Characteristics of Reflection as a Mechanism of Reentrant Arrhythmias and Its Relationship to Parasystole

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SUMMARY A model of "reflection" was developed in a sucrose gap preparation of Purkinje fibers. In this preparation, a driven impulse on the proximal side of a sucrose gap is electrotonically transmitted after a delay to the tissue distal to the gap. When the delay is long enough, electrotonic transmission in the reverse direction over the same blocked segment can reexcite the proximal segment. Frequency-dependent alterations of patterns of ectopic activity were qualitatively similar to those of a parasystolic model and to those described in previous in vivo demonstrations presumed to represent circus movement reentry. Moderate changes of frequency or in the degree of block were shown to convert a manifest bigeminal rhythm to a trigeminal or more complex rhythm with or without intervening periods of silence. Our observations suggest that reflection and parasystolic pacemaker activity are examples of a continuous spectrum of ectopic impulse generation.

ECTOPIC IMPULSE FORMATION in cardiac tissue must be caused either by reentry or pacemaker activity, but each mechanism has subclasses. The term reentry usually implies a circuit— one-way block in one of two parallel pathways permits passage of an impulse over one pathway, and a retrograde passage of the same impulse, after a conduction delay, over the other pathway. But another kind of reentry, to which the term "reflection" has been applied,\(^1\)\(^2\) can be readily demonstrated in isolated bundles of cardiac tissue. For example, in a false tendon in which an area of depressed conductivity has been induced by current pulses of long duration, as in the experiments of Wannemark et al.,\(^3\)\(^4\) or by the impedance of a sucrose gap,\(^5\) a driven response at one end of the fiber may induce a response beyond the area of block, but only after a delay so long that recovery of excitability has already occurred in the driven side, permitting a recurrent response (or reentry) of the driven end. Reflected responses have been observed in Purkinje fiber preparations exposed to high K\(^+\) by Wit et al.\(^6\) They also appear to occur in cultured strands of chick heart tissue.\(^6\)

The term reflection has previously been used to describe reentry in a linear bundle of conducting tissue, with the implication that a circuitous pathway at the microscopic level might be responsible.\(^1\)\(^2\) In the context of the present study, electrotonic transmission across an inexitable segment of tissue is more likely than a microcircuit in the depressed area, particularly in the sucrose gap experiments. This possibility was suggested to us by C. Mendez (personal communication), and has been briefly considered by Cranefield.\(^3\)

Pacemaker activity is, of course, an inherent property of the specialized conducting tissue of the ventricle, requiring only the protection of entrance block to permit its occasional expression in the form of parasystolic arrhythmias, or a sufficient elevation of its intrinsic frequency to become the dominant pacemaker, as in an episode of ventricular tachycar-
Pacemaker activity can also be triggered, as, for example, after exposure to moderate concentrations of cardiac glycosides, and by other, usually voltage-dependent, mechanisms.9,10

In sucrose gap preparations of Purkinje fibers, conditions exist, or can be developed, in which the reflection type of reentry (hereafter referred to as reflection) and a model of parasystolic impulse generation can occur in the same preparation. The experiments in this report were conducted to show the similarities of the two basically different mechanisms and the patterns of arrhythmia that may be generated by simple manipulations that switch the preparation from one set of conditions to the other.

Methods

The experimental procedure was essentially the same as described previously.5,12 Unbranched, free-running, false tendons were dissected from dog or calf ventricles and were placed in a three-chambered tissue bath. After an equilibration period of at least 1 hour, the central chamber was perfused with isotonic sucrose solution or, in a few experiments, high potassium (15 mM) to induce a region of conduction block. The outer chambers were perfused with Tyrode's solution containing 3.0 or 4.0 mM KCl.

Most preparations were driven electrically using one of two pairs of thin silver electrodes insulated except at their tips, applied close to the cut ends of the fiber segments in the outer chambers. Stimuli were rectangular 0.5−3-msec pulses delivered to either side of the preparation. Simultaneous records of transmembrane potentials were obtained from cells in the two active chambers as previously described.5,12

Modulation of the extracellular impedance and thus the extracellular flow of current was achieved by shorting the sucrose gap resistance with an external pathway (0−200 kΩ) placed in parallel.12,13 In some experiments compensatory pauses were artificially induced by altering the stimulation sequence.

Previously,12,14−16 17 we have used the terms SN to represent a simulated ventricular chamber responding to regular impulses of sinus nodal origin, and EP to refer to an ectopic pacemaker. These designations are not appropriate in the present context, and we have substituted the noncommittal terms proximal (P) and distal (D) to indicate the respective fiber segments in relation to the area of impaired conductivity (sucrose gap). The proximal segment in the model is analogous to the ventricle, subjected to rhythmic excitation from a normal pacemaker, and the distal segment is analogous to a protected ectopic pacemaker (when such activity was permitted), or to a site of reflection or microreentry when significant pacemaker activity was absent or suppressed.

Results

Characteristics of Reflection

When two ends of a strand of Purkinje tissue (false tendon) are separated by a short segment in which conductivity has been blocked by perfusion with an isotonic solution of sucrose, the intracellular channels permit the expression of electrotonically generated changes of membrane potential across the gap, even though actual propagation of an impulse cannot occur. If the segment in the distal chamber is induced to develop pacemaker activity, by reduction of [K] in the perfusate and by addition of epinephrine, the progressive increase in membrane resistance during phase 4 depolarization increases the length constant of the fiber, and thus progressively increases the amplitude of electrotonic depolarizations accompanying responses evoked in the tissue proximal to the gap.4,6 Electrotonic depolarizations occurring early in the pacemaker cycle of the distal segment delay the next discharge. When the membrane potential approaches threshold, and the amplitude of the depolarization increases sufficiently, the discharge of the pacemaker is accelerated or, in effect, captured. These characteristics of the preparation, which make it a suitable model of parasystole,5,6,12 are illustrated in figure 1A. Under these conditions the gap impedance was 12 kΩ; only electrotonic influences were propagated across the gap in either direction. The intrinsic pacemaker cycle of the tissue in the distal chamber (lower trace) was 1350 msec. The pacemaker was modulated by responses evoked in the proximal segment (upper trace), but impulse propagation did not occur in either direction. When the gap was shunted by an external resistor of 5 kΩ, the axial current flow through the tissue in the blocked area was increased, and the conditions for one-way conduction were established. Responses generated in the pacemaker segment could now be propagated, after a considerable delay, back to the driven end of the fiber as interpolated discharges (identified with stars in fig. 1B, upper trace). When the shunt resistance was further reduced, propagation of impulses in the reverse direction was also possible; 1:1 transmission from P to D occurred with a conduction interval of 100−200 msec (fig. 1C).

When impulse propagation occurs across the sucrose gap, the possibility of reflection exists. This requires “fine tuning” of the preparation, for the sum of the delays from P to D and from D to P must exceed the refractory period of the tissue in the proximal chamber. An example of reflection is shown in figure 2A. Conduction time to D from the driven response in P was 290 msec, and the corresponding interval in the reverse direction was 100 msec; the resulting coupling interval in P was 390 msec. The two conduction intervals do not represent slow propagation of an impulse in both directions in the same tissue; there could not be enough inward current within the ion-depleted region to support an active response. The sequential delays are imposed by the passive RC properties of the system accompanying the axial current flow first from P to D, then from D to P. If the RC time constant is too long (high external shunt resistance), the electrotonic depolarization in D will not reach threshold and the reflection will fail (fig. 2B). If the time constant is too brief (low shunt resistance), D will reach
successive capture will occur at approximately the same level of membrane potential of the fibers in the test compartment. Accordingly, the coupling interval will be approximately constant at a value determined by the functional refractory period of the tissue that receives the reciprocal impulse. Any response of the driven segment (P) falling later in the course of slow diastolic depolarization in D would be propagated from P to D with a briefer conduction interval, would always fall within the refractory period of P, and would therefore fail to generate a reciprocal response in P. Although exceptions to this rule are common, reflected responses often occur as closely coupled responses.

The Role of Refractoriness and Supernormality

For reflection to succeed, there must be an adequate conduction delay in the P -> D direction; i.e., there must be first-degree entrance block. The magnitude of the delay and the successful completion of a to-and-fro reciprocation depend critically on the precise degree of conduction impairment. The degree of block depends on the impedance of the segment within the gap, on the amplitude of the electrotonic stimulus relative to the excitability of the tissue beyond the gap and on the extracellular impedance of the system.

An experiment designed to illustrate the influence of some of these variables on the conduction interval from one segment to the other is illustrated in figure 3. The upper trace, P, was derived from the proximal side of the preparation, driven at a cycle length of 2100 msec. The lower trace, D, was recorded from a spontaneous pacemaker beyond the gap. Complete entrance block was present; only electrotonic modulation of the pacemaker was permitted to pass from P to D, but propagation from D to P was possible. The preparation functioned as a model of a parasystolic focus, but the examples in this figure permit an appraisal of the conductivity of the exit pathway; qualitatively, the characteristics of conduction across the sucrose gap apply also to propagation in either direction in the reflection model.

In figure 3A, the first driven response in P induced a subthreshold electrotonic depolarization in D and delayed the pacemaker response. Propagation of the spontaneous discharge back to P occurred promptly, with a delay of only 12 msec. The spontaneous responses recorded in figures 3B, C and D occurred progressively earlier in the driven cycle of the proximal segment, and were propagated with progressively greater delays. The coupling interval between the driven and ectopic responses reached in panels C and D was about 675 msec. An earlier response (fig. 3E) failed to cross the conduction barrier, but the still earlier response in F encountered a phase of supernormal excitability in P, and caused a response with a much briefer coupling interval (385 msec) than that recorded in C or D. The early spontaneous discharge in panel G encountered refractoriness in the proximal segment, and did not emerge.

Supernormality was not a constant feature of our
preparations, but when present it had an obvious effect on the recorded patterns of ectopic activity. The experiment shown in figure 3 represents a variant in which a relatively refractory gap followed the supernormal phase. Figure 4A illustrates a more common situation. In this example, regular driving stimuli (P1) were followed at intervals by premature stimuli (P2), both applied to the P side of the preparation (top trace). The graph relates the P1P2 conduction intervals across the gap to the P1P2 intervals on the driven side in a preparation exhibiting a pronounced supernormal phase. The relatively refractory period (P1P2 intervals between 390–425 msec) fused smoothly with a supernormal phase extending to about 520 msec, after which the conduction delays for P1D1 and P2D2 became equal at about 60 msec. The conduction time during the supernormal phase reached a minimum of little more than 30 msec at a P1P2 interval of 480 msec.

In most of the preparations, full recovery of excitability, expressed as conductivity across the blocked segment, did not occur until well after full repolarization; that is, a relatively refractory phase long outlasted action potential duration, particularly at higher driving frequencies. This was apparent in the experiment of figure 3, but it may occur without the complications of supernormality and conduction gaps. The example illustrated in figure 4B was taken from a preparation of calf Purkinje fibers driven at a cycle length of 2000 msec. The preparation was shunted by 30 kΩ. There was no phase of supernormality, but full recovery of conductivity had not been reached before 800 msec. These several patterns of recovery are greatly influenced by the basic driving frequency, and the patterns of manifest ectopic activity are therefore highly dependent on frequency.

Frequency dependence is illustrated in figure 5. In panel A, reflection was present on a 1:1 basis when the driving cycle in P was 1785 msec (upper trace). The manifest pattern of ectopic activity was a bigeminal rhythm in the proximal segment. The P-to-D conduction interval ranged from 340 msec at the start of the panel to 420 msec at the end, and the coupling interval was approximately fixed at 450 msec. In panel B, the

**Figure 2.** Reflection and its modulation by variation of external shunt resistance. The top and middle traces are recordings from proximal (P) and distal (D) segments. Bottom trace is stimulus marker. Pacemaker activity was very slow (intrinsic cycle length of pacemaker in distal segment 5500 msec). Panel A is an example of reflection occurring at a low shunt impedance value. In panel B, at a higher shunt resistance, reflection fails due to failure of impulse conduction in the orthograde direction (P-D). In panel C, shunt resistance was reduced to a value lower than that in A. In this instance, reflection did not occur because the distal segment fired too early. Retouched.

**Figure 3.** Evaluation of the conductivity of the "exit" pathway (D-P) in a parasystolic model. The proximal (P) segment (top), stimulated at a basic cycle length (BCL) of 2100 msec, electrotonically modulated the activity of the spontaneous pacemaker in the distal (D) segment (bottom trace). As the pacemaker fired at progressively earlier intervals in the driven cycle in panels B through G, the D-to-P conduction time increased progressively (panels B, C and D), failed (panel E), accelerated sharply (panel F) and failed again (panel G). Upstrokes retouched. SR = shunt resistance.
A) Basic stimuli (P₁) were applied to proximal segment of a canine false tendon (top trace of inset) at a cycle length of 1000 msec. After every tenth basic beat, a premature stimulus (P₂) was delivered to the proximal segment. The conduction time of the premature beat to the distal site (P₂D₂) is plotted as a function of the P₁P₂ interval. B) Results of similar experiment yield a variant of the curve in panel A. A calf Purkinje fiber was used in this case. Arrows indicate time of stimulus delivery to top trace.

Figure 5. Frequency dependence of reflection. The proximal (P) (top trace) and distal (D) (bottom) activities were recorded from opposite ends of a sucrose gap preparation. A) The basic cycle length (BCL) was 1785 msec and a bigeminal rhythm resulted in the proximal end. B) A slight increase of BCL to 1805 msec resulted in alternation of successful reflections, yielding a trigeminal pattern. C) A further increase of BCL to 1875 msec resulted in silence. Upstrokes retouched.

The bigeminal rhythm recorded in figure 4 was increased to 1805 msec, equivalent to a 1% slowing of the frequency. Although 1:1 transmission from P to D still occurred, the conduction intervals alternated, so alternate responses in D occurred too early in the recovery cycle of P, and failed to reexcite the proximal segment. The resulting pattern was trigeminy. When the driving cycle was increased to 1875 msec, the P-to-D conduction interval was diminished to 200 msec. All responses in D fell within the refractory period of P, and no manifest reflections occurred (panel C).

Within the limited range of cycle lengths shown in figure 5, major changes in the patterns of manifest ectopic activity accompanied slight changes of frequency, but 1:1 transmission from P to D was present throughout; when reflection failed it was due to failure in the retrograde passage of the impulse. Failure can also occur in the P-D direction (fig. 6). In panel A, as in figure 5, a bigeminal pattern was established when the proximal segment was driven at a cycle length of 1300 msec. Panel B was recorded without a change in the basic frequency, but after an increase in the shunt resistance (i.e., an increase in the degree of block between P and D). Every fourth driven response was followed by a successful reentrant beat, but a Wenckebach periodicity accompanied propagation from P to D. The third driven response in P was propagated promptly to D; a longer conduction interval attended the propagation of the fourth, but both responses occurred too early to return to P as reflected events. A still further delay of the fifth response per-
mitted a successful reentry; and the sixth driven response failed to initiate a discharge in the distal segment (entrance block).

The 4:3 Wenckebach periodicity between P and D in figure 6B is accompanied by a kind of inverse Wenckebach periodicity in which three successive failures in the D-P direction culminate in a successful transit, made possible by the prolongation of P-D conduction in the fifth response.

Sequences similar to those in figure 6 were also observed when the impairment of conductivity was achieved not by increasing the shunt resistance but by altering the driving frequency (fig. 7). In figure 7A, at a driven cycle of 1220 msec in the proximal segment, there was 2:1 block between P and D. The responses in D occurred after a conduction interval of about 270 msec, and fell within the refractory phase of the proximal segment; there was no manifest reentrant activity. When the cycle length was reduced to 1120 msec, a bigeminal pattern appeared, accompanied by artificially induced compensatory pauses (fig. 7B). When the cycle was reduced to 1020 msec, 3:1 block between P and D occurred, and again no manifest ectopic activity was present (fig. 7C). At the faster driving rate in panel D, a manifest trigeminal rhythm appeared.

The sequence illustrated in figure 7 is mandated by the frequency dependence of conductivity from the proximal to the distal segment. A gross approximation of the effect of frequency may be made by relating the P-to-D conduction interval to the output cycle (i.e., the interval between propagated responses in the distal segment). In panel A, the P-D conduction time averaged 270 msec, when D-D averaged 2440 msec. In figure 7B, the corresponding intervals were 340 and 2240 msec, and in figure 7C, 255 and 3060 msec; the considerably longer output cycle in panel C permitted an improvement of conductivity from P to D, which in

Figure 6. Dependence of reflection pattern on degree of block between proximal (P) (top trace) and distal (D) (middle trace) sites. Bottom trace is a stimulus marker. A) Basic cycle length of driven responses, 1300 msec. A bigeminal pattern was established. B) The same frequency as in panel A was maintained; an increase in shunt resistance resulted in manifest ectopic responses occurring after every fourth stimulated beat. Wenckebach-related intervals (msec): P₃D₅, 160; P₅D₅, 270; P₄D₃, 355; D₂D₄, 1410; D₄D₆, 1385. Upstrokes retouched.

Figure 7. Frequency dependence of manifest ectopic patterns resulting from reflected responses. The top trace is a transmembrane potential recorded from proximal segment. The middle trace was recorded from the distal segment. The bottom trace is a stimulus marker. A) The basic cycle length (BCL) of the proximal segment was 1220 msec, with no manifest ectopic activity. B) Reduction of the BCL to 1120 resulted in bigeminy with compensatory pauses. C) Further reduction of the BCL to 1020 was accompanied by 3:1 block and silence. D) A trigeminal rhythm with compensatory pauses appeared after an even further decrease of BCL to 820 msec. Retouched. Compensatory pauses were artificially induced.
turn prevented the emergence of a reflected response. At the even faster driving rate in panel D (cycle, 820 msec), a manifest trigeminal rhythm appeared, and the output cycle was reduced to 2460 msec. The coupling interval between the driven and reflected responses in the proximal segment was now much briefer than those recorded in panel B, suggesting the presence of a phase of relative supernormality. The supernormal phase was in fact demonstrated in this experiment by the method used in the experiment of figure 4A. The data recorded in this and other experiments indicate that coupling intervals need not be fixed, but may vary over rather wide ranges.

Fixed Coupling

Fixed coupling has long been considered a necessary attribute of a reentrant mechanism, and we presumed that fixed coupling would accompany the reflection mechanism. In many relatively stable situations, the coupling intervals do remain almost constant, and they appear to be determined by the functional refractory period of the system. When instability is present, however, the conduction time from P to D may vary over wide limits (fig. 4), and the coupling interval is correspondingly influenced.

An example of such instability, resulting in wide variations of coupling interval, is illustrated in figure 8. These results were recorded from the same experiment as figure 7, but at a much slower driving frequency, permitting 1:1 transmission from the driven to the distal segment. Each driven response in P was followed by a reflected response, P', yielding an unstable bigeminal response pattern. The intervals between driven and reflected responses (coupling interval, P-P') are plotted in figure 8 as a function of the P-D interval when the preparation was driven at a basic cycle length of 2530 msec. At that driving rate wide variations of the coupling interval, from 390–640 msec, accompanied variations in the P-D interval. When propagation from P to D was prompt (less than 300 msec), the distal responses fell within the relatively refractory period of P, and the reciprocal conduction times were correspondingly long. When the P-D interval increased to more than 300 msec, the reciprocal D-P' interval fell to as short as 45 msec as the distal responses occurred during the supernormal phase of the proximal fibers. The full range of coupling intervals (390–640 msec) in figure 8 encompasses variations in the entrance conduction time of only about 30 msec (P-D, 270–300 msec), emphasizing the remarkable pattern changes that may be expected to occur with minor variations in frequency.

Multiple Reflections

The process of reciprocation illustrated in figures 2, 5, 6 and 7 might sustain itself for two or more round trips. Although many attempts were made to induce the equivalent of an episode of ventricular tachycardia in the reflection model, the closest approach achieved was 1½ circuits. One of many successful trials is illustrated in figure 9. In this experiment conduction block was obtained by perfusing the central chamber.

![Figure 8](image1.png)

**Figure 8.** Variable coupling of reflected responses to the basic responses in a bigeminal run elicited at a basic cycle length of 2530 in a sucrose-gap preparation. The coupling interval (P-P') is plotted as a function of the P-D conduction interval. P = proximal; D = distal.

![Figure 9](image2.png)

**Figure 9.** One and one-half circuits observed in an experiment in which the central chamber was perfused with 15 mM K⁺ solution. Transmembrane potentials in the upper trace were recorded from the proximal (P) segment driven at a basic cycle length of 900 msec. The middle trace was recorded from the distal (D) segment. The bottom trace is the stimulus marker.
with a 15-mM potassium solution instead of sucrose. At a driving cycle length of 900 msec in the proximal segment (upper trace), delayed propagation from P to D and back generated closely coupled reflected responses in P, followed by a return to the distal segment. Careful manipulation of the driving frequency failed to extend the series to two complete reentrant cycles. This result is not surprising, for the success or failure of transmission is critically dependent on the frequency (as in figs. 5 and 7). The brief coupling interval as shown in figure 9 greatly reduces the chance of an additional transit. Examples of one and one-half circuits were also recorded in experiments in which the central chamber was perfused with sucrose.

Discussion

Reflection vs Circus Movement

Before comparing reflection and parasystole, we must assess whether reflection can be considered an adequate model of reentry. A proper assessment would require a comparison of a circus movement model with the reflection model under similar conditions, and this has not yet been achieved. However, there are certain features that are common to both, and there are reasons to believe that both would respond similarly to alterations in frequency.

Some degree of block is a prerequisite for both models. In the circuit model, one-way block is obviously necessary in one limb of the conduction pathway; in the reflection model, block must be present as a delay (cessation and resumption) of transmission. In either case, the total time for to-and-fro transmission must, of course, exceed the refractory period of the tissue proximal to the site of block. In the circuit, very slow conduction in the loop or a very brief refractory period in the proximal tissue or both will permit completion of the circuit. In the reflection model, the sum of the conduction delays serves the same purpose; reentry of the proximal elements can occur in either case.

The success of reentry depends on the degree of conduction impairment. If the conductivity of the tissue in the circus loop is only moderately depressed, or if the delay at the gap is too brief, reentry cannot occur. Acceleration of the basic frequency will further depress conductivity in the loop, and will prolong the delay at the gap. In both cases, the models should behave similarly; reentry should be facilitated, within limits, at faster heart rates. As described by El-Sherif et al., reentry may also be suppressed at still higher rates (fig. 7). The presence of a supernormal phase of excitability in the proximal tissue should also favor reentry in either model; in a critically balanced system, reentry would be possible only during a supernormal phase.

Finally, we may consider whether a reflection mechanism would be possible in the heart in situ. There is little doubt that the substrate for a circus loop reentry exists in the region of an infarct, but sucrose gaps are not to be expected. In the experimental model the sucrose gap is merely a convenient way of inducing the necessary conduction delay, but reflection was demonstrable when elevated potassium was substituted for sucrose (fig. 9), and any agency that sufficiently impairs conductivity could probably yield the same result. We conclude that reflection is possible in the damaged heart and that, within limits, reentry due to reflection and reentry due to a circus movement would respond similarly to changes in heart rate. The patterns of group-beating described by El-Sherif et al. in a model of circuous reentry are remarkably similar to those produced in the reflection model.

Reflection and Parasystole

Similarities in the behavior of the reflection model and that of a parasystolic pacemaker are apparent in our results. In fact, the differences are more quantitative than qualitative. For example, entrance block is a prerequisite for parasystolic activity, but two-way conduction is necessary for reflected reentry. The entrance block in the model of parasystole is not an absolute insulator; it permits the delivery of electrotonic modulating influences to the pacemaker from the surrounding tissue. The amplitude of the electrotonically mediated depolarizations will be increased if the extracellular impedance between the two chambers is reduced, or if the axial current flow is increased, or if the membrane impedance in the pacemaker cells is increased; that is, a sufficiently strong stimulus can overcome the block and quickly bring the pacemaker to its firing threshold. In this situation the delay phase of pacemaker modulation can no longer occur; the pacemaker, if intrinsically slower than the basic driving rate, will be repeatedly captured and its cycle abbreviated and reset.

Spontaneous impulse generation is also necessary for parasystolic activity, but it is clearly not necessary for reflection. Although most of our preparations of Purkinje fibers had some degree of slow diastolic depolarization, the intrinsic cycle length was often 10 seconds or more; reflection would be possible in tissue with no spontaneous impulse generation. Nevertheless, a progressive increase in membrane resistance with time, apparent as an increase in the amplitude of the subthreshold depolarizations in figure 7C, was often observed and was responsible in part for frequency-dependent changes in the patterns of ectopic activity.

Manifest Ectopic Response Patterns as a Function of Frequency

The effect of heart rate on the overt behavior of a parasystolic pacemaker protected by entrance block has been considered in detail in previous publications. When the intrinsic cycle length of the ectopic pacemaker falls in the range of 1.1-3.5 times that of the dominant pacemaker, and when the electrotonic modulation is of moderate degree (±20% of the intrinsic cycle length or less), predictable and even mandatory changes in the patterns of manifest
ectopic activity accompany changes in the basic heart rate. The sequence of the changes (for example, concealed bigeminy → manifest bigeminy → alternating bigeminy and trigeminy → concealed trigeminy → manifest trigeminy) as the basic heart rate increases is obligatory in the mathematical model of parasystole,14 is readily demonstrable in the biological model,12 and appears to fit the limited clinical observations in which a sufficient range of data has been available.12, 14

The sequence of pattern changes to be expected in the reflection model has not been established in comparable detail, and no general diagnostic criteria have been derived. Moderate changes in the basic driving rate or in the shunt resistance may convert a manifest bigeminal rhythm to a trigeminal rhythm, with or without an intervening period of silence (fig. 7). Similar changes were observed by Wit et al.1 and are also apparent in the reentry model of El-Sherif et al.19 Comparable patterns may also accompany acceleration in the parasystole model. The differences are principally in the extent of more complex ratios (e.g., 7:2, 9:4) intervening between zones of simple ratios (2:1, 3:1). The more complex entrainment zones, commonly observed in the true parasystolic model, are squeezed out as the electrotonic influence increases or the degree of block diminishes; i.e., as parasystole is gradually converted to reflection.

Because the major difference between the parasystolic model and the reflection model is quantitative, no sharply defined boundary probably exists between the two mechanisms; rather, there is a continuous spectrum ranging between ectopic activity that is clearly the result of modulated pacemaker discharges and coupled activity that is the result of reentry. In the experimental model we have described, the quantitative difference was achieved by altering the degree of block between the two active chambers. When entrance block is converted from third-degree to second- or first-degree block, the pattern changes from parasystolic to intermediate to reentrant. Quantitative changes of this type are surely possible in the damaged heart in situ, as suggested by Schamroth29 in what are only semantically different terms.

Fixed Coupling

In previous studies we have emphasized that fixed coupling of manifest premature beats can occur in a parasystolic system over relatively wide ranges of heart rate and may even be obligatory. Fixed coupling in the reflection model can be favored by a supernormal phase of excitability, as suggested by Lepeschkin and Rosenbaum20 and by Langendorf and Pick.24 In the present study we have shown that variable coupling intervals are by no means incompatible with a reentrant mechanism (fig. 8), a conclusion also reached by Michelson et al.25 and El-Sherif et al.19 However, we must qualify that conclusion. In the experimental model of reflection, the events are recorded from the site of the reentry, a point at which the coupling interval may be considerably briefer than at more remote levels of the conducting system. Conduction of the earliest responses from this site into the rest of the heart would be expected to be delayed more by relatively refractory tissue than would later responses. The coupling intervals as recorded on the body surface ECG may thus be held within narrower limits than those recorded at the level of microreentry.

Early Afterdepolarizations

When orthograde (P-D) conduction time of an impulse is long, but not long enough to permit a reflected response, an early afterdepolarization appears in the proximal recording (when the recording site is in close proximity to the block). This is evident in figures 1A, 3E, 5B, 7A, 7C and 9. In all cases the "hump" in the repolarization phase is coincident with and is a direct electrotonic manifestation of activity in the distal segment. In figure 9, these early afterdepolarizations appear in the distal segment but are coincident with the reflected responses in the proximal segment.

Similarly, as a result of entrance block (orthograde conduction failure), the distal segment may show activity resembling a late afterdepolarization (fig. 7A). These events are purely electrotonic images of regenerative activity beyond a site of block and should not be confused with oscillatory afterpotentials associated with digitalis or high calcium treatment. Likewise, these electrotonic events do not seem to have any relation to the early afterdepolarizations exhibited by fibers that manifest triggered activity.

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