Chronotropic and Dromotropic Responses to Stimulation of Intracardiac Sympathetic Nerves to Sinoatrial or Atrioventricular Nodal Region in Anesthetized Dogs

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We gave atropine intravenously to autonomically decentralized, open-chest, anesthetized dogs and stimulated the discrete intracardiac sympathetic nerve fibers to the sinoatrial (SA) (SAS stimulation) or atrioventricular (AV) (AVS stimulation) nodal region. A brief burst of neural stimuli was delivered during each cardiac cycle. SAS stimulation consistently decreased the atrial cycle length but had variable effects on the AV interval. The positive chronotropic response to SAS stimulation increased when the level of stimulation (i.e., stimulus pulse duration, pulse amplitude, and number of pulses per burst) was increased. When the heart rate was held constant by atrial pacing, SAS stimulation did not change the AV interval. AVS stimulation decreased the AV conduction time but did not change the atrial cycle length. The AV conduction response increased when the level of AVS stimulation was increased. A high level of AVS stimulation induced an AV junctional rhythm in seven of eight experiments. When the atrial pacing interval was decreased, the basal AV interval increased, and the decrease in AV interval induced by AVS stimulation was exaggerated. The chronotropic response to SAS stimulation and the dromotropic response to AVS stimulation were abolished by propranolol given systemically and by lidocaine given topically. From these results, we conclude that in anesthetized dogs treated with atropine, activation of the discrete intracardiac sympathetic nerves to the SA and AV nodal regions controls the sinus rate and AV conduction time independently and activation of the discrete sympathetic nerves may shift the dominant pacemaker site to a subsidiary site. (Circulation Research 1990;66:1391–1399)

Stimulation of the stellate ganglia usually elicits global responses from all structures of the dog heart, but excitation of the individual nerve trunks in the cardiac plexus induces discrete responses in localized regions of the heart.1–3 Localized epicardial denervation abolishes the responses to stimulation of the corresponding discrete nerve branches.1–3 After sequential dissection around the major cardiac vessels of the dog heart, the resulting deficits in the responses to ansa subclavia stimulation indicate that parallel but distinct sympathetic efferent fibers project to the automatic, conductile, and contractile tissues.4 Thus, discrete sympathetic nerve fibers to the sinoatrial (SA) or atrioventricular (AV) nodal area may control SA nodal pacemaker activity or AV conductivity, respectively.

In studies of the effects of sympathetic nerve stimulation on various aspects of cardiac functions, extracardiac sympathetic nerves (stellate ganglia or ansa subclavia) have been stimulated electrically in experiments in vivo to elicit global cardiac responses. The function of specific nerves in the cardiac plexus has been deduced by observing the deficits in the global cardiac responses. Inadequate attention has been directed toward assessing the responses to direct stimulation of the specific cardiac nerves.

In recent studies, dissection of the fatty tissue overlying the atrial junction of the right pulmonary veins and the fatty tissue at the junction of the inferior vena cava and left atrium eliminated vagal input to the SA and the AV nodal regions, respectively, in anesthetized dogs.5,6 Parasympathetic ganglia lie on those fatty tissues.7 When anesthetized dogs’ presynaptic parasympathetic nerves at each fatty tissue were stimulated with a very narrow pulse duration, stimulation of the parasympathetic nerve

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fibers to the SA nodal region prolonged the sinus cycle length without affecting AV conduction time directly, and stimulation of the parasympathetic nerve fibers to the AV nodal region prolonged AV conduction time without changes in sinus cycle length.\textsuperscript{8,9} We previously reported that stimulation of the parasympathetic and sympathetic nerve fibers to the SA nodal region at the fatty tissue overlying the atrial junction of the right pulmonary vein induced negative followed by positive chronotropic and inotropic responses in the isolated, blood-perfused dog atrium.\textsuperscript{10,11} Thus, we hypothesized that in anesthetized dogs after treatment with atropine, adequate electrical stimulation could directly activate intracardiac sympathetic nerve fibers to the SA or AV nodal region to decrease sinus cycle length or AV conduction time, respectively.

In the present study, therefore, we investigated whether there were separate loci at which the intracardiac sympathetic nerve fibers to the SA or AV nodal region could be directly stimulated independently in the heart in situ. We did find loci at which discrete intracardiac sympathetic nerve fibers to the SA (SAS stimulation) and AV nodal regions (AVS stimulation) could be stimulated independently. Then, we investigated whether SAS stimulation directly decreased the atrial cycle length and altered the pacemaker site and whether it had any detectable effect on the AV conduction time. We also investigated whether AVS stimulation decreased AV conduction time without affecting the sinus cycle length and whether it could induce an AV junctional rhythm when the SA nodal pacemaker was active.

Materials and Methods

Preparation

Seventeen mongrel dogs weighing 13–27 kg were used in the study. Each dog was anesthetized with sodium pentobarbital (30 mg/kg i.v.). A tracheal cannula was inserted, and intermittent positive-pressure ventilation was started. The chest was opened transversely at the fifth intercostal space. Each cervical vagus nerve was crushed with a tight ligature, and each stellate ganglion was ligated tightly at its junction with the ansa subclavia. These maneuvers remove virtually all tonic neural activity to the heart.\textsuperscript{12}

Two bipolar electrodes were placed on the base of the epicardial surface of the right atrial appendage to record the electrical activity and pace the atrium. A bipolar recording electrode was also placed on the epicardial surface of the right ventricle. The deflection recorded during depolarization of the right atrium is referred to as A, and the deflection recorded during depolarization of the right ventricle is referred to as V. Each beat of the atrial (AA) and AV intervals was measured and displayed on an oscillograph (model TA2000, Gould, Cleveland, Ohio).

His bundle activity was recorded from a quadripolar electrode catheter inserted via the right femoral artery and positioned in the noncoronary or right coronary cusp of the aortic valve. The position of the electrode was verified after the experiment was completed. The His bundle electrogram was filtered with a band pass of 30–300 Hz. The electrograms were recorded on the oscillograph at paper speeds of 100 or 200 mm/sec. In these electrograms, the atrial deflection is referred to as a, the His bundle deflection as h, and the ventricular deflection as v. Systemic arterial pressure also was recorded.

Two bipolar silver electrodes, each having a 2-mm interelectrode distance, were used to stimulate the regional intracardiac sympathetic nerve fibers.\textsuperscript{8–11} One bipolar electrode was placed on the fatty tissue overlying the right atrial side of the right pulmonary vein junctions. This electrode was used to stimulate the intracardiac sympathetic nerve fibers to the SA nodal region (SAS stimulation). The second electrode was placed on the fatty tissue at the junction of the inferior vena cava and the left atrium.\textsuperscript{5,6,8,9} This electrode was used to stimulate the intracardiac sympathetic nerve fibers to the AV nodal region (AVS stimulation).

Repetitive bursts of stimuli (model S88, Grass Instrument, Quincy, Massachusetts) with 10–15-mA pulse amplitude and 0.01–1-msec pulse duration were used.\textsuperscript{13} The interpulse interval within each burst was 10 msec. A brief burst of neural stimuli was delivered in each cardiac cycle; each stimulus burst contained from one to five pulses. Stimulation was triggered by the atrial depolarization (A wave); the time from the beginning of the A wave to the beginning of the stimulus burst was 20 msec. Thus, a burst with five pulses terminated within 65 msec from the beginning of atrial depolarization. Each 1-minute train of stimuli to the nerves was followed by a recovery period of at least 4 minutes.

To avoid excitation of these structures, brief bursts of stimuli were delivered at preselected times each cardiac cycle to coincide with the absolute refractory period. In the present study, submaximal levels of nerve stimulation were used because the cardiac responses gradually decreased with time with higher levels of stimulation (e.g., 3-msec pulse duration, 15-mA pulse amplitude, and five pulses per burst) and because excessively strong stimulation would excite myocytes as well as nerve fibers.

Experimental Protocols

At the start of each experiment, atropine sulfate (0.2 mg/kg i.v.) was given, and 0.1 or 0.2 mg/kg i.v. atropine was given each hour thereafter to block the responses mediated by the muscarinic receptors. These doses of atropine completely inhibited cardiac responses to stimulation of the cervical vagus nerves.

The first series of experiments were designed to characterize the cardiac chronotropic and dromotropic responses to various stimulus characteristics. Changes made include increasing the pulse duration...
over the range from 0.01 to 1 msec, the number of the pulses per burst over the range from one to five, and
the pulse amplitude over the range from 10 to 15 mA.

We then studied the effects of the pacing cycle length on responses to SAS or AVS stimulation. First,
the atrium was paced at a slightly shorter interval than the shortest cardiac cycle length induced by SAS
stimulation. Then the effects of pacing cycle lengths of 400, 300, and 250 msec on the dromotropic response
of AVS stimulation were studied.

The second series of experiments were designed to verify that the responses to stimulation were induced by
norepinephrine released from sympathetic nerve terminals. The effects of propranolol hydrochloride and
lidocaine hydrochloride on the responses to SAS and AVS stimulation were determined. Propranolol
was injected at cumulative doses (1–100 µg/kg i.v.) into the femoral vein. Lidocaine (1 or 3 mg) was
injected into the fatty tissue on which the electrode had been placed for nerve stimulation. Five minutes
after injection of propranolol or lidocaine, the effects of the drug on cardiac responses to stimulation were
determined.

The steady-state responses at 60 seconds were measured after the beginning of nerve stimulation,
unless otherwise stated. All data are expressed as mean±SEM. The data were analyzed by paired or
unpaired t test for comparison between two groups and by analysis of variance for comparisons among
more than two groups. p values of less than 0.05 were considered to be significant.

Results

SAS Stimulation

SAS stimulation decreased the atrial cycle length (Figure 1). As the pulse duration of SAS stimulation
increased stepwise from 0.01 to 0.3 msec, the reductions in atrial cycle length became greater. These
reductions in atrial cycle length were accompanied by variable changes in the AV interval. For example,
when a pulse duration of 0.3 msec was used, the AV interval first decreased and then increased (Figure 1).

Composite data from eight experiments are shown in Figure 2. As the pulse duration of SAS stimulation
was prolonged (Figure 2A), the atrial cycle length progressively decreased (p<0.001). The AV interval
tended to decrease as the pulse duration increased, but the changes were not significant. The reductions
in atrial cycle length induced by SAS stimulation were also augmented (p<0.005) as the number of pulses per burst (Figure 2B) or the pulse amplitude (data not shown) increased.
Figure 3A shows the shift in pacemaker site induced by SAS stimulation in a spontaneously beating heart. After 30 seconds of SAS stimulation (middle panel), the atrial cycle length decreased from 540 to 485 msec and the AV interval decreased from 145 to 120 msec. However, the deflection of the His electrogram started 20 msec before the A wave, and the shape of the His electrogram also changed. During SAS stimulation, the AV interval response was variable (Figures 1 and 3A). SAS stimulation decreased the AV interval by 18±4.5 msec in seven of eight experiments. However, neither the ah nor the hV interval changed significantly, but the interval from a to A increased from the control value of −1.0±1.8 to 19±3.9 msec (p<0.001). After 60 seconds of SAS stimulation (Figure 3, right panel), the atrial cycle length decreased further, but the AV interval returned to 150 msec. The a wave closely resembled the pretimulation a wave.

When the atrium was paced at a cycle length less than the shortest cycle length induced by SAS stimulation, there was no effect on the AV, ah, and hV intervals (Figure 3B). The composite data for eight experiments are shown in Figure 4. When the atrium was unpaced, SAS stimulation for 60 seconds decreased the atrial cycle length from 521±22 to 406±22 msec but did not significantly affect the AV interval statistically. When the atrium was paced (363±15.7 msec), SAS stimulation also did not change the AV interval significantly.

**AVS Stimulation**

In a representative experiment, AVS stimulation at pulse durations of 0.05 or 0.1 msec decreased the AV interval but did not affect the atrial cycle length (Figure 5). At a pulse duration of 0.3 msec, AVS stimulation first decreased the AV interval and then induced an AV junctional rhythm.

Figure 6 shows the electrophysiological changes induced by AVS stimulation for 1 minute in a representative experiment. After 10 seconds of AVS stimulation, the ah interval decreased, but the hV interval did not change (panels I and II). After 14 seconds of AVS stimulation (panel III), the AV interval decreased to 15 msec from the control value of 95 msec (first cycle), although the atrial cycle length had not changed. This response reflects an AV dissociation. Then, in the next three cycles, the His bundle...
deflections preceded the a and v deflections. The atrial cycle length diminished from 490 to 470 msec during the four cycles (panel III). These results show that an AV junctional rhythm supervened. Thus, an AV junctional rhythm was defined as that obtained when the His bundle deflection precedes the a wave and/or the V deflection precedes the A deflection. The AV junctional rhythm was maintained during the remainder of the AVS stimulation (panels IV and V). Two minutes after the cessation of stimulation, each response variable recovered to its prestimulation control value.

The reduction in AV interval induced by AVS stimulation increased as the pulse duration was prolonged in eight anesthetized dogs (Figure 7A; p<0.001) or the number of pulses per burst in the group of six animals increased (Figure 7B; p<0.05). The atrial cycle length did not change until an AV junctional rhythm superseded the original sinus rhythm. The magnitude of the dromotropic response to AVS stimulation also depended on the pulse amplitude (data not shown).

High levels of AVS stimulation induced an AV junctional rhythm; in 12 of 16 experiments, the V wave preceded the A wave. In seven of eight experiments, the AV junctional rhythm was confirmed by the His electrograms, and in two of these seven experiments, the AV junctional rhythm alternated with a rhythm that originated in the lower atrium. In another dog, AVS stimulation induced a pacemaker shift to the lower atrium.

When the atrial pacing interval was decreased from a mean value of 400 to 260 msec, the basal, prestimulation AV interval increased progressively in eight anesthetized dogs treated with atropine (Figure 8; p<0.001). The decrease in AV interval induced by AVS stimulation was augmented (p<0.001) as the pacing interval decreased (Figure 8). The decrease in the AV interval paralleled the decrease in the ah interval; the hv interval did not change during the experiment. A Wenckebach conduction block could be induced by pacing at short intervals; this conduction block was converted to 1:1 conduction by AVS stimulation.

**Effects of Propranolol and Lidocaine**

Before the animals received propranolol, SAS stimulation decreased the atrial cycle length by 84±12.4 msec from the control value of 527±23.1 msec in five experiments. AVS stimulation decreased the AV interval by 29±5.7 msec from the control value of 137±10.2 msec in the same five dogs. Propranolol (1–100 µg/kg i.v.) inhibited the positive chronotropic responses to SAS stimulation and the positive dromotropic responses to AVS stimulation (Figure 9); inhibitions depended on the dose of propranolol. The 50% inhibition doses (ID₅₀) for chronotropic (ID₅₀=7.3±1.5 µg/kg i.v.) and dromotrop-
A V S Stimulation (0.3 msec, 10 mA, 2 P/B)

![Graph showing AV S stimulation effects on atrium, ventricle, and His EG.](image)

**FIGURE 7.** Plots of decreases in atrial (AA) and atrioventricular (AV) intervals in response to stimulation of the intracardiac sympathetic nerves to the AV nodal region (AVS Stimulation) when the pulse duration was changed from 0.01 to 0.3 msec in eight experiments (A) and when the number of pulses per burst was increased from one to two or three in six experiments (B). Vertical bars show SEM. Numbers in parentheses and solid circles show the AV functional rhythm induced by AVS stimulation with atropine. AA and AV interval control values were 506±15.3 and 132±7.2 msec in eight open-chest, anesthetized dogs.

decreased the atrial cycle length (Figure 10, top panel). The chronotropic response to SAS stimulation reappeared about 15 minutes. This injection of lidocaine did not affect the positive dromotropic response to AVS stimulation (data not shown). Lidocaine injected into the fatty tissue at the AVS stimulation locus abolished the positive dromotropic response to AVS stimulation (Figure 10, bottom panel). The dromotropic response then reappeared about 15 minutes. This injection of lidocaine, however, did not affect the positive chronotropic response to SAS stimulation. Lidocaine (1 or 3 mg) in both fatty tissue loci inhibited the positive chronotropic response to SAS stimulation and the positive dromotropic response to AVS stimulation in five experiments. These doses of lidocaine did not affect the basal atrial cycle length or AV interval.

**Discussion**

Repetitive, brief bursts of electrical stimulation to two discrete loci in epicardial fatty tissues were given to anesthetized dogs treated with atropine. This is the first demonstration that such stimuli clearly activate intracardiac sympathetic nerve fibers to the SA or AV nodal region. Stimulation of the intracardiac sympathetic nerves to the SA nodal region (SAS stimulation) decreased the atrial cycle length, shifted the pacemaking site within the SA pacemaker complex, and changed the AV conduction time indirectly. Stimulation of the intracardiac sympathetic nerves to the AV nodal region (AVS stimulation) decreased the AV conduction time and induced an AV jun-

**FIGURE 6.** Recordings of electrical changes in the atrium, His bundle, and ventricle induced by stimulation of the intracardiac sympathetic nerve fibers to the atrioventricular nodal region (AVS Stimulation) before and at the beginning of stimulation with atropine (I) and 10 (II), 14 (III), 40 (IV), and 60 seconds (V) after the beginning of stimulation in an autonomicoly decentralized, open-chest anesthetized dog. AVS stimulation consisted of repetitive brief bursts of stimuli with 0.3-msec pulse duration, 10-mA pulse amplitude, and two pulses per burst (P/B) for 1 minute. A, electrogram from the base of the right atrial appendage; V, electrogram from the right ventricular surface; a, electrogram from the atrium by the His electrode; h, electrogram from the His bundle by the His electrode; v, electrogram from the ventricle by the His electrode; AA, atrial interval; aA, interval from a to A; ah, atrial-His bundle interval; hv, His bundle-ventricle (V) interval; St, stimulation; hA, interval from h to A.

tropic (ID$_{50}$=12.8±3.8 μg/kg i.v.) responses were not significantly different. At the doses used in the present study, propranolol did not change the basal atrial cycle length and AV interval significantly.

After lidocaine was injected into the fatty tissue at the SAS stimulation locus, SAS stimulation no longer
Figure 8.  Plots of the effects of atrial (AA) pacing interval on the changes in atrioventricular (AV) interval in response to stimulation with atropine of the intracardiac sympathetic nerves to the AV nodal region (○, AV Stim) and on the changes in basal, prestimulation control AV interval (●, Basal) in eight open-chest, anesthetized dogs. Vertical bars show SEM. The atrial interval was changed by electrically pacing the atrium at 400, 300, and 250 msec.

Figure 9.  Plots of the effects of propranolol (1–100 μg/kg i.v.) on the positive chronotropic response to stimulation with atropine of the intracardiac sympathetic nerves to the sinoatrial nodal region (●, AA) and on the positive dromotropic response to stimulation of the intracardiac sympathetic nerves to the AV nodal region (○, AV) in five open-chest, anesthetized dogs. Vertical bars show SEM.

Our results indicate that SAS stimulation in the dog heart activates discrete intracardiac sympathetic nerve fibers to the SA nodal region and thereby affects sinus cycle length. Similarly, AVS stimulation activates discrete intracardiac sympathetic nerve fibers to the AV nodal region and thereby affects AV conduction time. These conclusions are supported by the following.

Figure 10.  Recordings of the effects of lidocaine injected into the subepicardium (s.epi.) of the fatty tissue for stimulation on the changes in atrial (AA) and atrioventricular (AV) intervals induced by stimulation with atropine (horizontal bars) of the intracardiac sympathetic nerves to the sinoatrial (SAS Stim) or AV (AVS Stim) nodal region in an autonomically decentralized, open-chest, anesthetized dog. P/B, pulse per burst.
results. SAS stimulation decreased the atrial cycle length but did not change the ah interval (Figure 3), whereas AVS stimulation decreased the ah interval but did not change the atrial cycle length or the hV interval (Figure 6). When the positive chronotropic response to SAS stimulation was blocked by lidocaine injected into the fatty tissue used for SAS stimulation, the positive dromotropic response to AVS stimulation was not affected by that injection (Figure 10). On the other hand, when the positive dromotropic response to AVS stimulation was blocked by lidocaine injected into the fatty tissue used for AVS stimulation, the positive chronotropic response to SAS stimulation was not affected (Figure 10).

SAS stimulation shifted the pacemaker site (Figures 1, 3, and 4). During SAS stimulation, the electrograms recorded from the base of the right atrial appendage (A) did not change detectably; however, the shape of the atrial deflection from the His electrode (a) was affected, and the interval from a to A was prolonged. These results indicate that SAS stimulation changed the cardiac pacemaking site. Other studies have shown that stimulation of the extracardiac sympathetic nerve fibers may change the pacemaker site within the so-called atrial pacemaker complex (usually a cranial shift).14–17 These findings may explain the prolongation of the interval from a to A; the shifted pacemaker site was probably closer to the locus of the His electrode (i.e., the noncoronary sinus) than to the pacemaker site that prevailed before SAS stimulation.

When SAS stimulation moderately decreased the atrial cycle length, the change in the AV conduction time was variable (i.e., it decreased in some cases and increased in others) (Figures 3 and 4). However, when the atrium was paced, SAS stimulation did not affect the AV interval, and the ah interval did not change, regardless of whether the atrium was paced. Therefore, we conclude that moderate decreases in atrial cycle length and changes in pacemaker site do not affect AV conduction time in the dog heart in situ. However, more pronounced shortening of the pacing interval increases AV conduction time, as reported previously18,19 and shown in Figure 8.

We also emphasize that the AV interval, measured by the time between the atrial deflection and the right ventricular deflection, may not reflect the actual AV conduction time when the pacemaker site changes. During SAS stimulation, which does not stimulate sympathetic fibers to the AV nodal area, the AV interval depends on the location of the automatic focus and on the conduction time in the atrial tissue. Thus, when the AV interval from fixed sites on the right atrium and right ventricle was measured, the AV interval during SAS stimulation depended on the distance of the atrial recording electrode from the location of the automatic focus. That is, the distance of the atrial recording electrode from the focus of automaticity will alter the AV interval when a pacemaker shift occurs.

When the atria were paced, AVS stimulation decreased AV conduction time (Figure 8). When the heart was in sinus rhythm, we and others found that global sympathetic stimulation induced an AV junctional rate only after the SA nodal and subsidiary atrial pacemaker activities were suppressed surgically20 or pharmacologically.21,22 AVS stimulation, however, induced an AV junctional rhythm in more than 75% of our dogs. Conversely, left stellate ganglion stimulation evoked an AV junctional rhythm in less than 30% of anesthetized dogs, but right stellate ganglion stimulation did not evoke an AV junctional rhythm.14,15,17,23 Different pools of sympathetic nerve fibers may be stimulated by AVS stimulation instead of by left stellate stimulation; this may account for the above disparity. In our experiments, AVS stimulation usually induced an AV junctional rhythm, but in some cases it induced activity from a subsidiary atrial pacemaker. Additionally, AVS stimulation did not affect the atrial cycle length when the heart was in a sinus rhythm. Therefore, the intracardiac sympathetic nerves that were activated by AVS stimulation probably innervate mainly the AV nodal area, although some of those nerves may travel to the lower atrium. Conversely, the sympathetic nerves from the left stellate ganglion innervate the SA nodal area and other atrial regions in addition to the AV node.24–25 Thus, stimulation of the stellate ganglion decreases the atrial cycle length. This positive chronotropic effect may mask the induction of the AV junctional rhythm by overdrive suppression. Stimulation of the extracardiac ventrolateral cardiac nerve fibers induces an AV junctional rhythm similar to the effects of AVS stimulation.26,27 However, stimulation of the ventrolateral cardiac nerve fibers also induces lower atrial and ventricular rhythms because these nerves innervate the lower atrium, AV node, and left ventricle. Thus, the AVS stimulation site is closer to the AV nodal area than to the site of the stimulation of the ventrolateral cardiac nerves. Therefore, it is suggested that AVS stimulation activates the sympathetic nerves of the ventrolateral cardiac nerves that course to the AV junctional region in the dog heart.

When AVS stimulation in our experiments produced a junctional rhythm, it decreased the cardiac cycle length to as low as 385 msec (mean, 430 msec). Therefore, we suggest that activation of the discrete sympathetic nerves to subsidiary pacemaker cells, such as AV nodal pacemaker cells, may shift the dominant pacemaker site from the SA node to those ectopic sites.

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