Observations on the Ventricular Dysrhythmia Associated with Atrial Fibrillation in the Dog Heart

By G. K. Moe, M.D., Ph.D., and J. A. Abildskov, M.D.

The mechanism of irregular ventricular responses to atrial fibrillation has not been established. If atrioventricular transmission occurred via a single path with uniform properties, ventricular cycle lengths would be governed by the refractory period of the path and the temporal pattern of the input supplied by the fibrillating atria. Since the frequency of stimuli available to the A-V conduction system during atrial fibrillation is undoubtedly high, activation of the system would be expected at, or shortly after, each moment at which the system became excitable. Only slight variation of ventricular cycle lengths would be expected under these circumstances. The gross irregularity of ventricular rhythm usually associated with atrial fibrillation excludes such simple behavior of the A-V transmission system.

It is known that the various ventricular cycle lengths which occur during atrial fibrillation are not uniformly distributed.1-3 Frequency distribution curves of ventricular cycle lengths often show multiple peaks indicating the more frequent occurrence of certain cycle lengths. This finding is further evidence of the structural and/or functional complexity of the A-V transmission system.

The phenomenon of incomplete penetration of the transmission system which has been called "concealed conduction" has been postulated to explain the ventricular irregularity during atrial fibrillation.1-2 It is evident that if occasional or frequent atrial impulses enter the node, penetrate it to varying depths, and leave a refractory wake, then the node will be left inaccessible to a later atrial input. In other words, the interval between two ventricular beats will be prolonged.

The present report confirms the nonuniform frequency distribution of ventricular cycle lengths during atrial fibrillation, characterizes some features of this distribution, and presents evidence that concealed conduction may well explain the distribution.

Methods

Dogs of both sexes, weighing from 8 to 16 kg and anesthetized with sodium pentobarbital were employed. Under artificial respiration, the heart was exposed through a midsternal incision and cradled in the open pericardium. Bipolar stimulating and recording electrodes were attached to the right atrium and similar recording electrodes to the right ventricle. Electrograms from the atrium and ventricle were simultaneously recorded with an ink-writing polygraph at a paper speed of 50 or 100 mm per second. In a few experiments, observations were made before and after stellectomy. The other observations reported were made after stellectomy. In three experiments observations were made on hearts perfused via the aorta from a donor animal; the right atrium and ventricle were opened to permit the application of electrodes near the atrial margin of the A-V node.

In each experiment, the maximal regular frequency of atrial stimulation which resulted in 1:1 atrioventricular transmission was determined. At this basic driving frequency, the "concealment" zone was determined; i.e., the range of time following the atrial refractory period during which a premature atrial response could enter the A-V transmission system but fail to emerge.4 The premature response was judged to be concealed if its presence resulted in significant conduction delay of a subsequent propagated response. For various positions of a concealed premature atrial response (A2), the minimum possible V1V2 interval was determined by scanning the nodal recovery period.
with an $A_3$ response. Ventricular cycle lengths of this value or longer were classified as "long cycles"; i.e., cycles likely to bracket or contain a concealed beat. Shorter ventricular cycle lengths were considered to be unlikely to contain a concealed response and were classified as "short" cycles. These criteria were applied to the classification of cycles during episodes of atrial fibrillation.

Atrial fibrillation was produced and maintained by applying stimuli of at least twice threshold intensity to the atrium at a frequency of 20 to 50 cycles/sec. During atrial fibrillation, atrial and ventricular electrograms were recorded for a sufficient period of time to include approximately 1000 ventricular cycles. The duration of each of these cycles was measured and the frequency distribution of cycle lengths (in classes differing by 20 msec steps) was plotted. The overall percentage of long cycles in the total population was calculated on the basis of the criteria outlined above. Other experimental manipulations are described in the appropriate sections of the results.

**Results**

1. **THE HYPOTHESIS**

   During atrial fibrillation the atrial input to the A-V transmission system may be expected to be rapid and irregular. As a working hypothesis it was assumed that under these circumstances: (1) the opportunity for concealed conduction will occur frequently; (2) a ventricular cycle bracketing one or more interpolated "concealed" beats is likely to be longer than one representing two successive complete passages through the A-V transmission system without such interpolation; (3) because of irregularity of the atrial input, the A-V node may be expected to be "hit" at various times during its absolutely and rela-
VENTRICULAR DYSRHYTHMIA

Ventricular dysrhythmia is characterized by the occurrence of irregular or abnormal rhythms in the ventricles of the heart. This can be due to various factors such as myocardial infarction, hypertension, or arrhythmogenic cardiomyopathy. Understanding the mechanisms behind these dysrhythmias is crucial for effective treatment and management.

The diagram illustrates schematically the transmission of two successive beats without an interpolated concealed beat, and two beats bracketing a concealed beat. It is assumed that extinction of an impulse between atrium and ventricle occurs when that impulse encounters refractory tissue and cannot penetrate further. It is also assumed that the refractory period of each element is a function of the immediately preceding cycle length (C).

The diagram shows the duration of primary concealment zone following the last of a series of driven beats at maximum 1:1 frequency compared with secondary concealment zone following a "long cycle" (ordinate, scale in msec). "Primary" indicates duration of concealment zone following propagated A-V; "A, early" indicates duration of concealment zone following propagated A-V when A was concealed as early as possible, and "A, late" indicates corresponding zone when A was concealed as late as possible.

The reasons for the first four assumptions are self-evident, and are in accord with previous conclusions about the behavior of the A-V transmission system. The fifth has been suggested previously. The reasons for the final assumption may not be immediately apparent, but will become clear by reference to the diagram of figure 1.

The diagram illustrates schematically the transmission of two successive beats without an interpolated concealed beat, and two beats bracketing a concealed beat. It is assumed that extinction of an impulse between atrium and ventricle occurs when that impulse encounters refractory tissue and cannot penetrate further. It is also assumed that in each of the elements of the transmission system the refractory period will be a function of the immediately preceding cycle length (C). For illustrative purposes we have chosen the empirical formula \( R = K \sqrt{C} \) to express this relation. When two successive complete transits of the system occur, the value of \( C \) is the same at all levels, and the value of \( R_a \) and \( R_b \) will therefore be determined by the value of \( K \) assigned to each level. In the example shown, we have chosen values which would provide a period of 50 msec during which concealment could occur (i.e., block at some junctional point within the system). When an impulse penetrates to this junction but not beyond, then the value of \( C \) for the proximal element of the node (\( N_a \)) will be short, and its refractory period will be shortened accordingly. The next impulse, which now traverses the...
whole system, will leave the proximal element refractory for a time determined by $K_a \sqrt{C_a}$, while the more distal element ($N_b$) will be refractory for a time determined by $K_b \sqrt{C_b}$. As $C_o$ exceeds $C_a$ the disparity between $R_a$ and $R_b$ will be greater than it was following two successive complete transits, and the opportunity for concealment of a subsequent beat will be enhanced.

This oversimplified schema is presented for conjectural purposes only; it does not accurately represent nodal behavior. For example, the model would develop a broader zone of concealment at the junction of proximal.

### Distribution of Ventricular Cycle Lengths Recorded During Atrial Fibrillation

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**Table 1**

Experiments are arranged in order of proportion of long cycles. Categories to left of dividing line are defined as short cycles, unlikely to contain concealed beats. Categories to the right represent cycles likely to include concealed beats. For each experiment, the upper horizontal row of figures indicates the distribution of cycle lengths; i.e., the per cent of the total population in each category. The last figure in each row includes longer cycles too few in number to be separately categorized. The lower row indicates the percentage of "long" cycles following each category.
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...mal and distal elements at slow than at high frequencies, whereas the opposite is true. Whatever the detailed nature of incomplete nodal penetration may be, it is still likely that when proximal elements are subjected to premature excitation from which more distal elements are protected, any pre-existing disparity of refractory periods at those levels will be increased following the next complete passage of an impulse. We propose, then, that concealment of impulses is a fundamental feature of nodal transmission during atrial fibrillation, and that the rules which pertain to the phenomena of concealed conduction must

|   | Columns at the right record the total number of cycles measured, the percentage of long cycles in the total population, and, where determined, the duration of the primary concealment zone. Data in this experiment obtained before (group A) and after (group B) stellectomy. Figures in parentheses represent percentages based on arbitrary definition of long cycles as 440 msec or more. In fact, all cycles of 360 msec or more were “long,” comprising 99.3% of the population. |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 440 | 460 | 480 | 500 | 520 | 540 | Total cycles | % L.C. | Conc. zone |
| 3.4 | 3.2 | 2.4 | 1.4 |   |   | 978 | 43 |   |
| 77 | 96 | 95 | 95 |   |   | 1481 | 48 | 60 |
| 1.3 | 8 |   |   |   |   | 973 | 50 |   |
| 77 | 81 |   |   |   |   |   |   |   |
| 2.6 |   |   |   |   |   | 1773 | 56 | 45 |
| 2.2 | 1.6 | 1.7 |   |   |   | 1964 | 58 |   |
| 93 | 78 | 88 |   |   |   |   |   |   |
| 3.3 | 1.8 | 2.0 |   |   |   | 1849 | 59 | 65 |
| 69 | 68 | 68 |   |   |   |   |   |   |
| 4.8 | 3.2 | 2.5 |   |   |   | 1352 | 60 |   |
| 82 | 84 | 84 |   |   |   |   |   |   |
| 3.9 | 2.2 |   |   |   |   | 1434 | 70 |   |
| 89 | 78 |   |   |   |   |   |   |   |
| 5.9 | 4.5 | 2.8 | 9.4 |   |   | 1392 | 70 | 90 |
| 72 | 73 | 81 | 82 |   |   |   |   |   |
| 6.8 | 3.6 | 5.4 | 4.0 | 2.4 | 9.5 | 1291 | 72 | 70 |
| 77 | 79 | 76 | 84 | 90 | 76 |   |   |   |
| 7.0 | 5.6 | 3.9 | 8.4 |   |   | 1377 | 80 | 70 |
| 84 | 78 | 89 | 88 |   |   |   |   |   |
| 6.3 | 5.4 | 2.8 | 4.5 |   |   | 1126 | 78 |   |
| 86 | 87 | 84 | 88 |   |   |   |   |   |
| 13.6 | 14.1 | 6.9 | 4.9 | 7.7 |   | 1139 | 89 | 80 |
| 85 | 89 | 91 | 89 | 94 |   |   |   |   |
| 11.6 | 12.2 | 7.8 | 7.3 | 5.5 | 5.4 | 13.2 |   |   |
| 93 | 94 | 97 | 93 | 93 | 100 | 100 |   |   |
| 9.6 | 10.8 | 9.1 | 8.5 | 6.2 | 6.7 | 5.1 | 3.5 | 16.4 |   |
| (74) | (82) | (83) | (72) | (74) | (87) | (80) | (74) | (74) | 1187 | (77) | 145 |

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exert a predictable influence on the output of the node during the arrhythmia.

2. EFFECT OF A "CONCEALED BEAT" CYCLE UPON SUBSEQUENT EVENTS

To test the postulate schematized in figure 1, the experiments illustrated in figure 2 were done. After bilateral stellectomy, driving stimuli were delivered to the right atrium at the maximum frequency which permitted 1:1 transmission to the ventricles. The duration of the concealment zone (the period of time during which a premature atrial response, \( A_2 \), would fail to reach the ventricles) was measured and recorded as the "primary" concealment zone. After a series of 8 to 10 regular driving pulses, the premature \( A_2 \) response was initiated early in the primary concealment zone, and a subsequent atrial response, \( A_3 \), was evoked at a time which allowed passage to the ventricles and yielded the shortest possible \( V_1V_3 \) interval. Following the propagated \( A_3V_3 \) response, the "secondary" concealment zone was determined by scanning with yet a fourth serial stimulus, evoking nonpropagated \( A_4 \) responses. The procedure was repeated when \( A_2 \) was placed as late as possible in the primary concealment zone. The duration of the secondary concealment zone was not significantly greater than the primary zone when \( A_2 \) was placed as early as possible, but was always conspicuously prolonged when \( A_2 \) was late.

The duration of the secondary zone was dependent not only on the temporal position of the concealed \( A_2 \) response, but was also influenced by the placement of the propagated response, \( A_3 \). This is illustrated in part B of figure 2, in which the spacing of \( A_1A_2 \) was constant (\( A_2 \) as late as possible for concealment). The secondary concealment zone, recorded for four different positions of \( A_3 \) (\( A_1A_3 \) intervals from 365 to 415 msec), was maximal when \( A_2 \) was early, and was sharply reduced as \( A_3 \) was progressively delayed.

The experiments illustrated by figure 2 indicate that a cycle "containing" a concealed beat does indeed leave the transmission pathway in a condition which increases the chance of secondary concealment; i.e., a long ventricular cycle is more likely to be followed by another long cycle than is a short cycle. The data also indicate that the chance of concealment in the cycle following a primary concealed beat cycle is greater when the \( A_2 \) response is late, i.e., a relatively long \( V_1V_3 \) interval is more likely to be followed by a second concealed beat cycle than is the shortest possible \( V_1V_3 \) interval. With this information available, the records of episodes of atrial fibrillation were examined to determine whether the same conditions could be operative when the atrial input to the node was rapid, irregular, and uncontrolled. It must be emphasized at this point that the criteria for classifying ventricular cycles as long or short were established at regular, though rapid, driving frequencies. We cannot be certain, therefore, that the same criteria can be rigidly applied when the nodal input is uncontrolled. Some of the cycles classified as short may include concealed beat cycles, and some of those judged to be long may not, but clearly the chance that a given cycle includes a concealed response must increase with the cycle length. With this reservation in mind, the analysis described below was undertaken.

3. INFLUENCE OF LONG CYCLES UPON SUBSEQUENT CYCLES

According to the assumptions discussed above, long cycles should be preferentially followed by long cycles. This hypothesis was tested in the experiments listed in table 1. The data have been divided arbitrarily into two groups depending upon the incidence of long cycles.

In the experiments of group A, the minimum short cycles observed ranged from 220 to 240 msec, and the minimum long cycles ranged from 280 to 300 msec. Long cycles represented 43 to 70% of the total population. In group B the minimum cycle lengths were longer, 260 to 340 msec; the minimum long cycle length was 320 to 360; and long cycles represented 73 to 99% of the population.

These experiments were analysed by determining, for each category of cycle lengths in the distribution curve, the relative incidence of long cycles immediately following. The
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percentage of cycles in each category and the percentage incidence of long cycles following are listed in the horizontal rows for each experiment in the table. For example, in the experiment of 12/15/58, cycle lengths of 280 msec or more were judged to be long; 48% of the population fell into this class. There were 25 cycles in the category 220, representing 1.7% of the total population of 1481 measured cycles. Of these 25, only one (4%) was followed by a long cycle. In the category 300, 78 cycles were recorded and 67 of these, or 86%, were followed by long cycles.

A composite graphic representation of all the data listed in the table is shown in figure 3 (A and B). In figure 3 (A), the mean frequency distribution curves for group A and group B are separately plotted on an adjusted time scale. The vertical dividing line at zero represents the cutoff point between long and short cycle categories; deviation from the boundary to the left or right is indicated on the abscissae as — or + in msec. The average incidence of short cycles was 42% in group A and 15% in group B.

The incidence of long cycles following cycles of each category in the distribution curve is plotted in figure 3 (B). For group A, the average incidence of long cycles in the total population of all experiments is indicated by the horizontal line drawn at 58%. Following cycles in the shortest category (—50 msec), the observed incidence of long cycles was 31%; long cycles followed this category little more than half as frequently as would be expected on the basis of random occurrence. The incidence of following long cycles increased progressively with the cycle length to reach a plateau at about +50 msec; long cycles followed long cycles considerably more often than expected for random occurrence. The homogeneity of the data in this respect can be seen by inspection of the data in table 1, and it is indicated in the figure by the vertical brackets which encompass ± one standard deviation. It appears, then, that under the conditions of these experiments the hypothesis is supported; i.e., long cycles favor the genesis of succeeding long cycles.

The data for the experiments classed as group B are similarly plotted about a horizontal line which indicates the average incidence of long cycles at 85% of the total population. Although the curve suggests a similar trend, it does not deviate from the random standard by as much as 10% at any point; as deviations of this magnitude were not significant, the range has not been indicated. In all the experiments of group B, the minimum cycle length observed at maximum 1:1 A-V driving frequency was in excess of 250 msec, and the incidence of long cycles was in excess of 70% in every instance, with a mean value of 85%. In other words, nearly all the cycles were long; i.e., nearly all contained concealed beats. Since our initial premise was that a long cycle should favor the

![Figure 3](http://circres.ahajournals.org/)

A. Mean frequency distribution curves of cycle lengths in experiments of groups A and B of table 1; data adjusted to common scale. Ordinate scale, % of total population; abscissa, deviation from short-long boundary in msec. Short cycles to left, long cycles to right of vertical dividing line. B. Incidence of long cycles following cycles in each category. Mean incidence of long cycles in group A indicated by horizontal line at 58%; group B, horizontal line at 85%. Vertical brackets include ± one SD. Abscissa, same as part A; ordinate scale, per cent incidence.

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occurrence of a subsequent long cycle, it is obvious that in a population consisting almost entirely of long cycles, no major deviation from the random could be expected.

At the stage of analysis at which the above relationships became apparent, it was also evident that when the concealment zone was long (relative to the atrial input cycle lengths), the A-V node was likely to be "hit" during its extinction zone every time the opportunity presented; i.e., nearly all cycles should be long. Unfortunately, the dimensions of this zone had not been delineated in each experiment. For those in which the information was available the data are listed in the last column of table 1. The data are too few to permit a correlation, but it is evident that the duration of the concealment zone is not the sole determinant of the incidence of long cycles.

4. ADRENERGIC INFLUENCES

Sympathetic denervation of the heart prolongs the functional refractory period of the A-V transmission system, increases the A-V conduction time, and increases the ease with which concealed conduction may be demonstrated; i.e., it increases the duration of that interval following a propagated response during which a premature atrial response can be initiated without propagation to the ventricle. It should therefore be expected that the minimum ventricular cycle length observed during atrial fibrillation should be increased by stellectomy, that the distribution of ventricular cycle lengths should be shifted to the right and broadened, and that the incidence of "long" cycles, indicative of increased numbers of concealed beats, should increase.

The effect of stellectomy upon the distribution of ventricular cycle lengths is illustrated in figure 4 (A). Before sympathetic denervation, the cycles were narrowly distributed about a peak at 220 msec. More than 80% of the cycles fell within the range of 180 to 240 msec. In this experiment the ventricular cycle length at the maximum 1:1 A-V driving frequency was 180 msec, which coincides with the minimum cycle length observed during the induced fibrillation. The minimum cycle length containing a concealed beat when the atria were driven at maximum 1:1 A-V frequency was found to be 240 msec, or 60 msec more than the minimum duration of "short" cycles. When that figure is chosen as the minimum "long" cycle length, about 40% of the cycles can be considered to contain an intervening concealed beat. After sympathectomy the primary peak and the minimum short cycle were shifted to the right. The

![Graph](image-url)

**FIGURE 4**

Adrenergic influences on the frequency distribution of ventricular cycle lengths during atrial fibrillation.

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minimum long cycle was 290 msec, and 58% of the population were therefore classified as long cycles.

The effect of epinephrine infusion upon the distribution of ventricular cycle lengths is illustrated in fig. 4 (B). The control data (broken line) were obtained after sympathectomy. The minimum long cycle, determined at maximal 1:1 driving frequency, was 340 msec, and nearly 90% of the population were of this length or longer. No cycles of less than 260 msec were recorded. Epinephrine reduced the minimum cycle length to 200 msec, and shifted the distribution curve to the left. About 80% of the population were in the range of 200 to 260.

Prior to sympathectomy, or in the presence of epinephrine, the earliest possible atrial premature beat, even at the maximal 1:1 driving frequency, was usually propagated to the ventricle; i.e., there was no concealment zone under these circumstances. Accordingly it was usually impossible to determine the minimum duration of a long cycle. The curves of figure 4, however, indicate that deprivation of adrenergic influences, which leads to prolongation of the concealment zone, also causes an increased range of ventricular cycle lengths during atrial fibrillation.

5. CALCULATION OF ATRIAL INPUT FREQUENCY

We have called attention to the probability of A-V nodal extinction of impulses in relation to the duration of the concealment zone and the atrial input frequency. It should be possible to estimate the latter when the former is known, and when the incidence of long cycles is also known. The details of this assumption were analysed in the experiment illustrated in figure 5.

In this experiment, the zone of concealment was recorded while the heart was driven from the right atrium at a basic cycle length of 260 msec, close to the maximum possible 1:1 frequency. Under these conditions the atrial refractory period was 150 msec; an atrial response initiated at this moment was demonstrated to penetrate the node without traversing it. The latest concealed atrial response was recorded at 210 msec; the concealment zone was therefore 60 msec. When $A_2$ was concealed and $A_3$ propagated, the shortest possible $V_1V_2$ interval was found to be 325 msec. Following such a concealed beat cycle, a secondary concealment zone of 145 msec was recorded. When $A_4$ was concealed as early as possible, the minimum possible $V_2V_5$ interval was 280 msec. It was therefore assumed that a ventricular cycle of 280 msec or more occurring during induced atrial fibrillation was likely to "contain" a concealed nodal penetration, and was therefore a long cycle, while cycles of less than 280 msec were classified as short cycles.

After assessment of the range of concealment under controlled conditions, the atria were caused to fibrillate, and nearly 1500 successive ventricular cycles were recorded. In this series, 48% of the population were 280 msec or more, and were therefore classified as long cycles. It was assumed that when four successive short cycles occurred, the node
would be left in a state comparable to that obtaining during maximal 1:1 driving, and that it should therefore be vulnerable to entry without propagation to the ventricles during a period of 60 msec; i.e., from 150 to 210 msec after the last successful atrial input. In other words, if an atrial input impulse occurred during this period, it should enter the node and die as a concealed beat, and the corresponding ventricular cycle should therefore be 280 msec or more in duration.

Short cycles in this record occurred frequently in bursts of four or more. (A run of six short cycles would comprise three series of four, namely, one to four, two to five, and three to six, of which the first two series are followed by short cycles and the last by a long cycle). A total of 299 runs of four were counted, of which 86% were followed by short cycles. Under these circumstances, it follows that after a previous nodal entry an atrial input to the node was available during the period 150 to 210 msec only 14% of the time.

These data permit an estimate of the range of atrial input frequencies as diagrammed in figure 5. In this schema, the abscissae represent the time in msec following the last successful penetration of the atrial margin of the node. The node itself is assumed to be refractory up to 150 msec, and to be available for penetration without passage from 150 msec to 210 msec (i.e., concealment zone of 60 msec). The ordinates represent hypothetical atrial input cycle lengths. The diagonal lines labelled A2, A3, and A4 represent the occurrence of a second, third, and fourth atrial input, following a primary response (which traversed the node) at time zero. If the average atrial cycle length were 105 msec or less, an A3, or A4, atrial impulse would fall within the nodal concealment zone; if it were between 150 and 210, there would be an atrial impulse A2 available for concealment; but if atrial cycles fell in the range of 105 to 150, atrial inputs would occur when the node was refractory (A2) or when it was capable of complete transit (A3), but no input would be available during the concealment zone. The recorded incidence of short cycles following a run of four short cycles was 86%; therefore, 86% of the atrial input cycles under these conditions can be assumed to have fallen in the range of 105 to 150 msec.

The same record was also examined for the incidence of long cycles following long cycles. As it was established earlier that the concealment zone was increased to 145 msec following a concealed beat cycle, it follows that if 86% of the input cycles are in the range of 105 to 150 msec, then input impulses should be available during the secondary concealment zone at least 86% of the time, and therefore 86% of the corresponding ventricular cycles should be long. As itemized in table 1, (expt. 12/15/58) cycles of 300 to 360 msec were followed by long cycles approximately 90% of the time. Similar analysis in another experiment yielded the estimate of 59% of effective atrial input cycles in the range of 87 to 110 msec.

In the example chosen for illustration in figure 5, 86% of the atrial input cycles appear to fall in the range of 105 to 150 msec. This is little shorter than the range of cycle lengths at which the atria can follow repetitive stimulation without degenerating into fibrillation. When first observed, this appeared to be a paradox, for we had conceived of fibrillation as a completely fractionated dysrhythmia in which closely adjacent fibers (or groups of fibers) were out of phase. Histological study of the atrionodal junction indicates a fimbriated junctional area in which many atrial fibers appear to intermingle and make effective contact with A-V nodal cells.

Fractionated activity at the junctional area should provide a very rapid input. Let us suppose that four such contacts exist, each of which responds at an average frequency of 10/sec. If these four contact points were completely out of phase with each other, then the average input frequency to the A-V transmission system should be, not 10/sec, but

* Cycles longer than 210 msec, under the conditions of these experiments, would be extremely unlikely.
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40/sec. At an input frequency of this magnitude, nearly all of the ventricular cycles in the experiment described above should have been "long"; i.e., there should have been an atrial input impulse available within each successive "concealment zone." There are, of course, some assumptions inherent in these statements. First, it cannot be asserted that the concealment zone is accurately measurable. The zone, as measured, is limited at its proximate margin by the atrial refractory period. It is, however, unlikely that the atrial margin of the node has a shorter refractory period than atrial muscle. It is also presumptive that the fimbriated insertion of atrial muscle into A-V nodal tissue should be capable of fractionation. It is, furthermore, presumptive that the dysrhythmia produced by 50/sec stimulation of the atrial appendage is truly fibrillation.

Turbulent activity, with gross temporal dispersion of excitation and recovery in closely adjacent fibers, may be expected to take place in the neighborhood of the stimulating electrodes when stimulation at a frequency of 50/sec is applied to the atria. It does not follow that comparable turbulence and dephasing exist in more remote regions. In other words, it is possible that the atrial input to the node in the experiments described above was slower and more regular than indicated by electrograms recorded near the stimulating electrodes on the right atrial appendage.

This possibility was examined in three experiments in which the right atrium was opened to permit attachment of recording electrodes to the atrial margin of the node. The electrodes, bipolar steel needles about 1 mm apart, recorded atrial activity close to the area of nodal entry; they were remote from the stimulating electrodes through which atrial fibrillation was induced and maintained. While repetitive excitation of the atrium was continued at a frequency of 50/sec, and the atria appeared to be fibrillating, the electrodes attached to the endocardial atrial surface near the A-V node recorded frequent episodes of flutter-like activity at a frequency of about six to seven per second, alternating with episodes of very irregular activity suggesting fractionation of the nodal input at a considerably higher frequency. The tracing of figure 6 was excerpted from one of these experiments. While the atrial activity (upper trace) was of relatively low frequency, the ventricular rate was rapid; ventricular cycle lengths were about 300 to 320 msec. While the atrial input was fractionated and grossly irregular, and the effective nodal input frequency must have been correspondingly increased, the ventricular rate was slower (cycle lengths 390 to 500 msec). These experiments support the conclusion that a rapid input frequency increases the probability of concealment and accordingly reduces the average ventricular frequency.

From these considerations it becomes apparent that, as a general rule, the probability of concealment will be directly proportional to the duration of the concealment zone ($Z_c$), and inversely proportional to the mean atrial
input cycle length \((C_a)\); i.e.,

\[
P = K \frac{\bar{Z}}{C_a}
\]

Theoretically, the probability should also be dependent upon the absolute refractory period, \((RP)\), of the A-V node, for this will determine the exact multiple of the input cycle length which may impinge upon the concealment zone. Since neither the value of \(C_a\) nor the value of \(Z\) can be constant during fibrillation, but must be distributed within limits about mean values, it follows that the value of the absolute refractory period of the A-V node assumes lesser importance. At any rate, the relationship points out the important, though obvious, fact that the incidence of "long" cycles in the ventricular spectrum should be increased (and the mean frequency of the ventricles therefore reduced) by any agency which increases the effective atrial input frequency or increases the duration of the concealment zone.

6. EFFECT OF VAGAL STIMULATION ON VENTRICULAR CYCLE LENGTHS

It is well established that increased vagal activity reduces the ventricular frequency during atrial fibrillation. Ventricular slowing is commonly attributed to a prolongation of the A-V nodal RP; but vagal stimulation increases the duration of the concealment zone and, by reducing the atrial refractory period, must also increase the mean atrial input frequency during fibrillation. Three experiments were performed to examine the relative importance of these several factors in determining the ventricular frequency.

The frequency distributions of ventricular cycle lengths at several levels of vagal activity during atrial fibrillation are plotted in figure 7. The control data were obtained after bilateral cervical vagotomy. No cycle lengths of less than 180 nor more than 440 msec were recorded, and the curve is skewed toward the short end of the spectrum with a sharp peak at 220 msec. During right vagal stimulation at three and five cycles per second, the incidence of longer cycles increased, but short cycles were still present in both runs. No cycles of less than 200 msec were recorded, but the minimal cycle length was increased only 20 msec by vagal stimulation. In other words, the functional refractory period of the A-V transmission system (i.e., the shortest possible interval between two beats propagated from the atrium) was only slightly increased. It can be concluded that the reduction of average ventricular rate resulted, not from an increased nodal RP, but from the increased duration of the concealment zone and the increased atrial input frequency.

Vagal stimulation at a frequency of 10 cycles/sec shifted the distribution curve still further to the right; cycles of more than one second duration occurred, but no cycles of less than 280 msec were recorded.

Discussion

The results reported are consistent with the occurrence of concealed conduction as a major factor in determining the pattern of ventricular responses to atrial fibrillation. Theoretic considerations which have been
presented indicate that if concealed conduction is such a factor, cycles containing a concealed impulse may be expected to be followed by similarly long cycles with greater than random frequency. Experimental findings showed a definite tendency for an increasing percentage of cycles likely to contain a concealed beat to follow cycles of increasing length. This tendency was exhibited as a gradual increase which probably reflects overlap of cycles with and without concealed impulses. The experimental determination of the minimum ventricular cycle length containing a concealed impulse which was employed in this study may not represent the shortest possible cycle length containing a concealed impulse under the conditions of atrial fibrillation. In other words some of the cycles which for the purposes of this study were not considered to contain concealed impulses may actually contain such impulses. It is likely, however, that few if any of the briefest cycles contained concealed impulses, while a progressively increasing proportion of concealed beat cycles should occur with increasing cycle lengths.

The dependence of nodal behavior upon immediately preceding events demonstrated in these experiments suggested the possibility that a given set of events might exert an influence lasting beyond the succeeding cycle. If this were true, the technique of autocorrelation should expose the relationship. A preliminary assessment was made "by hand" on a limited sample in one experiment. As expected, there was a relatively high correlation between the duration of one cycle and that of its successor, but no significant relationship persisted beyond the immediate successor. The autocorrelation of ventricular intervals in patients with atrial fibrillation reported by Braunstein and Franke revealed a correlation lasting through several cycles, and with a basic period approximating the normal heart rate. It is possible that a more thorough application of the technique to the material presented in the present study would also expose a longer lasting relationship.

As expected, deprivation of adrenergic influences on the heart increased the likelihood of concealment, and also decreased the mean ventricular frequency. In some of the animals subjected to thoracic sympathectomy, more than 90% of the ventricular cycles recorded during atrial fibrillation were classified as long cycles. Redistribution of cycle lengths during exercise, with presumed increased sympathetic and decreased vagal discharge to the heart, was noted by Söderström.

Vagal stimulation, which also decreased the mean ventricular frequency, appeared to do so by increasing the mean atrial input frequency and by increasing the duration of the concealment zone, rather than by simply prolonging the A-V nodal RP. In line with this conclusion, it was shown that the ventricular frequency was less when the atrionodal input frequency was fractionated and rapid than when it was slower and more or less regular. It is possible of course, that the fractionated and asynchronous atrial input was incapable of penetrating the node; this would be likely if summation were necessary for nodal entry. Intracellular recordings of single nodal unit action potentials during application of acetylcholine do not indicate prolongation of the nodal RP, and it appears that the filtering function of the node is not due to atrionodal block, but rather to decremental conduction or block (i.e., concealed conduction) within the node.

It can be concluded that the probability of concealment of impulses within the node during atrial fibrillation is a direct function of the average duration of the concealment zone, and an inverse function of the mean atrial input cycle length.

In the observations recorded above, the peaks in the frequency distribution of ventricular cycle lengths did not coincide with the ranges observed for one or more concealed beats. In other words, considerable overlap occurred between ventricular "short" cycles (no concealed beats) and "long" cycles (one or more concealed beats). If the atrial input is rapid, all cycles should "contain" concealed beats; if the atrial input is relatively slow (of the order of 10 or less per second), most cycles should be short. But if the atrial input
is at one time fast and fractionated and at another slow and regular, the incidence of long and short cycles should be expected to overlap. Similarly, there should be fusion of distribution curves representing cycles containing two concealed beats with those representing one or three serially concealed beats. If all these distributions are skewed, the overall distribution curve must become complex indeed.

Summary

The distribution of ventricular cycle lengths and the incidence of "long" cycles were studied during episodes of atrial fibrillation induced by electrical stimulation of the right atrium in exposed dog hearts. It was concluded that the ventricular dysrhythmia can be interpreted in terms of concealed conduction. Long cycles (bracketing one or more responses concealed in the A-V node) tend to favor the occurrence of subsequent long cycles. The probability of occurrence of long cycles is shown to be a function of the duration of the "concealment zone" and of the atrial input frequency.

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