The Mechanism of Atrioventricular Conduction

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Potentials recorded at various sites in the atrioventricular (A-V) conduction system indicate that conduction is continuously electrical in nature and involves no synapse-like (i.e., chemical) conduction. The region between atrium and atrioventricular node has the slowest conduction velocity (~0.05 M/sec.) and lowest safety factor. Conduction through the A-V node is at about ~0.12 M/sec. Results demonstrate shapes of potentials recorded extracellularly at various sites within the A-V node, first degree and complete block during rapid atrial stimulation, and echo-like phenomena.

In 1883 Gaskell established the relationship of atrial and ventricular conduction. Shortly thereafter, the anatomical connection between the atria and ventricles was described by Tawara. In 1910 Hering estimated the time required for conduction through the A-V node by stimulating either above or below it and recording ventricular contraction. He found the conduction time about four times longer when stimulation was above the node, and concluded that this difference indicates the fraction of the atrioventricular (A-V) interval consumed within the node.

In subsequent years, electrical recording techniques were developed which permitted measurement of the interval between atrial and ventricular activation. Hering's studies were extended with electrical rather than mechanical records by Lewis and Master, Rosenblueth and Rubio, Krayer et al., and Moe and associates.

The fundamental physicochemical processes in muscle conduction were studied by Weidmann and coworkers. Several workers recorded from the Purkinje tissue in situ. Also important to theories of A-V conduction have been effects of drugs, attempt to stimulate the node directly and to damage it, and information about clinical A-V arrhythmias.

A study by Puech et al. indicated that the atrial musculature in the region of the A-V node is depolarized when the P wave is about two thirds completed. The interval during which the impulse is in the node and bundles thus extends from this time to the beginning of ventricular depolarization.

Several theories have been advanced to explain events in the A-V node. It has been claimed that the node is activated by atrial repolarization, that it is a continuous oscillator which fires when the atrial impulse coincides with a nodal oscillation, that it normally inhibits A-V conduction, and that the A-V conduction system has separate "fast" and "slow" pathways. Recently, van der Kooi and associates reported numerous, rapid, negative-going and positive-going potentials from small bipolar electrodes within the A-V node. Such potentials never occurred in the A-V node in our own experiments.

The several speculations concerning A-V conduction have been based on indirect evidence; for this reason, a search for A-V nodal potentials was undertaken with two types of multipolar electrodes and a multichannel recording apparatus previously described. While this work was being prepared for publication, a study of potentials recorded intracellularly in the A-V node of the rabbit heart was reported by Hoffman and his associates. Their results are similar to some in this report, although a different recording electrode was used.

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METHODS

The search for potentials from the A-V node required electrodes and recording equipment which would permit rapid scanning of many points in the A-V nodal region. We used two types of electrodes. The first consisted of 3 insulated wires with their cut ends staggered at 1 mm. intervals. Five such assemblies were connected to a single 15 terminal Jones plug. The second type contained 28 three terminal electrodes mounted at 1 mm. intervals on a plastic sheet to form an assembly resembling a 28 bristle brush. The three-terminal electrodes were in a rectangular pattern, 4 mm. by 7 mm., so that the 84 recording points were positioned at every millimeter along rectangular coordinates in a volume 2 mm. by 3 mm. by 6 mm. The recording points were connected to six 15 terminal Jones plugs. This electrode will be referred to as three-dimensional (fig. 1).

The preamplifiers were direct-coupled, with input impedance of 1,000 megohms. The response of these amplifiers was flat to 50 kc. and they had a common-mode rejection of 1,500. The oscilloscope consisted of 15 separate cathode ray tubes with a common sweep generator. Time signals were fed into all channels from a single oscillator. The stimulator was assembled from Tektronix wave form generators and Tektronix pulse generators with a separate mixer amplifier and transformer isolation unit. In some cases, a Grass stimulator with an RF isolation unit was triggered by this stimulator, since the Grass unit provides better isolation of the stimulus from ground.

As the tubes of the 16 channel oscilloscope are in a square array, it is difficult to record more than 4 channels with moving film. In some experiments a Rycorn 12 channel oscilloscope was also used, since this unit provides better time resolution when records are taken with a sweep and permits recording more than 4 channels with moving film.

In the early experiments the heart was exposed in the open-chest dog, and electrodes were inserted into the A-V nodal region of the interatrial septum through the right atrial wall and across the right atrial cavity. Because accurate placement of electrodes in the A-V nodal region was difficult with this "blind" procedure, a modified Langendorff perfusion was used in many later experiments.

The heart of a small (about 8 Kg.) dog was perfused by feeding blood from the carotid artery of a large (15 to 20 Kg.) dog to a cannula which was installed in the aorta and directed toward the perfused heart. The venous outflow was returned to the jugular vein of the donor. When the perfusion had been established, the right coronary artery was tied, and the right atrium and ventricle were incised to expose the right surface of the interatrial and interventricular septa. The donor animal was kept slightly hyperthermic and the temperature of the perfused heart was between 36 and 40 C. Electrodes were then inserted perpendicular to the septum into the region of the A-V node and the common bundle.

A potential which seemed to be from the node or bundle was always examined by stimulating the S-A nodal region at several interstimulus intervals (usually 630, 500, 400, 320, 250, 200, and 160 msec.) to see if first degree block of this potential could be produced. Marked first degree A-V block is produced when the S-A node is stimulated at frequencies of 4/sec. and faster.* Unfortunately, when stimuli are delivered at this rate, the atrial, nodal and bundle potentials will be superimposed on the ventricular complexes of the preceding beat.

*Potentials between atrial and ventricular depolarization which were not from the A-V conduction system were found on two occasions. These potentials were from a strand of atrial muscle which had been mechanically separated from the interatrial septum. They did not display first degree block on rapid stimulation.
RESULTS

Potentials from the A-V node were recorded in more than 27 hearts. Figure 2 shows potentials recorded at several sites near and within the A-V node and in the common bundle in one experiment. The accompanying drawing indicates the time relationship of these potentials to the normal electrocardiogram.

The atrial potentials upstream from the A-V node showed a positive-negative contour. In the upper A-V node the atrial potential was followed by a negative or positive-negative potential, which may be in part superimposed on the atrial potentials. In the center of the node the potential was of the positive-negative type. Near the common bundle the A-V nodal potential was positive, and was terminated by a rapid negative-going bundle potential. One millimeter closer to the ventricle a smaller positive “slow” potential was terminated by the fast positive-negative common bundle potential. Two millimeters farther down the bundle no “slow” potential is seen.

Figure 3 shows the changes in the A-V nodal potential which appear when first degree block is produced by altering the rate at which the atrium is stimulated. When the interstimulus interval was 630 msec, the “slow” potential began about 30 msec after the beginning of the rapid atrial potential. At a 500 msec interval, the A-V nodal potential occurred earlier, and was superimposed on the terminal phase of the atrial potential. As the interstimulus interval was further decreased the A-V nodal potential occurred progressively later until, when the interstimulus interval was 160 msec, it disappeared. The right hand column indicates that the potential of the common bundle occurred at the end of the “slow” potential at all frequencies, and was missing when the “slow” potential was absent. The common bundle potential is preceded by a slight but significant positive “slow” potential which is prolonged as first degree block occurs. It can best be seen by superimposing a tracing of the potential at 500 msec stimulation interval over those at shorter intervals in B.
Figure 4 shows the effects of forward and retrograde stimulation at various frequencies on “slow” potentials, and on the time between firing of the atrium and of the upper A-V node (A-AV) and between A-V node and atrium (AV-A). In A the positive-negative atrial potential follows the stimulus artefact and is in turn followed by the negative A-V nodal potential. In B the positive-negative A-V nodal potential is at the left of the sweep and is followed by the negative atrial potential. On forward stimulation first degree block was first seen at an interstimulus interval of 230 msec. The A-AV time was further prolonged at shorter intervals. The AV-A time was longer at all frequencies and showed first degree block at an interstimulus interval of 360 msec.

A Wenckebach phenomenon (intermittent complete block following increasing first degree block) was seen during both forward and backward stimulation, and occurred at a slower frequency on retrograde stimulation (interstimulus interval, 285 msec., compared with 180 msec.), as did complete block (230 msec, as compared with 180 msec.). On forward stimulation some prolongation of the local A-V nodal potential was seen during block. The point of lowest safety factor for both forward and retrograde stimulation was between the atrium and the A-V node.

In some experiments involving retrograde stimulation, an apparent “echo” was seen (fig. 4C). At an interstimulus interval (290 msec.) near that which produced complete block on retrograde stimulation, the impulse passed to the A-V node, giving an A-V nodal potential identical with that seen at slower stimulation rates during V-A conduction; the atrium then followed the node but at a very long interval (125 msec.), indicating extreme first degree block at the nodo-atrial junction. The A-V nodal potential then recurred following the atrial depolarization. The configuration of this potential was identical with that seen in normal forward conduction, and the potential followed the atrial potential at an interval similar to that seen in forward conduction at a rate of 5/sec.

Figure 5 shows the effects of stimulation at various frequencies on A-V nodal and bundle potentials. Column A shows a negative-going A-V nodal potential which follows a large negative atrial potential. This recording electrode was within A-V node. Column B illustrates potentials recorded 2 mm. away, near origin of common bundle. Small negative potential following atrial potential in A and positive-going potential preceding depolarization of bundle in B are due to activation of A-V node. Magnitude of A-V nodal potential in both A and B can be seen by comparison with potentials recorded at interstimulus interval of 160 msec., which show neither A-V nodal nor bundle activity (complete block). Atrial potentials in A are of 2 mv. magnitude; time pips are at 20 msec. Discussion in text.

Figure 5 shows the effects of stimulation at various frequencies on the time required for conduction between atrial cells in the nodal region and the common bundle. The time required for retrograde conduction between the same two points under similar conditions is also shown. Only those intervals which give 1:1 conduction are illustrated. The conduction interval was somewhat longer than the
FIG. 4. Potentials recorded within A-V node on forward (A) and retrograde (B) conduction. Inter-
stimulus interval indicated at left of each column. Stimulus artefact in A is followed by positive-negative
atrial potential and by negative A-V nodal potential. Stimulus in B was delivered to right bundle. Stimulus
artefact does not appear in B but stimulus was de-
ivered at time corresponding to beginning of the
sweep. Positive-negative potential at left of B is
from A-V node. Negative potential which follows is
from atrium; C shows an echo-like phenomenon.
Stimulation of right bundle leads to nodal depolariza-
tion (at left of top trace) followed by atrial depolari-
zation which is followed by a second A-V nodal
depolarization. Second trace shows simultaneous com-
mon bundle potential at left and right, and lowest
trace shows simultaneous atrial potential recorded up-
stream from A-V node. Discussion in text.

minimal (30 msec.) atrial bundle interval. First
degree block occurred at a slower fre-
cquency during retrograde conduction than
during forward conduction. As the inter-
stimulus interval was decreased, retrograde
conduction showed a greater slowing than did
forward conduction.

Discussion

Shape of the A-V Nodal Potential. The poten-
tial in the upper A-V node (figs. 2, 3 and
4) consists of a negative-going deflection
which develops slowly, stays near its maxi-
mum value for some time, and then returns
toward the baseline (which often is not flat
but is slightly positive (figs. 2 and 3) due
to atrial injury and/or repolarization). As
the electrode moves toward the common
bundle the potential becomes positive-negative
and then positive. These potential shapes
lead to the conclusion that the impulse is
conducted through the node. The nodal
potentials are almost continuous with the local
atrial potential but usually there is a period
of from 5 to 15 msec. during which the poten-
tial changes very little. If conduction is
indeed continuous there may be some cells
which generate potentials undetectable with
our technic. In ultrimicroelectrode records
presented by Hoffman and co-workers22 there
is also an interval during which no records of
depolarizing cells are shown. The atrio-A-V
nodal junction2 consists of a series of parallel
strands of muscle interspersed with connec-
tive tissue and it seems likely that activity
of these strands is not usually recorded with
our technic. The slow development of the
A-V nodal potential is quite contrary to what
would be expected in a muscle strip. In the
latter case, a rapid negative-going potential
with slower return to zero would be recorded
at the end of the strip at which activity com-
cenced. That the upper A-V nodal potential
increases in negativity, or stays at its peak
value for some time, indicates that the solid
angle subtended by the wave front does not
alter and/or that the resistive changes accom-
panying depolarization increase the voltage
at the recording electrode as the wave recedes.
The potential shape is in harmony with the
idea that excitation proceeds from small num-
bers of fibers into a larger mass and with the
general shape of the A-V node.

Intracellular potentials of the A-V node22
do not differ greatly from potentials of other
cardiac fibers. Differences between extracel-
ular records in the node and those recorded
elsewhere in the heart reflect differences in
cell size, conduction velocity and geometry of
the region.

Electrodes within the A-V node record the
potentials of the entire node over a distance
of about 2 mm. Electrodes 2 mm. outside the
node (and usually electrodes 1 mm. outside)
do not show the nodal potentials. This sug-
gests a resistive inhomogeneity of the peri-
nodal region.

Conduction Velocities. The multichannel
recording technic permits concurrent meas-
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Measurements from many sites. In several experiments, simultaneous records were taken from many points showing A-V nodal, bundle and atrial potentials. The slow rate of change of the nodal potentials from the node makes velocity calculations approximate. The region of fine fiber bridges above the node appears to have a conduction velocity of about 0.05 M./sec. The node itself conducts somewhat more rapidly, i.e., about 0.12 M./sec. The over-all velocity of normal conduction between atrium and common bundle is about 0.10 M./sec.

Retrograde conduction usually is somewhat slower over all, i.e., about 0.08 M./sec. The retrograde conduction velocity through the node appears to be the same as the forward velocity, but the retrograde velocity through the atrio-A-V nodal junction is slower than the forward velocity.

Possible Mechanism of First Degree and Complete A-V Block. In most excitable tissues, conduction is slowed when a stimulus is delivered before repolarization is complete. The action potential of the A-V nodal cells lasts about 150 to 200 msec. Slowing of conduction would be expected at this interstimulus interval. Surprisingly, slowing of A-V conduction usually occurs with intervals of 300 msec. or more. Several explanations are possible: 1. It is possible that conduction in the atrio-A-V nodal bridge involves some electrical mechanism which differs from that in other cardiac tissues. 2. The cells at the atrio-A-V nodal junction may have action potentials of very long duration. 3. Some ionic permeability changes may persist beyond the action potential in these cells.

Ordinarily, effects of rapid stimulation are not cumulative within the range of 2 to 4 impulses/sec., i.e., the atrio-A-V conduction time at a certain interstimulus interval is independent of the previous rate. At higher stimulation rates cumulative effects are noted and a Wenckebach phenomenon may occur (fig. 4). When it occurs the ionic shifts (K+ efflux) may be undergoing summation to some extent from beat to beat.

Dual A-V Conduction System: Echo-Like Phenomenon. In our experiments A-V conduction, forward or retrograde and with or without block, follows a single pathway through the A-V node and common bundle for forward (lower curve) and retrograde (upper curve) conduction. Description in text.

The Atrio-A-V Nodal Junction. In this region the atrial muscle fibers separate into discrete strands, interspersed with connective tissue. Slow conduction and low safety factor might be expected here as a result of the decreased number of fibers per unit volume. Furthermore, these fine strands of fibers must excite a larger volume of fibers in the A-V node. This junction should also display a low safety factor. However, the A-V conduction system exhibits a lower safety factor for retrograde than for forward conduction. In
this case the lowest safety factor may be between the junctional fibers and the atrium rather than between the nodal and junctional fibers. In any event, the upper A-V node is the weakest link between the atrium and the ventricle and can be broken down into multiple pathways.

Other Theories of A-V Conduction. The theory that A-V nodal depolarization is initiated by the rapid phase of atrial repolarization19 is untenable, since the latter occurs 40 msec. or more after the former. It is however possible that some current flow from resting nodal cells into depolarized atrial cells continues through part of the interval we ascribe to conduction in the A-V node. The belief that the A-V node is a continuous oscillator20 is unsupported by our results, since no such oscillations are seen. That the A-V node normally slows A-V conduction14-18 is not supported by any of our experiments; the experiments which produced this theory probably involved extrasystoles rather than conducted impulses.

Mechanism of Conduction between Atrium and Ventricle. Several lines of evidence indicate that only electrical conduction of impulses is important in A-V nodal transmission. First, the potentials recorded at various sites in the node have shapes which are consistent with electrical conduction: negative in the upper node, positive-negative in the center, and positive near the common bundle. These shapes change appropriately with retrograde conduction and A-V rhythm,23 and occupy almost the entire time between the firing of atrial cells in the nodal region and the activation of the common bundle. A synaptic, endplate-like, or other chemical process is further contraindicated by the occurrence of retrograde conduction.

SUMMARY

The shapes of A-V nodal potentials lead to the conclusion that continuous electrical conduction of the impulse occurs through this region, and that A-V nodal conduction involves no mechanisms different from those seen elsewhere in myocardial conduction. The atrio-A-V nodal junction is the region of lowest safety factor and slowest conduction velocity (about 0.05 M./sec.). The conduction velocity within the A-V node is about 0.12 M./sec. The interval between the firing of the atrial cells in the nodal region and the firing of the common bundle in the dog is about 30 msec. Examples are given of the shapes of potentials recorded on small extracellular electrodes at various sites along the atrioventricular conduction pathway, conduction block during rapid stimulation, time course of retrograde conduction, and Wenckebach and echo-like phenomena.

SUMMARIO IN INTERLINGUA

Le conformation del potentiates del nodo atrio-ventricular suggere le conclusion que un continue conduction electric del impulso occurre a transverso iste region e que le conduction del nodo atrio-ventricular depende de nulle mechanismos a parte illos observate alterubi in le conduction myocardial. Le junction del nodo atrio-ventricular es le region del plus basse coefficiente de securitate e del plus lente conduction (circa 0,05 m/sec). Le conduction intra le nodo atrio-ventricular es circa 0,12 m/sec. Le intervallo inter le igni- tion del cellulas atrial in le region nodal e le ignition del fasce commun in canes es circa 30 msec. Es presentate exemplos del conformation de registrationes del potential per medio de micre electrodos extracellular a varie sitos al longo del via de conduction atrio-ventricular, de bloco de conduction in stimu- lation rapide, de curso de tempore in conduc- tion retrograde, e de phenomenos de Wenke- bach e echo-oide.

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