# THE NATURE OF FIBRILLARY CONTRACTION OF THE HEART. — ITS RELATION TO TISSUE MASS AND FORM [1]

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IT is a noteworthy fact that the hearts (ventricles) of large animals fibrillate with great ease and only rarely recover from the fibrillary state, while small hearts rarely fail to recover. It was noted by McWilliam [2] that "spontaneous recovery may take place readily in the hearts of the cat, rabbit, rat, mouse, hedgehog, and fowl." The ventricles of dogs do not usually recover spontaneously from fibrillation, although they do so in rare instances, as noted by Porter. [3] The larger beef heart is one which enters into the fibrillary state with greatest ease and caprice. Erlanger [4] records this fact and states "that it is not often that fibrillation of the calves' heart can be stopped, as in other hearts, by means of temporary perfusion with potassium chloride solution." In this connection we may also refer to the well-known fact that fibrillation of the thin walled auricles is usually of a transitory nature, while that of the thicker ventricles of the same heart is much more prone to persist. It would appear obvious, from a consideration of these facts, that the size of the tissue masses involved in the process may have an important bearing on the induction of and recovery from the fibrillary state, yet, so far as we have been able to ascertain, these phenomena have never been systematically investigated from this viewpoint,

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[1] The main features of this work were reported to the St. Louis Medical Science Club, November 12, 1912, and a synopsis appears in the Proceedings of the Society, Interstate medical journal, December, 1912, xix, p. 1081.

[2] J. A. McWilliam: Journal of physiology, 1887, viii, p. 296 et seq.

[3] W. T. Porter: This journal, 1898, i, p. 80.

[4] J. Erlanger: This journal, 1912, xxx, p. 400.

although Porter[1] found that he could suppress fibrillation of pieces of the heart more easily than the whole heart, and McWilliam[2] found that the isolated ventricular apices of all mammals worked with could recover from fibrillation again and again.

Our investigations give substantial support to the a priori view, based upon the above mentioned facts, that the ease with which the fibrillary process may be induced and with which spontaneous recovery from the fibrillary contractions takes place is inversely proportional to the mass of fibrillating tissue. In harmony with these facts is the finding that the extension of fibrillary process from any portion of the heart to another is dependent upon the cross sectional area of the conducting tissue connecting them. Our experiments support Porter's view that the essential nature of fibrillary contractions must be referred to abnormalities in impulse conduction — to the existence or establishment of blocks, or at least to relative differences in conductivity,[3] rather than to any peculiarity or alteration of contractile properties.

## I. EXPERIMENTS WITH FIBRILLATING AURICLES

**Any Small Auricular Piece will Cease Fibrillating.**—When the auricles of cats, rabbits, or dogs are stimulated with strong faradic shocks, localized at any point, the whole musculature of both auricles enters into violent fibrillary contractions which usually persist for a time varying from a few seconds to several minutes, or more rarely for hours, after stimulation has ceased. In experiments conducted upon these mammals it was found that when a portion of the wall of fibrillating auricles was picked up by forceps and functionally separated from the heart by ligating, or by clamping with haemostatic forceps, the portion so separated ceased fibrillating at once, although the organ from which it was removed continued its inco-ordinated contractions unaltered. Such

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[1] W. T. PORTER: This journal, 1898, i, pp. 71–82.

[2] J. A. McWILLIAM: *loc. cit.*, p. 301.

[3] The block hypothesis originated with W. T. PORTER: The journal of physiology, 1894, xv, p. 135; This journal, 1899, ii, p. 129; 1905, xiii, pp. xxiii and xxiv; 1905, xv, p. 5.

a procedure is especially applicable to the auricular appendices, and it was found that a whole appendix, either right or left, could be functionally removed in this way and would invariably stop fibrillating and come to complete rest. The appendices or other pieces could, subsequently, be removed by section and their properties studied.

**The Excised Pieces Retain their Normal Properties.**—It was important to determine whether pieces cut away from the fibrillating auricles had, as a result of their previous abnormality and removal from the heart, lost any of their physiological properties. It was found that they responded with a single normal co-ordinated contraction in response to a single mechanical or electrical stimulus. When the stimuli were repeated regularly a rhythmic response was elicited. Many of the pieces removed in the above experiments were immediately placed in warm (40° C.) sodium chloride solutions, or in Ringer's mixture, and all beat with perfect rhythms.

The normal functional capacity of the quiescent portions of the fibrillating auricles was strikingly illustrated by experiments of the following type: The heart of a dog was exposed and the auricles made to fibrillate by faradizing the tip of the right auricular appendix. The left appendix was then clamped off with a flexible intestinal clamp, the jaws of which were covered with rubber tubing. Compression was carefully graded to avoid any crushing injury and, as it increased in degree, fibrillation was seen to be supplanted by irregularly recurring co-ordinated contractions, the appendix finally coming to rest when block was complete. When the clamp was suddenly released, the appendix gave a few co-ordinated contractions and then fibrillated. These procedures could be repeated as many times as desired with the same results. The experiment became at once more striking and significant when the clamp was gradually released, for it was possible, in such cases, to obtain a degree of compression with which the appendix was kept beating in a perfectly co-ordinated manner, although irregularly. With further decompression these contractions passed over into a mere flutter and then fibrillation ensued. In two experiments the whole atrium assumed its normal rhythmic contractions while the clamp was in position and the appendix

was at rest; upon releasing the clamp the appendix beat as in partial block, later taking up the rhythm of the heart.

It is obvious from these experiments that pieces of auricular tissue possess normal capacity for rhythmic contractions when functionally separated from the fibrillating auricles. It is also clear that when connected normally they may fibrillate in response to an irregular shower of impulses which originate in the fibrillating auricular mass; when the number of these impulses is decreased by clamping, the piece may beat co-ordinately in spite of the inco-ordination of the auricular tissue with which it is connected.

**The Fibrillary Contractions are not Sustained from the Point faradized in Initiating them.** — Fibrillation has been looked upon as an inco-ordination which results from the fact that the irritability of certain areas is increased to such an extent that they become independently and highly rhythmic. In such a view the inco-ordination resolves itself into a response to extra-systole formation (Lewis).[1] Since faradization localized to a circumscribed area may precipitate the fibrillary process, it would seem logical to assume, as McWilliam [2] did, that the fibrillary contractions started in and were sustained from this area. This view would seem the more plausible since recent work has demonstrated that faradization of auricular tissue markedly increases its rhythmicity and force of beat (Erlanger).[3]

To test the validity of this idea of the nature of fibrillation a series of experiments was instituted to determine whether, after inducing fibrillation by stimuli localized within a very circumscribed area, the process persisted because impulses were continuously and inco-ordinately sent out from this area. The experiments were conducted along the lines of those described above. The tip of one auricular appendix was faradized until sustained fibrillary contractions were instituted, after which this appendix was functionally separated from the fibrillating auricles either by ligating, cutting, or clamping. As a result of this procedure the appendix came to rest, but the auricles invariably continued their delirium unaltered. The stimulated appendix behaved exactly

[1] THOS. LEWIS: Heart, 1910, i, p. 353.

[2] J. A. MCWILLIAM: *loc. cit.*, p. 309.

[3] J. ERLANGER: This journal, 1910, xxvii, p. 102.

as any other portion of the auricles behaved when removed in a similar way.

Fibrillary contractions, then, are not dependent upon impulses initiated in any given area, even if the area be the one from which the process was started, but is a process in which the whole tissue mass is involved. It is dependent upon the integrity of a considerable mass of tissue, and subdivision of this mass into smaller bits brings all of the tissue out of the state of inco-ordinated contractions, the pieces either coming to rest or beating independently with a perfect rhythm depending upon the portion of the heart from which they were removed and upon the conditions to which they are subjected.

## II. Experiments with Fibrillating Ventricles

**Effects of Subdivision of Ventricles.** — Any extended study of the relation of mass to fibrillary contractions is impossible with the hearts of cats or rabbits, owing to their well-known tendency to recover spontaneously from this condition, a tendency which may be due, at least in part, to their small size. It was determined, however, that cutting these small ventricles into two or four pieces would stop fibrillation immediately. More extended observations were conducted upon the ventricles of dogs, in which persistence of the fibrillary contractions is the rule. The results of subdivision of the ventricular tissue were independent of the cause inciting to fibrillation, i.e., whether the process was started by mechanical stimuli, by faradization, or spontaneously after the injection of, digitalis, salts of barium and calcium, or other drugs.

Pieces were shaved from the wall of the fibrillating left ventricle by a cut parallel to the surface, the cut being so made that the cavity of the heart was not entered. These pieces ceased fibrillating at once, although some were two centimetres wide and four centimetres long, and as thick as could safely be made. In other instances the whole of the apices were removed by cut, clamp, or ligature after the manner described above for the auricular appendix. The piece thus removed always came to rest while the main fibrillating mass of the ventricles continued its abnormal

delirium. When pieces were cut away from the fibrillating ventricles it was noted that, like the apex, they ceased their incoordination and it was immaterial whether the pieces came from the walls of either ventricle or from the septum; they all behaved in identically the same way, provided they were of the same size.

It was noted, however, that larger pieces might fibrillate several seconds, or even half a minute after removal, while small bits ceased immediately. Pieces of equal surface area but including the whole thickness of the wall of the left and right ventricles, respectively, showed distinct differences in the time of persistence of the fibrillary contractions after removal; the thicker pieces taken from the left ventricle always fibrillated for a longer period before coming to rest. That the persistence of fibrillation is in direct proportion to the mass of the tissue is also indicated in the following type of experiment: Two cuts were made in the ventricle on either side of the septum and extending from the apex to the auriculo-ventricular ring, thus dividing the fibrillating heart into three pieces, the thin wall of the right ventricle, the thicker septal and left ventricular pieces. The two thick pieces continued to fibrillate, but the thinner right ventricle stopped within fifteen seconds. Additional cuts dividing each of the two fibrillating masses into two equal parts brought all the fragments to rest.

It was clear, from the numerous experiments made, that any piece cut from any part of the mass of ventricular tissue would cease fibrillating if small enough, e.g., if its surface area was less than four square centimetres. As was indicated for auricular tissue, even the portion to which the localized faradic stimuli had been applied in starting the fibrillary contractions could be excised and would come to rest while the remaining mass would fibrillate. A large part of the septum, when excised, acted in a similar way. Thus in the case of the ventricles, as with that of the auricles, fibrillation involves the whole tissue mass and is not dependent upon impulses coming from any single area of the tissue, nor is the recovery from the condition dependent upon any co-ordinating centre within the tissue (e.g., the septum), for any piece can recover.

**Properties of Pieces Excised from Fibrillating Ventricles. —** Quiescent pieces which have been excised from the fibrillating

ventricles of the dog are capable of responding with co-ordinated contractions when stimulated and will beat rhythmically when placed in warm $M/6$ solutions of sodium chloride. After recovery due to diminishing the size of the fibrillating mass, the pieces are also capable of responding to the normal physiological stimulus as the following experiment will indicate. By faradization the ventricles were made to fibrillate, in which process the auricles did not participate, but beat with their own rhythm, interrupted, however, by extra-systolic irregularities due to retrograde ventricular impulses. From the ventricles bits the size of a chestnut were removed piecemeal beginning at the apex. Each piece upon removal became quiet. When approximately three-fourths of the ventricle had thus been removed piecemeal, the remaining basal ring suddenly ceased fibrillating and beat in regular sequence with the auricles, indicating its return to relative normality. That, in this experiment, so large a mass of ventricle as one-fourth of the whole should have spontaneously ceased fibrillating may have been related to the fact that it was the basal portion with the shape of a ring (the importance of such a shape will appear in a subsequent section), or it may have been due in part to a slight cooling, which, as indicated by Porter's experiments, favors recovery; but the point of chief importance to us lies in the fact that so long as the mass was larger than one-fourth, fibrillation did not cease, while small pieces cut from it, and obviously of the same temperature, recovered immediately.[1]

[1] It should be emphasized that our method throughout has been one in which the relations of tissue mass and shape to the fibrillary contractions were determined upon tissues under like conditions; for example, the pieces compared had the same temperature as the fibrillating mass from which they were removed, yet they did not fibrillate. On the other hand the results were made doubly striking by the cessation of fibrillation in pieces which were transferred immediately to physiological saline solutions, the temperature of which was distinctly above that of the pieces. High temperatures have been shown by McWilliam (J. A. McWILLIAM: Journal of physiology, 1887, viii, p. 303) to increase the tendency to fibrillate. In our experiments, in which a clamp was applied to the auricle and alternately tightened and released to show cessation of fibrillation of the auricular appendix, and in similar experiments with ventricular tissue, as noted below, no question of differences in temperature can enter, and this is, of course, true in the experiments with the various turtle hearts.

In testing the reaction of pieces cut away in the above experiments faradic shocks were used in some instances. In these tests we obtained the significant result that very small pieces fibrillated only during stimulation, while larger pieces fibrillated for several seconds, or more, the duration of the fibrillary condition being in direct proportion to the mass of the tissue, emphasizing in another way the result obtained by the method of excision.

**The Relation of Shape to Persistence of Fibrillation.**—In performing the experiments described in the preceding paragraph, it was noticed that when faradic stimuli were applied to detached narrow strips several centimetres in length, the fibrillary contractions were confined to the region about the electrodes, but that the tissue at the other end of the strips beat co-ordinately, although irregularly. All contractions ceased when stimulation was stopped. This experiment suggested at once that fibrillation was impossible in sufficiently narrow strips.[1] This suspicion was at once justified when a fibrillating mass, such as the entire right or left ventricle or septum, was so incised as to make a trouser or trident preparation with individual parts connected by narrower bridges. Fibrillation ceased in such a preparation and faradization of one component always resulted in co-ordinate contractions of the other components. Similarly, it was found that when a cut was made into the apex of the fibrillating ventricles and continued spirally in such a manner as to produce a strip with a width of approximately one centimetre, the distal end of the strip would beat co-ordinately in response to irregular impulses coming from the fibrillating mass at its proximal end. It was possible to continue the incision and to progressively incorporate more and more of the fibrillating mass into the strip until, in some instances, it reached a length of thirty or even fifty centimetres. For a short time perfectly co-ordinate waves could be seen traversing the whole length of these strips. With the progressive reduction of the size of the fibrillating mass it was found that upon reaching a certain limit fibrillation ceased and beats, co-ordinate with the auricular contractions, intervened. The development of blocks in these strips will always take place sooner or later to interfere with the ideal picture just presented.

[1] J. ERLANGER: This journal, 1910, xxvii, p. 99 *et seq.*

Owing to the rapid succession of impulses it is not always easy to determine whether the contractions of such strips are co-ordinated or not. Two procedures quickly revealed the true nature of the conditions; first, gentle compression of the proximal end of the strip established the condition of partial block and, by this means, the contraction waves could be made to progress down the strip with any desired intervals; second, single stimuli applied to the strip produced in it well-marked extra-systoles, which cannot be detected in fibrillating cardiac tissue.

In some instances success attended efforts to cut these strips, beginning at the apical portion of the ventricles, without precipitating the ventricles into the fibrillary state. The application of faradic stimuli to the strip produced inco-ordination in the region of the electrodes, but in no instance did this manipulation result in fibrillation of the ventricular tissue to which the strip was attached; it beat co-ordinately, rapidly, and with a surprisingly regular rhythm.

**Conduction of the Fibrillary State.**—It has been firmly established by the work of Vulpian and others[1] that in the mammalian heart the fibrillary state is not transmitted from fibrillating auricles to ventricles, or from fibrillating ventricles to auricles, but that the structures not participating in the delirium may contract as a whole and in a perfectly co-ordinate manner.

In the explanation of the fact that the fibrillary state is not transmitted through the auriculo-ventricular bundle, it might seem warrantable, in the absence of experimental data, to attribute it to special physiologic properties of the tissue composing the bundle, to the fact, for example, that contractility has not yet been demonstrated for Purkinje tissue unmixed with muscle cells.[2] On the other hand it is possible that the narrowness of this conducting isthmus may suffice to account for its relation to the spread of the fibrillary process.

[1] VULPIAN: Archives de physiologie, 1874, p. 976. W. T. PORTER: This journal, 1898, i, pp. 77–81. ERLANGER and HIRSCHFELDER: This journal, 1906, xv, p. 167. CUSHNEY and EDMUNDS: American journal of medical sciences, 1907, cxxxiii, p. 74 *et seq*. W. E. GARREY: This journal, 1908, xxi, p. 287.

[2] J. ERLANGER: This journal, 1912, xxx, p. 405.

That the latter view is the probable one is indicated by the behavior of narrow strips as described in the previous section; that it is the correct one was easily proven by direct experiments in which only a narrow isthmus of muscle was left between portions of the auricles in order to determine whether fibrillation could pass from one side to the other. The following abbreviated protocols give the results of the experiments.[1]

*Dec. 16, 1912.* — The heart of an etherized cat was removed and perfused through. the aorta and coronary arteries with Locke's solution (without glucose or oxygen). A cut was made between the auricles in the anterior part of the vault to the left of the septum. This cut was extended until a distinct delay in the passage of impulses from the right to the left auricle was noticed, then very carefully extended until a permanent partial block for normal impulses was induced. Faradization of the right auricle produced fibrillation which continued for a short time after faradization was stopped. The fibrillation did not involve the left auricle, which beat co-ordinately but irregularly. In similar manner fibrillation of the left auricle, which lasted only during the period of stimulation, did not extend to the right auricle across the connecting isthmus of muscular tissue. Owing to the ready recovery of co-ordinated contractions in these auricles the same experimental results were repeatedly obtained.

*Dec. 18, 1912.* — Artificial respiration was established on a large etherized cat. The heart was exposed by cutting away the anterior chest wall. With heavy-jawed haemostatic forceps the auricular tissue, at the left of the pulmonary veins, was crushed in a line so directed that a little more than the left appendix was separated from the auricles except for a narrow isthmus of normal muscular tissue, in which there was evident delay in the passage of impulses from the right to the left appendix. Fibrillation of the right auricle outlasted the causative faradization for a short time, but the left appendix continued to beat co-ordinately, although irregularly. Fibrillation of the (smaller) left appendix ceased when the causative faradization was stopped. During fibrillation of the left appendix, the right side of the auricles beat co-ordinately but irregularly.

[1] I am indebted to Dr. J. Erlanger for helpful co-operation in the performance of these experiments.

It is obvious from these experiments that a narrow bridge of normal auricular tissue behaved, so far as conduction of fibrillation was concerned, just as does the narrow auriculo-ventricular bundle.

The author extended these observations to the ventricular musculature of the dog, where permanent fibrillation is the rule. It was found that a sufficiently narrow bridge of tissue (a strip somewhat less than a centimetre wide was usually found to be sufficiently narrow) [1] left connecting the basal and apical halves can conduct normal impulses but will prevent the extension of fibrillation from one piece to the other, although individual impulses do pass and produce, at irregular intervals, contractions of the apical piece when the basal portion of the ventricles is fibrillating, or extra-systoles in the basal portion when the apical portion is fibrillating. In two of the experiments the ventricles were divided into two approximately equal masses, an apical and a basal portion, connected only by the moderator band. The results with this natural isthmus of normal muscular tissue were the same as those quoted above and need not be described in detail.

These experiments prove conclusively that it is impossible for the fibrillary state to be transmitted across a sufficiently narrow conducting bridge to non-fibrillating muscle; they offer the most obvious explanation of the fact that in the mammalian heart fibrillation does not extend through the His bundle, either from the auricles to ventricles, or in the reverse direction. It is not necessary to refer this property to any specialization or differentiation of the tissue or to any anatomic peculiarity other than the narrowness of the conducting bridge.

[1] The degree of narrowing necessary to prevent the extension of fibrillation will, naturally, vary with the physiological condition of the muscle. It would seem probable that the more irritable the tissue, the narrower the bridge must be; thus it was found by Porter (This journal, 1899, ii, p. 132) that fibrillation did extend across a very small muscular bridge, but that in other hearts it did not, "probably because the power of conduction in the bridge was too much reduced." Our clamping experiments show conclusively that the extension of the fibrillary process may be prevented in a bridge of any width when the conductivity is decreased by compression, although it is possible in such cases to still have some of the impulses pass the region of block and produce co-ordinate contractions.

### III. Experiments with the Hearts of Turtles

The hearts of cold blooded animals are subject to inco-ordinated contractions which have been referred to in various terms, such as " undulatory movements " (Gaskell), " inter-vernucular action " (Mills), and by German writers as " Wogen und Wühlen." Bätke [1] has concluded, and we agree with him, that these are all true fibrillary contractions. We have repeated the procedures, which have been described above, in our work with mammalian hearts upon the hearts of large Pseudemys elegans. In the winter state of these hearts the inco-ordinated contractions of both auricles and ventricles are easily induced by faradization or by repeated or long continued vago-sympathetic stimulation, especially after the administration of atropine. It would be a needless repetition to detail the experiments; suffice it to say that in the recovery of the heart when subdivided, and in the relation of narrow strips and bridges of tissue toward conduction of the inco-ordination, the behavior of such hearts was identical with that of fibrillating mammalian cardiac tissue — an indication that the cardiac inco-ordinations are indeed true fibrillations.

What appears to be a striking example of the fact that large masses of tissue fibrillate more easily and recover less readily from the fibrillary state, is seen in the behavior of the ventricles of the large marine loggerhead turtle. Mills [2] noted the tendency of these hearts to fibrillate, and our experience indicates that it is indeed difficult to manipulate them in situ, or to remove them from the animals without precipitating the fibrillary contractions of the ventricles, although the auricles continue beating co-ordinately. Recovery from fibrillation may take place spontaneously, but not invariably, and the fibrillary process usually persists for a long time. When such ventricles are cut into centimetre cubes, these bits stop fibrillating, although they frequently contract rhythmically in the blood serum for several minutes before coming to rest. When stimulated by a few mechanical stimuli or faradically they contract rhythmically again but do not fibrillate. The

[1] H. Bätke: Archiv für die gesammte Physiologie, 1898, lxxi, p. 412; also cf. Langendorf: Archiv für die gesammte Physiologie, 1895, lxi, p. 314.

[2] T. W. Mills: Journal of anatomy and physiology, 1887, xxi, p. 1.

greater excitability and rhythmicity of these hearts may be in part responsible for the fibrillary tendency, but this factor only accentuates the importance of the mass factor. The large size, slow conductivity, and relative independence of vascular nutrition, as compared with the mammalian heart, coupled with the pronounced tendency to fibrillate, made it feasible to conduct upon the ventricles of marine turtles some experiments which have a fundamental bearing on the nature of the fibrillary contractions.

**The Ring Experiment.**—It was found that rings, two centimetres broad, cut from the base of the fibrillating ventricles of large loggerhead turtles did not recover from the fibrillary contractions. A most striking phenomenon resulted when such broad fibrillating rings were narrowed by incising midway between the outer and inner margins, the incisions in these cases not being carried completely around the ring. In this way, by separation of the inner and outer portions, a figure 8 was formed, the two loops being connected by the broad fibrillating isthmus; a second cut across this mass connecting the inner margins of the two loops converted the tissue into a single large ring one centimetre broad and from six to ten centimetres in diameter. As soon as this narrowing was completed it was found that the inco-ordinated fibrillary contractions had resolved themselves into a number of contraction waves which followed each other successively and repeatedly around and around the ring, all progressing in the same direction, an exhibition to which we may apply the term " circus contractions." [1] It usually so happened that the number of contraction waves gradually decreased until but a single contraction wave was left repeating its circuit again and again. In one instance such a wave continued around the ring for seven hours, making each circuit in from six to seven seconds, the diameter of the ring being ten centimetres. When such waves died out new ones were easily started by single mechanical stimuli. Faradic

[1] These experiments were conducted and publicly demonstrated at Woods Hole, Mass., before the appearance of the paper of R. G. Mines (Journal of physiology, 1913, xlvi, p. 349). Our rings were, however, cut from fibrillating tissue, which makes the results especially significant for the interpretation of the nature of the fibrillary process. Our conclusions are, in many respects similar to those of Mines (*l. c.*, p. 373).

stimuli did not cause fibrillation, but started a succession of waves, the number and distance between them being dependent upon the rate of progression and the duration of the refractory phases.

Experiments of this nature prove conclusively that fibrillary contractions are in reality normal in character when progressing along a narrow path, and that the abnormality is dependent upon the presence and relative complexity of the bypaths available. Romanes [1] studied the passage of impulses in rings of contractile tissue cut from the umbrella of the cover eyed medusa (Aurelia), and his studies have been extended by Mayer [2] working with the jelly fish (Cassiopea xamachana). The latter investigator has shown that by properly grading the compression applied to a ring near the point of stimulation, it is possible to block the progress of the contraction wave passing in one direction from the point stimulated, and by release at the proper moment to allow the wave which took the opposite course to continue its progress about the ring. By repeating the manoeuvre a number of waves, all making the circuits in the same direction, were started by what may be called the method of block.

Now the presence of blocks is exactly what we noticed in our ring preparations of the turtles' ventricles. The blocks, however, had developed spontaneously and affected the contraction waves passing in one direction only; those moving in the opposite direction passed the region of block and continued their progress about the ring. It was thus possible by simply touching the tissue at a point near the region of block to add a new wave to those already present.

The causes underlying the unidirectional selection by such blocks is not altogether clear, but appeared to be related to the irregular width of the strips on either side of the points of blocking, and consequently to differences in strengths of the impulses passing a given point of block. Be this as it may, the fact remains that spontaneous blocks of this type do appear, and, in our opinion, this fact is of greatest importance for any adequate theory of fibrillation. Furthermore, the close examination of these ring

[1] G. J. Romanes: Jelly fish, star fish and sea urchins, 1885, p. 67.
[2] A. G. Mayer: Popular science monthly, December, 1908, p. 481.

preparations revealed the equally important fact that *shifting* points of block are easily distinguishable. If, for example, a given area of the ring be closely watched each time the contraction passes it, it will often be found that at one time, only the tissue of the outer edge contracts and transmits the wave, while the inner edge remains quiescent. The next wave, however, may involve the inner margin, but the outer may not contract; or upon another circuit closest scrutiny reveals no superficial evidence of contraction, yet a wave of contraction may be seen to emerge again beyond the quiescent region and to proceed as if no obstruction had been offered to its progress; in reality none had been offered — the contracting elements were simply obscured by others which did not contract. In the very next circuit this same region may contract with all the appearances of normality. We possess in these observations the visible record of one of the fundamental phenomena of block which apparently are the cause of fibrillation.

## IV. The Nature of the Fibrillary Process

For a complete refutation of the idea that fibrillation is due to the destruction of a co-ordinating centre (Kronecker), the work of McWilliam and of Porter has been conclusive. Our experiments amplify the proofs they have adduced.

That in the fibrillary process there is altered conductivity was clearly stated by McWilliam in 1887 (*loc. cit.*). We believe, however, that experiment does not confirm the view that the fibrillary process is sustained by new impulse formation in tissue of heightened excitability, a belief which also includes the more recent statement of this view by Lewis, who looks upon fibrillation as the result of extra-systole formation. Fibrillation of cardiac tissue may be induced by a sharply localized faradization, and while it is certainly true that the result of such stimulation is to raise the excitability with the possibility of extra-systole formation, our experiments have shown conclusively, however surprising the result may be, that the fibrillary process is not sustained by impulses arising in the portion of the tissue directly stimulated, for these portions may be removed without stopping the inco-

ordination, and once started, fibrillation may continue for a long time in tissue remote and physiologically isolated from the point stimulated.

Concerning the probable nature of the fibrillary process, Porter in 1894 made the following statement: " Fibrillar contractions of the heart may be due to an interruption of the contraction wave. The contraction wave would thus be prevented from running its usual course, and the normal co-ordinated action of the ventricular cells would give place to the confusion conspicuous in fibrillary contractions."

The results of our investigation are in complete harmony with and add substantial support to this block hypothesis. The experiments which we have described above brought out the fact that fibrillation could not persist in small pieces, which, however, were still large enough to be the seat of blocks. In explanation of this fact and of the fact that larger masses do fibrillate persistently, the following conception seems to be adequately supported by experimental data.

Normally the impulse to contract does not spread throughout the whole musculature from fibre to fibre, but is delivered simultaneously to many different parts of the musculature of the ventricle from the auriculo-ventricular conducting system. The probability of this condition was pointed out by Tawara[1] and the electrocardiographic studies of Erfmann[2] indicate the correctness of the surmise. The musculature of the ventricles thus beats apparently as a unit but in reality as a group of isolated segments each of which receives its impulse from a different branch of the conducting system. When, however, the stimuli are applied to the musculature directly, as in the induction of fibrillation, the transmission is from muscle fibre to muscle fibre and a distinct time interval elapses between the contractions of different portions of the structure. (This has also been shown to be the case by Erfmann, (*loc. cit.*). From the point stimulated the impulses can spread in any and all directions, their progress being limited only by the pre-existence or development of localized blocks within the tissue mass. Such blocks divert the impulse into other and

[1] S. TAWARA: Das Reizleitungssystem des Säugethierherzens, 1906, p. 187.
[2] WILH. ERFMANN: Zeitschrift für Biologie, 1913, lxi, pp. 155–182.

more circuitous paths and the area so blocked off can participate in contraction only when an impulse which has passed to other portions of the ventricle approaches it from another direction; this area thus in turn becomes the centre from which the progress of contraction is continued, to be in its turn diverted by other blocks. The existence of such blocks, and especially of blocks of transitory character and shifting location, has been noted in the experiments detailed above. These conditions make possible the propagation of the contraction wave in a series of ringlike circuits of shifting locations and multiply complexity. It is in these " circus contractions " determined by the presence of blocks, that we see the essential phenomena of fibrillation.

In small masses of tissue blocks may exist, but the time necessary for the impulse to traverse all available circuits is within the refractory period and the mass contracts as a unit and fibrillation is thus impossible. In larger masses this is not true, for the larger the mass the greater the possible number and length of the circuits, and the greater the probability that each impulse will circulate until it reaches tissue which has once contracted but has passed out of the refractory state; thus a continuous circulation of impulses is inaugurated, which is fibrillation. Such a mechanism would account for the greater liability of large hearts to fibrillate and for the greater persistence of the fibrillary state in large tissue masses.

It is conceivable that the establishment of relative differences in excitability and conductivity in different parts of the musculature without the condition of absolute block might result in the same phenomena of "circus contractions" and fibrillation. Thus inequalities in temperature or unequal action of such drugs as digitalis or barium salts may precipitate fibrillation in some such manner, although we venture the suggestion that the action of the latter. in inducing this state of inco-ordination will be found to lie in their well-known tendency to produce blocks. There is evidence at hand which indicates that this view of fibrillation is in complete harmony with the effects produced upon the fibrillary state by vagus stimulation.

## SUMMARY

The persistence of cardiac fibrillation is, other conditions being equal, directly proportional to the size of the tissue masses involved whether the pieces are cut from hearts already fibrillating or are faradically stimulated to start the process in them. The form of the tissue is important; for long narrow or thin pieces recover promptly, and narrow strips when connected with a fibrillating mass or when faradically stimulated do not fibrillate, but beat co-ordinately. Tissue rings cut from fibrillating hearts of marine turtles ceased fibrillating, but the contraction waves continued, repeating the circuit about the ring in co-ordinate " circus contractions." Sufficiently narrow bridges of any portion of the musculature of auricles or ventricles will prevent the extension of the fibrillary process and act thus like the auriculo-ventricular conducting bundle. When fibrillation is induced by localized faradization this locus may be subsequently excised, its inco-ordination will cease, just as will that of any other piece of similar size, while that of the remaining (larger) mass will continue, showing that the process, therefore, involves the whole tissue mass and is not sustained by impulses arising in any definite location.

The experiments support the block hypothesis and suggest that the blocks probably result in intramuscular ringlike circuits with resulting "circus contractions" which are fundamentally essential to the fibrillary process. Such ring circuits can exist in large masses but not in sufficiently small ones.