Vagaries of acceleration dependent aberration

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The earliest electrocardiogram illustrating bizarre intraventricular conduction of supraventricular impulses was published by Sir Thomas Lewis in 1910.¹ In a subsequent communication Lewis labelled this form of abnormal conduction "aberration" and the ventricular complexes as "aberrant beats." ² In that same paper he also proposed a mechanism for the aberration, namely "...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".³ The underlying milieu for aberration proposed by Lewis stood the tests of further observation and experimentation. Altered, asynchronous conduction has been demonstrated for all segments of the His-Purkinje system as well as the Purkinje-myocardial junctional areas and, rarely, as a result of preferential atrioventricular and, perhaps, His bundle conduction. The mechanisms responsible for initiating the conduction alterations are, however, even more complex as attested to by the vast number of published reports, both basic and clinical, on aberrancy that has been generated since Lewis' initial observations.

In 1983, on the occasion of the 75th anniversary of Sir Thomas Lewis' description of aberration, Dr Dennis Krikler, Editor of the British Heart Journal, invited an editorial on that subject.⁴ As our contribution to this Festschrift issue of the British Heart Journal honouring Dr Krikler, we have elected to continue that discussion and focus on the vagaries of acceleration dependent aberration. The subject is particularly well suited to Dr Krikler's long time interest in the history of cardiology and, in particular, in tracing the development of concepts in electrophysiology.

We have collated scattered reports on eccentric forms of acceleration dependent aberration and on mechanisms that could explain the vagaries proposed in the hope that further interest in the mechanisms underlying aberration will be stimulated. The material comes from our files and our earlier publications.

**Background and observations**

In 1913, Lewis published two electrocardiograms illustrating the disappearance of bundle branch block with slowing of the heart rate (fig 1).⁴ Although the tracings were recorded on different days, they probably are the earliest example of acceleration dependent aberration.

The classic manifestation of acceleration dependent aberration is the appearance of aberration at a critical cycle length reached in the course of an increase in heart rate, and normalisation of conduction with slowing of the heart rate to the point that the RR cycle is again longer than that at which aberration was initiated (fig 2).⁵

While the predictability of the relation between rate and aberrancy is characteristic for acceleration dependent aberration, there are exceptions to this heart rate dependency that we will refer to as vagaries or eccentric forms of acceleration dependent aberration, an example of which also was first reported by Lewis.⁶ The vagaries will be divided into two groups: Group 1—unexpected normalisation of conduction when aberration would be expected to continue—and Group 2—unexpected appearance or persistence of aberration under conditions in which it would not be expected. Examples under each group are presented and discussed below.
GROUP 1

Normalisation with abrupt shortening of the cycle length

One of the most common vagaries of acceleration dependent aberration is normalisation of intraventricular conduction at cycles shorter than those of the aberrantly conducted complexes. This occurs with an abrupt shortening of the RR interval such as that which may be seen with atrial fibrillation (figs 3 and 4), single atrial premature complexes (fig 5), runs of atrial premature complexes, or 3:2 atrioventricular block.

The most likely mechanism responsible for unexpected normalisation of conduction with abrupt shortening of RR interval is conduction during the supernormal period of His-Purkinje recovery. This is supported by the fact that there is a constant, or rarely a shorter, H-V interval, and that the coupling of the normally conducted impulses, in most cases, varies directionally with the preceding bundle branch to bundle branch interval the duration of which may be dependent on the presence or absence of concealed transseptal conduction from the contralateral bundle (figs 3 and 5).

Equal delay of conduction in the bundle branches has been suggested as an alternative to supernormality as an explanation for unexpected normalisation of the QRS at short cycles. The finding that would support this mechanism for paradoxical normalisation would be prolongation of the H-V interval recorded simultaneously with normalisation of the intraventricular conduction. Such observations have, as yet, not been reported. Prolongation of the PR interval commonly accompanies the normal QRS, but this may be an expression of atrioventricular nodal rather than bundle branch prolongation.

Normalisation during an accelerating tachycardia

Occasionally intraventricular conduction becomes normal after several cycles of acceleration dependent aberration.

While the initial aberration in fig 6 represents acceleration dependent aberration due to bundle branch refractoriness, normalisation of conduction is most likely due to a gradual shortening of the bundle branch refractory period over several cycles. This may be a normal adaptation of action potential to rate or possibly a result of an increase in the concentration of circulating catecholamines. Increased speed of conduction in the contralateral bundle branch or an equal delay in both bundles also are possible, but, as discussed above, these are unlikely mechanisms for normalisation of conduction.

On rare occasions, aberration disappears in the course of a gradual acceleration of heart rate, a phenomenon that has been observed during stress tests (fig 7). In such instances a 2:1
bundle branch block may precede or follow normalisation of conduction.

To the best of our knowledge the record reproduced in fig 8 is the only known example of paradoxical normalisation of conduction after a long preceding cycle when, according to the Ashman phenomenon, aberrant conduction would be expected rather than the normal conduction noted in this tracing. It is most likely that prolongation of the transmembrane action potential after the long pause fortuitously allows for conduction during the supernormal period of recovery.

**Intermittent normalisation and aberration**

Bundle branch block and normal conduction may be recorded intermittently during a regular rhythm. The ratio of bundle branch block to normal conduction may vary from a sporadic bundle branch block to 2:1 or higher ratios of bundle branch block to the normally conducted QRS complexes (figs 9 and 10).

The mechanisms proposed to explain the intermittent bundle branch block include:

(a) small changes in cycle length not recognisable in the electrocardiogram,

(b) block of the impulse above the bundle branch lesion responsible for the bundle branch block allowing for a prolonged recovery time,

(c) Wenckebach conduction in the bundle branch,

(d) deceleration and acceleration dependent bundle branch block,

(e) supernormal conduction.

The two latter mechanisms may be facilitated by concealed transseptal conduction (fig 10) that alters the duration of the bundle branch to bundle branch interval, the duration of the action potential, and thus the position of the supernormal period of recovery.

**Phase 4 depolarisation** has been suggested as a mechanism for 2:1 bundle branch block. With phase 4 depolarisation, it has been postulated that after a normal QRS the left bundle branch to left bundle branch interval is relatively “long” and thus results in bundle branch block. In the presence of the left bundle branch block, an impulse conducts along the right bundle branch, traverses the septum, and reaches the left bundle branch after some delay. The result is a “short” left bundle branch to left bundle branch interval, dissolution of phase 4 depolarisation, and as a result normal conduction. Although electrocardiographic observations tend to support phase 4 depolarisation as a possible mechanism of deceleration dependent aberration, some believe, based on cellular observations, that deceleration dependent aberration is the result of “complex oscillatory changes in membrane properties of depressed bundle branch Purkinje fibres during diastole.”

Another mechanism that could explain 2:1 bundle branch block is that block above an area of injury occurs so that the left bundle branch to left bundle branch interval encompassing the normal QRS is equal to two sine cycles, allowing for bundle branch recovery and normal conduction. This is also possible that delay of conduction above an area of injury could allow for recovery of excitability of an injured area and/or other electrophysiological parameters necessary for normal conduction. This mechanism resembles the gap phenomenon. For these two latter mechanisms to be possible, the bundle branch must not be activated retrogradely. Should retrograde conduction take place, prolonged recovery is no longer possible.

**GROUP 2**

**Onset of aberrant conduction without a recognisable shortening of RR interval**

This is a common phenomenon (fig 2). While
there is no doubt that the aberration is a function of acceleration of the heart rate, this may become obvious only when long records are available to allow the gradual shortening of the cycle length to be recognised. Failure to appreciate shortening to the "critical" aberrancy-inducing RR interval reflects a limitation of electrocardiographic technology; aberration may be a function of small changes of the cycle, often measured in milliseconds, and such changes may not be recognisable in the surface electrocardiogram. It is also possible under certain conditions that with gradual acceleration of the heart rate the refractory period inappropriately lengthens, resulting in conduction delay or block without the need for shortening of the "critical" cycle.

Persistence of aberration at a cycle longer than the "critical" cycle

This phenomenon also is a frequent finding in clinical electrocardiograms (fig 2). The most likely mechanism is concealed transseptal conduction that shortens the bundle branch to bundle branch interval. As a result of transseptal conduction the actual bundle branch to bundle branch interval is shorter than the manifest QRS to QRS interval (fig 2). Not only is the bundle branch to bundle branch interval altered but the duration of the subsequent refractory period also is changed. Transseptal conduction has been shown experimentally in the dog9,10,11 and in humans.12 22 23 Whereas concealed transseptal conduction alone may shorten the bundle branch to bundle branch cycle sufficiently to result in acceleration dependent aberration and its persistence, often it combines with other mechanisms to propagate aberrancy at cycles longer than the "critical" cycle. In some patients the discrepancy between the "critical" cycle and cycle at which normal conduction resumes may be on the order of 210 ms, an interval longer than could be explained simply on basis of the transseptal conduction.24

Alternate mechanisms for persistence of aberration may be "fatigue" and overdrive suppression, both of which are a function of increased rates. "Fatigue" is a concept proposed by Shearn and Rytand in 1953 to explain the unexpected persistence of aberration with slowing of the rate1 and is a descriptive phenomenon, the cellular basis for which is unclear. It is an attractive and logical concept that suggests that a persistently accelerated rate, sufficiently rapid to induce acceleration dependent aberration, alters the electrolyte milieu and that such alterations may persist over several cardiac cycles, some longer than the "critical" cycles at which aberrancy was initiated.

Overdrive suppression of conduction, first demonstrated by Scherf in the dog,25 is manifest by the appearance of bundle branch block upon cessation of a rapid heart rate or, on occasion, after a single early excitation or stimulus (fig 11). Overdrive suppression of bundle branch conduction is in many ways
followed by persistent aberration, the result of a slight acceleration of the heart rate. TC, transseptal concealment.

Figure 10 2:1 Left bundle branch block followed by persistent aberration, the result of a slight acceleration of the heart rate. TC, transseptal concealment.

A similar to overdrive suppression of atrioventricular conduction. The duration of suppression depends on the rate of the overdriving impulse: the higher the rate the longer the recovery time. Overdrive suppression after ventricular tachycardia is manifest by a gradual normalisation of bundle branch conduction in the face of acceleration of the sinus rate (fig 11). It is a phenomenon which, unlike "fatigue", could explain aberration after a single early excitation or stimulus. The exact electrophysiological basis responsible for overdrive suppression is uncertain.

Unexpected persistence of aberration induced by the Ashman phenomenon
A relatively frequent observation first recorded by Lewis is the persistence of aberration once initiated by sudden prolongation of the refractory period in response to a long cycle—the Ashman phenomenon (figs 12 and 13). The aberration persists at cycle lengths identical to those manifesting normal conduction.

Whereas the Ashman phenomenon is responsible for aberration of the first complex, persistence of the aberration may be due to delayed concealed transseptal conduction from the left to the right bundle branch resulting in shortening the right bundle branch to right bundle branch interval and thus initiation of acceleration dependent aberration. A constant heart rate and a fixed relation of transseptal conduction to anterograde conduction in the contralateral bundle branch are critical for perpetuation of the aberration.

Appearance of aberration during a regular heart rate
Acceleration dependent aberration may appear after several normally conducting impulses during a regular heart rate (fig 14). The appearance of aberration without a demonstrable change in the heart rate is most likely due to gradual prolongation of either voltage or the time dependent refractoriness (fig 15). Inappropriate restitution of ionic concentrations may contribute to the time dependent refractoriness and may to some extent also explain "fatigue" and overdrive suppression (see above).

Aberration secondary to gradual delay of bundle branch conduction
Gradual delay of bundle branch conduction (fig 16), evidenced by a gradual widening of the QRS, has been equated with type I, Wenckebach, second degree bundle branch block. Similarly, intermittent normalisation of bundle branch conduction may represent concealed Wenckebach conduction (fig 9). Once the delay of bundle branch conduction reaches a critical point and a complete bundle branch block is inscribed, any further delay of bundle
branch conduction cannot alter the QRS duration and thus will go unrecognised.

**Aberration and the "crossover" phenomenon**

The paradox of left bundle branch block at shorter coupling intervals and of right bundle branch block at longer coupling intervals (fig 17) has been recognised for years. It is often referred to as the "crossover" phenomenon and reflects the paradox of a longer refractory period of the left bundle branch at short coupling intervals and a longer refractory period of the right bundle branch at longer coupling intervals. The mechanism responsible for this phenomenon is unclear but is probably secondary to injury.

**Aberrant conduction after premature complexes or pauses**

Aberrant conduction may terminate a compensatory pause after an atrial premature complex while, paradoxically, normal conduction may follow a shorter compensatory pause induced by a ventricular premature complex (fig 18).

The most likely mechanism for aberration after the atrial premature complex is concealed conduction of the atrial premature complex into the bundle branch thus shortening the bundle branch interval as discussed above. A possible but unlikely mechanism for aberration after an atrial premature complex is diastolic depolarisation. Phase 4 depolarisation is, however, incompatible with bundle branch block during sinus rhythm at considerably shorter cycles, unless one accepts the presence of acceleration and deceleration aberration.

In the presence of multiform ventricular premature complexes a compensatory pause following one pattern of ventricular premature complex may be terminated with aberration while the compensatory pause of a different form of ventricular premature complex may terminate with a normally conducting QRS (fig 19). The most probable explanation for such observations is that concealed conduction into the bundle branch with shortening the bundle branch interval occurs with one type of ventricular premature complex and not the other.

Rarely, intermittent supraventricular tachycardia is interrupted by pauses that are followed by aberrant conduction at a rate identical with that of the normally conducted complexes (fig 20). The mechanism for the aberration in such cases is unclear. One can postulate that the first aberrant QRS after the pause is due to diastolic depolarisation and that propagation of aberration is due to concealed transseptal conduction from the contralateral bundle branch thus shortening the bundle branch to bundle branch interval.
Acceleration dependent aberration appearing at slow heart rates
One of the most intriguing vagaries of acceleration dependent aberration is its appearance at extremely slow heart rates. While the vast majority of patients manifest acceleration dependent aberration at cycles longer than 750 ms, aberration at intervals as long as 1000 ms and occasionally as long as 1800 and 2000 ms have been recorded (fig 21). Although significant prolongation of the action potential duration has been recorded in abnormally functioning Purkinje fibres,\textsuperscript{30-32} aberration at such strikingly slow rates cannot be readily explained by simple prolongation of recovery of transmembrane potential (voltage dependent refractoriness). Time dependent refractoriness can be postulated (fig 15). It is also possible that a delay or block of conduction in the His-Purkinje system can result because of an abnormal state of the His-Purkinje system, with a reduction of diastolic potential,\textsuperscript{33} coupled with gradual diastolic depolarisation and slowing of the upstroke velocity and a shift in threshold toward zero. Injury of the His-Purkinje system may cause such changes.\textsuperscript{35}

Another mechanism for aberration at unexpectedly long cycles may be concealed conduction into a bundle branch block. This has been observed with atrial and ventricular premature complexes. Similarly, during atrial fibrillation, persistence of aberration at long cycles may be due to concealed conduction of fibrillatory waves into a bundle branch as mentioned above.

**Discussion**
While a strong case can be made in favour of one or another mechanism for aberration in any given setting and some have been documented experimentally, the fact remains that most explanations still are based in deductive reasoning and extrapolations from the behaviour of the myocardium as reflected in the electrocardiogram by the P and QRS and, occasionally, the His-bundle electrocardiogram. It is almost certain that some of the conclusions so arrived at are in error. Many of the basic, cellular processes responsible for aberration remain to be elucidated. More sophisticated techniques for recording activation sequences and local action potential characteristics in the human will be required to allow more precise assessment of the mechanism for aberrancy under physiological and pathological conditions. However, for the purpose of giving structure to the observations presented above, it may be helpful to review some concepts about aberrancy that have developed since Lewis's original observations.

There is strong evidence indicating that acceleration dependent aberration is a marker of heart disease. While the heart disease may not be clinically evident initially, clinical signs...
Aberration is acceleration at Electrocadiography of arrhythmias. Philadelphia: the of acceleration dependent aberration LI.1 compensatory pause that the of the normally such follows at long cycles may be different with the A-H wave. Thus, it is possible that the considerable shorter coupling interval of the left bundle branch as compared to that of the right bundle branch reflects the crossover phenomenon of the refractory periods of the bundle branch. (Reproduced with permission from Fisch C. Electrocardiography of arrhythmias. Philadelphia: Lea and Febiger, 1990:66.)

Acceleration dependent aberration differs from physiological or “expected” forms of aberration as follows: “expected” aberration is seen in normal hearts; “normal” aberration is elicited by a premature impulse or stimulus and rarely, if ever, by a gradual acceleration of the rate because atrioventricular refractoriness will usually exceed His-Purkinje refractoriness thus precluding aberration; physiological aberration is nearly always of right bundle branch block pattern; coupling of a stimulus that elicits physiological aberration is quite short so that the stimulus occurs during the recovery of the action potential and the aberration can be readily explained by voltage dependent refractoriness; and the presence or absence of aberration is dependent on the duration of the preceding cycle length (Fig 22).

Because of the differences between aberration that may be present in the normal heart and acceleration dependent aberration which is nearly always an expression of an abnormal state, the two forms should be considered to be different phenomena if interpretation of the data dealing with aberration is to be meaningful.

Proposed mechanisms for acceleration dependent aberration as presented above include: (a) prolongation or failure of the action potential to shorten appropriately in response to an increase in the heart rate, creating the milieu for voltage dependent refractoriness; (b) refractoriness persisting after completion of repolarisation (time dependent refractoriness) or, (c) myocardial injury involving one of the bundle branches or fascicles resulting in partial depolarisation of cells within the affected bundle creating conduction delay or block that is independent of refractoriness. Local action potential alterations also may electrotonically affect cells more proximal in the conduction system creating slowed conduction or block at that level.

While it is possible that in pathological states voltage or time dependent refractoriness may be altered sufficiently to be responsible for acceleration dependent aberration, and, while functional conduction disturbances have been

Figure 20 Aberration follows paradoxically longer cycles and continues at a rate identical to that of the normally conducted complexes.

Figure 21 Aberration at cycle lengths varying from 920 to 1250 ms. The fact that aberration is acceleration dependent is documented by normalization of conduction after the long compensatory pause induced by the blocked atrial premature complex. Aberration at such long cycles may be due to time dependent refractoriness, to injury, or a combination of the two. (Reproduced with permission from Fisch C. Electrocardiography of arrhythmias. Philadelphia: Lea and Febiger, 1990:62.)

Figure 22 Relation of the coupling interval (abscissa) to preceding cycle length (ordinate) of the right and left bundle branch block aberration. Whereas left bundle branch block is independent of the duration of preceding cycle, right bundle branch is dependent on the duration of the preceding cycle. The right bundle branch block follows long preceding cycles in keeping with the A-H wave phenomenon. The appearance of bundle branch block follows: (a) prolongation of the refractory period stability and/or acceleration dependent aberrancy, (b) the predominant of left bundle branch block aberrancy, (c) the frequent coexistence of acceleration with deceleration dependent aberration, the latter being a sign of heart disease, (d) the occasional appearance of acceleration dependent aberration after several equal RR cycles indicating inappropriate refractory period stability and/or abnormal electrophysiological properties, (e) independence from the duration of the preceding cycle (Fig 22).
shown to be favoured at low basic heart rates, it is unlikely that either could account for aberration at cycle lengths of 1000 ms or longer, a not infrequent finding in acceleration dependent aberration. In such instances, disturbances of conduction are more likely to be secondary to alterations in action potential characteristics such as phase 4 depolarisation, slowing of the upstroke of phase 0, or reduction of threshold potential due to electropathology. A unifying concept could, therefore, be injury to the conduction tissue, at diverse levels, is the basic defect that underlies acceleration dependent aberration.

When the vagaries of acceleration dependent aberration are under consideration still other mechanisms or combinations of mechanisms need to be invoked. Examples of these are presented above and include: (a) shortening of the bundle branch to bundle branch cycle without change in the manifest QRS to QRS cycle secondary to concealed transmural conduction [12, 17, 25] or concealment of atrial and ventricular premature complexes into the bundle branches, (b) local injury enhanced by acceleration of the heart rate and a resultant depression or block of conduction manifesting as fatigue, or overdrive suppression, (c) conduction during the supernormal period of recovery, (d) block above the area of injury allowing for bundle branch recovery, (e) "crossover" of the refractory period duration of right and left bundles, (f) equal prolongation of bundle branch conduction, (g) diastolic (phase 4) depolarisation, [17, 19] or, (h) Wenckebach block in a bundle branch. [19, 26]

Aberration under normal physiological conditions, acceleration dependent aberration and its vagaries, and the similarities and differences between the various "normal" and "abnormal" forms of aberrancy provide a model for understanding electrophysiological functioning that is unequalled by any other concept. Even if basic cellular and intracellular mechanisms for electrophysiological alteration are eventually totally understood there will continue to be the need for an integrated approach to the conducting system and its functional vagaries. Knowledge of ion channel functioning under a wide variety of intervention and injury, action potential characteristics in response to such changes, the effects on refractoriness, cell-to-cell communications, and the effects of all of these on conduction patterns is essential if we are to be able to delineate mechanisms for aberrancy with more precision that has been possible to date. There is a large body of experimental data about the cellular electrophysiological properties underlying aberration. A systems approach is needed to make these observations applicable to the human.

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Br Heart J 1992 67: 16-24
doi: 10.1136/hrt.67.1.16

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