blood flowing into the auricles likewise offers an obstacle to its return. There is really no valvular apparatus which operates to prevent regurgitation from the heart into the veins; for the valvular folds, which are so abundant in the general venous system and particularly in the veins of the extremities, do not exist in the venæ cavæ. The continuous flow of blood from the veins into the auricles, the feeble character of the auricular contractions, the arrangement of the fibres around the orifices of the vessels, and the great size of the auriculo-ventricular openings, are conditions which provide sufficiently for the flow of blood into the ventricles.

Action of the Auriculo-Ventricular Valves.—After the ventricles have become completely distended by the auricular systole, they take on their contraction, which is very many times more powerful than the contraction of the auricles. They force open the valves which close the orifices of the pulmonary artery and aorta and empty their contents into these vessels. To accomplish this, at the moment of the ventricular systole, there is a complete closure of the auriculo-ventricular valves, leaving only the auriculo-ventricular opening through which the blood can pass. That these valves close at the moment of contraction of the ventricles, was demonstrated by the experiments of Chauveau and Faivre, who introduced the finger through an opening into the auricle and actually felt the valves close at the instant of the ventricular systole. This tactile demonstration, and the fact that the first sound of the heart, which is produced in part by the closure of the auriculo-ventricular valves, is synchronous with the ventricular systole, leave no doubt as to the mechanism of the closure of these valves. It is probable that as the blood flows into the ventricles, the valves are slightly floated out, but they are not closed until the ventricles contract.

If a bullock's heart be prepared by cutting away the auricles so as to expose the mitral and tricuspid valves, securing the nozzles of a double syringe in the pulmonary artery and aorta after having destroyed the semilunar valves, and if fluid be injected simultaneously into both ventricles, the play of the valves will be exhibited. The mitral valve effectually prevents the passage of fluid, its edges being so accurately adapted that not a drop passes between them; but when the pressure is considerable, a certain quantity of fluid passes the tricuspid valve (T. W. King). There is, indeed, a certain degree of insufficiency of the tricuspid valve, which does not exist on the opposite side; but it is very questionable whether there can be sufficient force exerted by the right ventricle to produce regurgitation of blood at the right auriculo-ventricular orifice.

Action of the Aortic and Pulmonic Valves.—The action of the semilunar valves is nearly the same upon both sides. In the intervals of the ventricular contractions, they are closed and prevent regurgitation of blood into the ventricles. The systole, however, overcomes the resistance of these valves and forces the contents of the ventricles into the arteries. During this time, the valves are applied, or nearly applied, to the walls of the vessel; but so soon as the ventricles cease their contraction, the constant pressure of the blood, which is very great, closes the openings.

The action of the semilunar valves can be studied by cutting away a portion of the ventricles in the heart of a large animal, securing the nozzles of a double syringe in the aorta and pulmonary artery and forcing water into the vessels. It has been observed that while the aortic semilunar valves oppose the passage of the liquid so effectually that the aorta may be ruptured before the valves will give way, a certain degree of insufficiency exists, under a high pressure, at the orifice of the pulmonary artery (Flint, 1864). A slight insufficiency of the pulmonic valves was observed by John Hunter, in 1794. It is not probable, however, that the pressure of blood in the pulmonary artery is ever sufficient to produce regurgitation when the valves are normal.

It is probable that the corpuscles of Arantius, which are situated in the middle of each valvular curtain, assist in the accurate closure of the orifice. The sinuses of Valsalva, situated in the artery behind the valves, are regarded as facilitating the closure of the valves by allowing the blood to pass easily behind them.

Sounds of the Heart.—The appreciable phenomena which attend the heart's action are connected with the systole of the ventricles. It is this

which produces the impulse against the walls of the thorax, and as will be seen farther on, the dilatation of the arterial system, indicated by the pulse. It is natural, therefore, in studying these phenomena, to take the systole as a point of departure, instead of the action of the auricles; and the sounds, which are two in number, have been called first and second, with reference to the ventricular systole.

The first sound is absolutely synchronous with the apex-beat. The second sound follows the first with scarcely an appreciable interval. Between the second and the first sound, there is an interval of silence.

Some writers have attempted to represent the sounds of the heart and their relations to each other, by certain syllables, as "*lubb-dup* or *lubb-tub*"; but it seems unnecessary to attempt to make such a comparison, which can only be appreciated by one who is practically acquainted with the heart-sounds, when the sounds themselves can be so easily studied.

Both sounds are generally heard with distinctness over the entire præcordial region. The first sound is heard with its maximum of intensity over the body of the heart, a little below and within the nipple, between the fourth and fifth ribs, and is propagated with greatest intensity downward, toward the apex. The second sound is heard with its maximum of intensity at the base of the heart, between the nipple and the sternum, at about the third rib, and is propagated upward, along the course of the great vessels. If the stethoscope be placed between the point of the apex-beat and the left nipple, the first sound will be heard strongly accentuated, and presenting a certain quality in its valvular element, due to the closure of the mitral valve. If the stethoscope be then removed to a point a little to the left of the ensiform cartilage, the element due to the closure of the tricuspid valve will predominate, and a slight but distinct difference in quality may frequently be noted. An analogous difference in the valvular elements of the second sound may also be observed. When the stethoscope is placed at the base of the heart, just to the right of the sternum and near the aortic valves, the character of the second sound is often notably different from the character of the sound heard with the stethoscope placed just to the left of the sternum, over the pulmonic valves. In this way the valvular elements of the two sounds of the heart may be separated, each one into two, one produced by closure of the valves on the left side, and one by closure of the valves of the right side. A recognition of these nice distinctions is useful in physical examinations of the heart in disease.

The rhythm of the sounds bears a definite relation to the rhythm of the heart's action. Laennec was the first to direct special attention to the rhythm of the heart-sounds, although the sounds themselves were recognized by Harvey, who compared them to the sounds made by the passage of fluids along the œsophagus of a horse when drinking. Laennec divided a single revolution of the heart into four equal parts: the first two parts, occupied by the first sound; the third part, by the second sound; and the fourth part, with no sound. He regarded the second sound as following immediately after the first. Some authors have described a "short silence" as occurring after the first sound, and a "long silence," after the second sound. The short silence, if appreciable at all, is so indistinct that it may practically be disregarded.

Most physiologists regard the duration of the first sound as a little less than two-fourths of the heart's action, and the second sound as a little more than one-fourth. When the mechanism of the production of the two sounds is considered, it will be seen that if the views on that point be correct, the first sound should occupy the period of the ventricular systole, or four-tenths of the heart's action. The second sound occupies about three-tenths, and the repose, three-tenths.

The first sound is relatively dull, low in pitch, and is made up of two elements; one, a valvular element, in which it resembles in character the second sound, and the other, an element which is directly due to the action of the heart as a muscle. It has been ascertained that all muscular contraction is attended with a certain sound. To this is added an impulsion element, which is produced by the striking of the heart against the walls of the thorax.

The second sound is relatively sharp, high in pitch, and has but one element, which is purely valvular.

Causes of the Sounds of the Heart.—There is now scarcely any difference of opinion with regard to the cause of the second sound of the heart. The experiments of Rouanet (1832) settled beyond a doubt that it is due to closure of the aortic and pulmonic semilunar valves. In these experiments, the second sound was imitated by producing sudden closure of the aortic valves by a column of water. In the experiments of the British Commission, the semilunar valves were caught up by curved hooks introduced through the vessels of a living animal (the ass), with the result of abolishing the second sound and substituting for it a hissing murmur. When the instruments were withdrawn and the valves permitted to resume their action, the normal sound returned.

The cause of the first sound of the heart has not been so well understood. It was maintained by Rouanet that this sound was produced by the closure of the auriculo-ventricular valves; but the situation of these valves rendered it difficult to demonstrate this by actual experiment. While the second sound is purely valvular in its character, the first sound is composed of a certain number of different elements; but auscultatory experiments have been made by which all but the valvular element are eliminated, when the first sound assumes a purely valvular quality. These observations were made in 1858 by the late Dr. Austin Flint:

If a folded handkerchief be placed between the stethoscope and integument, the first sound is divested of some of its most distinctive features. It loses the quality of impulsion and presents a well marked valvular quality.

In many instances, when the stethoscope is applied to the præcordia while the subject is in a recumbent posture and the heart is removed by force of gravity from the anterior wall of the thorax, the first sound becomes purely valvular in character and as short as the second.

When the stethoscope is applied to the chest a little distance from the point where the first sound is heard with its maximum of intensity, it presents only its valvular element.

These observations, taken in connection with the fact that the first sound occurs when the ventricles contract and necessarily accompanies the closure of the auriculo-ventricular valves, show that these valves produce at least one element of the sound. In farther support of this opinion, is the fact that the first sound is heard with its maximum of intensity over the site of the valves and is propagated downward along the ventricles, to which the valves are attached. Actual experiments are not wanting to confirm this view. Chauveau and Faivre succeeded in abolishing the first sound by the introduction of a wire ring into the auriculo-ventricular orifice through a little opening in the auricle, so as to prevent the closure of the valves. When this is done, the first sound is lost; but on taking it out of the opening, the sound returns. These observers also abolished the first sound by introducing a small curved tenotomy-knife through the auriculo-ventricular orifice and dividing the chordæ tendineæ. In this experiment a loud rushing murmur took the place of the sound. These observations and experiments seem to settle the fact that the closure of the auriculo-ventricular valves produces one element of the first sound.

The other elements which enter into the composition of the first sound are not so prominent as the one just mentioned, although they serve to give it its prolonged and "booming" character. These elements are a sound like that produced by any large muscle during its contraction, called by some the muscular murmur, and the sound produced by the impulse of the heart against the walls of the chest.

There can be no doubt that the muscular murmur is one of the elements of the first sound; and it is this which gives to the sound its prolonged character when the stethoscope is applied over the body of the organ, as the sound produced in muscles continues during the whole period of their contraction. Admitting this to be an element of the first sound, its duration must necessarily coincide with that of the ventricular systole.

The impulse of the heart against the walls of the thorax also has a share in the production of the first sound. This is demonstrated by noting the difference in the sound when the subject is lying upon the back, and when he is upright, by interposing any soft substance between the stethoscope and the chest, or by auscultating the heart after the sternum has been removed. Under these conditions, the first sound loses its booming character, retaining, however, the muscular element when the instrument is applied to the exposed organ.

The observations showing the valvular character of one of the elements of the first sound have been so definite and positive in their results that one can hardly regard them as entirely controverted by the recent experiments (1885) of Yeo and Barrett, upon the hearts, cut from the body, of cats and dogs, which show, it is claimed, that "a definite and characteristic tone similar in quality to the first sound is produced by the heart-muscle under circumstances that render it impossible for any tension of the valves to contrib-