Editorial

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Aberration: seventy five years after Sir Thomas Lewis

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Seventy five years after Lewis documented aberrant intraventricular conduction, this phenomenon continues to intrigue the clinician and investigator alike. Differentiation of ventricular tachycardia and aberration with all its diagnostic and therapeutic implications is often elusive and continues to challenge the clinician and electrocardiographer. Similarly, the basic electrophysiological mechanisms responsible for the many permutations of aberration continue to attract the attention of the clinical and basic investigator.

The earliest reference to abnormal intraventricular conduction of supraventricular impulses resulting from premature excitation can be found in a paper published in 1910 entitled, "Paroxysmal tachycardia, the result of ectopic impulse formation." In this paper Sir Thomas Lewis described atrial premature complexes with "three separate types of ventricular electrocardiogram." Interestingly, in the same communication, he illustrated five consecutive atrial premature complexes with the first QRS complex of the sequence, the complex preceded by the long cycle of the sinus rhythm being abnormal.[1] Forty eight years later, aberration dependent on a long preceding cycle became known as the Ashman phenomenon.[2] In a subsequent communication, Lewis suggested that the "abnormal ventricular electrocardiograms" . . . "are due to disturbances of conduction in the smaller branches of this system; and it is held that definite branches are affected in this manner, though these branches cannot be identified at the present time. It is proposed that the phenomena discussed should be termed "aberration of supraventricular impulses" or simply "aberration"; the anomalous beats may be conveniently spoken of as "aberrant beats" or "aberrant ventricular contraction".[3] The suggestion that abnormal intraventricular conduction is responsible for aberration has since been confirmed experimentally with the possible sites of the disturbed conduction localised to be the bundle branches, Purkinje fibres, the Purkinje-myocardial "gates", or, at times, a combination of the above.

Over the years since Lewis first called our attention to intraventricular aberration, a number of permutations of this phenomenon have been described, and, interestingly, not always a result of acceleration of the heart rate.

With the advent of intracellular and His bundle recording, coupled with intracardiac pacing, it is possible to define a number of electrocardiographic manifestations of aberration in terms of intracardiac and intracellular events, always mindful that such extrapolation may at times be misleading.

Aberration caused by premature excitation

In the normal case, aberration accompanying an atrial premature systole is, with rare exception, caused by excitation before full recovery of the transmembrane action potential, during the voltage dependent refractoriness. The degree of prematurity determines whether the conduction will be delayed or blocked. Though Lewis recorded "three separate types of ventricular electrocardiograms," in the normal man and animal,[4] the morphology of the aberrant QRS is nearly always that of a right bundle-branch block.[5] This is because of the longer refractory period of the right bundle.

On occasion when the aberrancy is caused both by right and left bundle-branch block, the latter occurs at cycles shorter than the right bundle-branch block and is independent of the duration of the preceding cycle.[6] Such observations suggest that the duration of the refractory periods of the two bundles cross over, so that at short cycles the refractory period of the left bundle is longer while at longer cycles the duration of the refractory period of the right bundle exceeds that of the left.[7] The duration of the refractory periods

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alone may not always explain the changing conduction in the two bundles and in such cases it is likely that changing conduction contributes to the aberration.[8] (C Fisch, unpublished observations).

The coupling interval at which the conduction of a premature impulse is either delayed or blocked depends, in addition to the prematurity, on the basic heart rate. With acceleration of the heart rate, the refractory period shortens and consequently a shorter coupling interval is necessary to evoke aberration.[8] The opposite is also true, namely prolongation of the basic cycle length results in a longer refractory period, and a longer coupling interval is required to induce aberration. With increasing heart rate, the greater shortening of the refractory period of the bundle-branches than that of the atrioventricular node explains the occasional disappearance of bundle-branch block at higher heart rates. Similarly, aberration initiated by an abrupt acceleration of the heart rate may disappear with persistence of the rapid rate, this the result of a gradual shortening of the refractory period in response to the increased rate.

Because of the directional relation of the refractory period and the basic heart rate, aberrant conduction of the premature impulse can be induced in the presence of a fixed coupling interval by prolonging the immediately preceding basic cycle. Such a mechanism of aberration was first illustrated by Lewis,[1] subsequently emphasised by Langendorf,[9] and is commonly referred to as the Ashman phenomenon.[2] Interestingly, aberration caused by the Ashman phenomenon may persist for a number of cycles. This persistence of aberration may reflect a time dependent adjustment of refractoriness of the bundle-branch to an abrupt change in cycle length or may be the result of concealed transseptal activation detailed below.[4]

With rapid pacing or during vagal stimulation, the refractory period of the atrioventricular node exceeds that of the bundle and aberration is not possible. Similarly, a very early atrial impulse will block in the atrioventricular node. A somewhat later impulse will conduct slowly through the atrioventricular node, will allow sufficient time for the bundle to recover, and will conduct normally through the ventricle. A still later impulse will conduct normally across the atrioventricular node, will reach the bundle after it has recovered, and will inscribe a normal intraventricular complex. Only an impulse properly timed between these two extremes will find the bundle refractory and result in intraventricular aberration.[4]

Aberration caused by acceleration of heart rate

In 1913 Lewis documented normalisation of left bundle-branch conduction with slowing of the heart rate. Even though the left bundle-branch block and the normal QRS were recorded on different days, this series of electrocardiograms is probably the first reported instance of acceleration dependent left bundle-branch block.[10] Failure of the refractory period to shorten, or in fact possible lengthening in response to acceleration of the rate is responsible for the aberration. Acceleration dependent aberration differs in many respects from aberration recorded in the normal heart in response to premature stimulation.[6] The former usually displays left bundle-branch block; appears at relatively slow rates, often below 75 a minute; is independent of any change in the duration of the preceding cycle; is independent of abrupt change in cycle length, often appearing with gradual acceleration and frequently with a small, 0·5 ms or shorter, change of the cycle length; after an acceleration of the rate it may appear only after a number of cycles, all the cycles equal in duration; rarely disappears with acceleration of the heart rate; and is nearly always a marker of cardiac abnormality. Because of the small changes in duration of the cycle length which finally initiate aberration, a diagnosis of acceleration dependent aberration may not be possible without a long record documenting the gradual and minimal foreshortening of the individual cycles.

Four manifestations of acceleration dependent aberration are of particular interest. These include (1) the surprisingly slow heart rate at which aberration may appear, (2) the inverse relation of the duration of the refractory period to the basic cycle length, (3) normalisation of intraventricular conduction at cycles longer than the "critical cycle," the latter defined as the cycle at which aberration first appears, (4) after acceleration of the rate and without change in cycle length, aberration may appear only after a number of cycles.[6] Mechanisms invoked to explain these manifestations include prolongation of the duration of the voltage or time dependent refractoriness, or both; changing electrophysiological determinants of conduction such as decrease in the speed of upstroke of phase O, reduction of resting membrane potential or shift of membrance responsiveness to the right; time dependency of the changes; geometry of the bundle-branch lesion and its relation to the impulse; "fatigue,"[11] "overdrive suppression",[6] and concealed conduction.[4 12 13]

Acceleration dependent aberration appearing at rapid rates can be explained by the failure of the action potential to shorten or actually by a prolongation of the action potential duration. Often, however, acceleration dependent aberration occurs at relatively long cycles, not infrequently exceeding 800 ms, and mechanisms other than simple prolongation of the action potential duration must be considered. These may include time dependent refractoriness, quantitative change of the determinants of conduction in

response to increase in heart rate, or both. The exact mechanism responsible for the paradoxical behaviour of the refractory period, however, which distinguishes acceleration dependent aberration from aberration in the normal, is obscure. Some have suggested that geometry of the bundle-branch lesion coupled with a change in current strength may contribute to aberration.[14] In the presence of such "impedance mismatch" where a few fibres carry the current, small changes in intensity and strength of input may result in slowing or failure of conduction. Such "mismatch" may be caused in part by changes in the determinants of conduction.

Evidence suggests that with a change of the heart rate, attainment of the new steady state of conduction is time dependent requiring a number of cycles to reach this new steady state. Similarly, the more rapidly the "critical cycle" length is attained the longer it may take for aberration to become manifest, attesting further to the time dependency of the new steady state of conduction. Such a behaviour of conduction can be noted after the onset of a regular atrial tachycardia with the aberration manifest only after a number of cycles.

During slowing of the heart rate intraventricular conduction frequently fails to normalise when the "critical cycle" length is reached and the aberration persists at cycles longer than the "critical cycle."[11] This paradox is ascribed most commonly to conduction from the contralateral, the conducting bundle-branch, across the septum resulting in delayed activation of the blocked bundle. Such concealed transseptal activation results in a bundle-branch to bundle-branch interval which is shorter than the manifest QRS cycle. It is this foreshortening which explains the paradoxical, unexpected persistence of aberration. Not all instances, however, of unexpected delay of normalisation of conduction can be explained solely by concealed transseptal activation. In some, for example, the aberration ceases with slowing of the heart rate only to recur at cycles that are still longer than the "critical cycle." Such a sequence precludes transseptal concealment as the mechanism of the recurrence of aberration. Similarly, when the discrepancy between the "critical cycle" and the cycle at which normalisation finally occurs is as long, as for example 210 ms, transseptal concealment alone cannot explain the delay. "Fatigue"[11] and "overdrive suppression"[6] have also been suggested as possible mechanisms of the delayed normalisation of conduction. "Overdrive suppression" is in some respects similar to the overdrive suppression recorded in the sinus node, atrioventricular node, (C Fisch, unpublished observations) the accessory bypass,[14] and the bundle-branch block after termination of ventricular rhythms.

In man, overdrive suppression as the mechanism of the bundle-branch block is suggested by the fact that with cessation of the ventricular rhythm the bundle-branch block gradually disappears in the face of an accelerating heart rate. The "fatigue" or "overdrive suppression" as a mechanism of aberration have been proven experimentally. After initially mechanically damaging the bundle-branches and inducing bundle-branch block, the conduction was allowed to recover. After recovery, the bundles were "fatigued" and the conduction again blocked by a rapid succession of ventricular complexes induced by ventricular stimulation. In addition to overdrive suppression this was probably the earliest demonstration of concealed conduction of ventricular extrasystoles into a bundle-branch.[15]

While "fatigue" may not explain persistence of bundle-branch block after only a single cycle shorter than the basic cycle length, such an unexpected persistence of aberration may reflect "overdrive suppression." The duration of suppression of conduction is dependent on the rate; the more rapid the rate, the longer the recovery time. Both "fatigue" and "overdrive suppression" induced bundle-branch block support the proposition that with a change of heart rate the adjustment of conduction to the new steady state is time dependent. This time dependent adjustment is often exaggerated and, with rare exception, this exaggeration is an expression of an abnormal state.

It is evident from the above discussion that the behaviour and mechanisms of aberration in the normal and acceleration dependent aberration, as a rule an expression of an abnormal state, differ. It is imperative that the two be treated separately as different phenomena, if interpretation of data dealing with the subject of aberration is to be meaningful.

It is interesting to speculate about the role of acceleration dependent aberration in alternating bundle-branch block. The fact that alternating bundle-branch block is often dependent on the changing heart rate is supported by the observation that in face of a gradual slowing of the heart rate, left bundle-branch block may give way to 2:1 left bundle-branch block and with further slowing of the heart rate the intraventricular conduction may return to normal. It is reasonable to extrapolate from the above that a 2:1 left bundle-branch block may be caused by small alternation of the cycle length. The rate related nature of a 2:1 left bundle-branch block is rarely recognisable in the routine clinical electrocardiogram because the very small changes in cycle length can be documented only when long records are available. Unfortunately, sufficiently long tracings necessary to document the changing rate are rarely available. Another and perhaps more likely explanation for the 2:1 left

bundle-branch block suggests that because of the left bundle-branch block, the left bundle to left bundle interval of the two manifest normal QRS complexes encompassing the QRS with the left bundle-branch block is twice as long as the basic cycle.[16 17] The left bundle, being blocked high, has sufficient time to recover and the next sinus impulse is conducted with a normal QRS. Such a sequence of events is possible provided the bundle is not activated retrogradely.[11] Still another explanation of the 2:1 left bundle-branch block invokes phase 4, or deceleration dependent aberration. After normal conduction the left bundle-branch to left bundle-branch cycle is relatively "long" and allows for a gradual phase 4 depolarisation with activation from a reduced potential and thus block of conduction in the left bundle-branch. As a result of the left bundle-branch block, impulse conducted along the right bundle activates the left bundle transseptally after a delay, the left bundle to left bundle interval is foreshortened, phase 4 depolarisation is no longer operative, and conduction along the left bundle proceeds normally.[18] For this mechanism to be applicable one has to assume that extremely small changes in cycle length can result in deceleration dependent aberration.

Aberration caused by concealed transseptal conduction

Alternation of aberration caused by atrial bigeminy was first published in 1922 by Stenström.[19] He proposed 3:2 block of the alternate bundles as the mechanism responsible for this phenomenon.

Studies which followed some 40 years later suggest that concealed transseptal conduction, by altering the duration of the cycle length and the refractory period, may result in aberrant intraventricular conduction of an early ("premature") supraventricular impulse of a bigeminal rhythm. The alternation of the intraventricular conduction may be between normal conduction and bundle-branch block or between right and left bundle-branch block. The bigeminal rhythm may be the result of atrial bigeminy, 3:2 atrioventricular block with Wenckebach structure, or atrial flutter with alternating 2:1 and 4:1 block.

When the alternation is between a normal QRS and right bundle-branch block, the following sequence of events is assumed. The bundle to bundle interval after a normally conducted early complex is relatively "long," resulting in a relatively "longer" refractory period. Since the refractory period of the right bundle is normally longer that that of the left bundle, the premature impulse results in a right bundle-branch block. In the presence of right bundle-branch block, the impulse is conducted along the left bundle, across the septum activating the right bundle after some delay, and shortens the right bundle to right bundle interval and the respective refractory period. As a result, the next early QRS is normal.[20] The same electrophysiological phenomena, namely, the effects of concealed transseptal conduction on both the bundle-branch to bundle-branch interval and on the refractory period, explain alternation of right and left bundle-branch block. In the presence of right bundle-branch block, transseptal concealed conduction into the right bundle from the left bundle results in a foreshortened right bundle to right bundle interval and a relatively longer left bundle to left bundle interval. As a result, the refractory period of the left bundle is also longer and conduction in the left bundle fails. With the left bundle-branch block, conduction along the right bundle with delayed transseptal activation of the left bundle shortens the left bundle to left bundle interval, the refractory period of the right bundle is now relatively longer, and conduction blocks in the right bundle.

Aberration caused by deceleration of heart rate

In 1934, Drury and Mackenzie[21] performed a series of elegant experiments, in which, after injury to either the right or left bundle the heart rate was slowed with vagal stimulation. The slowing of the ventricular rate in the presence of either 2:1 or 1:1 atrioventricular conduction, resulted in aberration. They also noted that, "when the branch is damaged on several occasions, the recovery time and period during which aberrant beats are seen lengthens after each successive damage," indicating that while appearance of aberration is dependent on deceleration of the heart rate and bundle-branch injury, the duration of aberration is directionally related to severity of bundle-branch damage. Noting that slowing of the heart rate with interventions other than vagal stimulation did not cause aberration, they suggested that factors other than mere slowing of the heart rate contribute to the aberration. They proposed that the vagal action altered the quality of the impulse at the level of the atrioventricular node resulting in, for example, "decremental"[21] conduction and that the altered impulse was of insufficient strength to traverse the site of injury. Interestingly, in reference to man, they suggest that, "in the human subject as a result of deficient arterial supply or other factors" local impairment occurs and vagal "action on the impulse in the upper part of the junctional tissue in these conditions produce aberrant beats." Subsequent studies[22] using a similar experimental design confirmed the observations made by Drury and Mackenzie. Though the first comprehensive study of deceleration dependent aberration in man was published by Dressler in 1959,[23] an isolated case illustrat-

ing this phenomenon was documented by Kisch and Grishman many years earlier.[24]

The most widely accepted mechanism of deceleration dependent aberration is a gradual spontaneous reduction of phase 4 of the action potential in an abnormal cell. It is suggested that as a result of the spontaneous depolarisation made possible by a prolonged cycle, the cell is activated from a less negative potential resulting in impaired conduction.[25] If the concept of deceleration dependent aberration is correct, incomplete bundle-branch block should terminate cycles shorter than cycles terminated by complete left bundle-branch block. Similarly, if the spontaneous diastolic depolarisation is allowed to reach the threshold potential, an escape complex with a QRS morphology opposite to that of the aberrant QRS complex should result. Both phenomena have been documented clinically and tend to support, at least in man, the diastolic depolarisation mechanisms of deceleration dependent aberration.[22 26]

It has been suggested that since the full width of the bundle-branch must be affected in order to slow conduction, the thickness of the left bundle-branch argues against this hypothesis. This objection does not seem particularly valid in the presence of an abnormal bundle because of the likelihood of a reduced number of conducting fibres. Other investigators point to the fact that diastolic depolarisation may actually enhance conduction by bringing the resting potential closer to threshold potential.[27] To circumvent this argument, it has been proposed that both generalised reduction of the resting potential, gradual spontaneous depolarisation, and a shift of the threshold potential all play a role.[22 28] Others have suggested that deceleration dependent bundle-branch block is the result of "complex oscillatory changes of membrane properties of depressed bundle-branch Purkinje fibers during diastole."[29]

It is possible that the mechanism suggested by Drury and Mackenzie is operative in clinical instances of deceleration dependent aberration. In response to slowing of rate, a baroreceptor reflex mediated via the vagus alters the quality or strength of the supraventricular impulse, affects conduction, and results in aberration. Deceleration dependent aberration may also reflect a direct effect of the vagus at the level of the bundle-branch. While such an effect of the vagus may not depress bundle-branch conduction in the normal subject, it may possibly be of sufficient magnitude to delay or block conduction in a previously damaged bundle.

The foregoing discussion indicates that while many of the questions relating to the basic mechanism of rate dependent aberration posed by the early investigators remain unresolved, a number have been answered and very likely many more, if not all, will be answered by the time of the one hundredth anniversary of aberration.

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