Cardiac Arrhythmias in the Conscious Dog
After Excision of the Sinoatrial Node and Crista Terminalis

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SUMMARY  A stable junctional rhythm was produced in 16 dogs after surgical excision of the sinoatrial node and a large section of the crista terminalis. An unstable ectopic atrial rhythm appeared within the first week after surgery in 94% of the dogs. The pacemaker instability was characterized by spontaneous pacemaker shifts and periodic episodes of asystole which were prominent for several months after surgery in most of the dogs. In contrast to sinus arrhythmia observed before surgery, the ectopic atrial arrhythmias were not related to the respiratory cycle. The prompt disappearance of the asystoles after atropine or during treadmill exercise indicated the essential role of the vagus in producing the unstable rhythms. Atropine increased the average rate of the ectopic rhythms from 63 ± 3 beats/min to 107 ± 9 beats/min (p < 0.001) and shortened the corrected recovery time (CRT) following overdrive pacing from 3.8 ± 0.3 seconds to 1.9 ± 0.6 seconds (p < 0.001). Propranolol, in the absence of atropine, decreased the spontaneous heart rate from 56 ± 5 beats/min to 39 ± 6 beats/min (p < 0.01), and increased the CRT to 6.5 ± 2 seconds (p < 0.001) when administered after atropine. The data suggest that unstable ectopic atrial pacemakers could be responsible for some of the arrhythmias associated with the sick sinus syndrome in man.

THE PRODUCTION OF A STABLE junctional rhythm (JR) or ectopic atrial rhythm (EAR) after the removal or suppression of the sinoatrial node (SAN) in acute animal experiments has long been recognized. However, little is known about the stability of supraventricular subsidiary pacemakers in chronic SAN dysfunction. Depression of automaticity in escape pacemakers has been implicated in the production of arrhythmias associated with the sick sinus syndrome in man. Early experimental studies by Borman and Meek showed that atrial pauses were common for several days after experimental destruction of the SAN by implantation of radon seeds. In more recent experiments, surgical exclusion of the SAN from the remainder of the right atrium resulted in a transitory period of pacemaker instability after the animals recovered from anesthesia. The instability was characterized by shifting pacemaker sites, asystole, and tachycardias with a gradual return to a stable EAR within the first 3 weeks after surgery.

The SAN in the dog has been shown histologically to extend for a distance of 8–20 mm along the sulcus terminalis starting at the cavo-auricular junction. Surgical excision of just the SAN, with little damage to the crista terminalis, produces an immediate, stable EAR with little change in P-wave morphology or P-R interval in both the anesthetized and conscious dog. Epicardial mapping of these ectopic rhythms in the anesthetized dog locates the earliest point of negativity on the sulcus terminalis just distal to the site of the excised SAN. Since the crista terminalis underlying the sulcus terminalis contains specialized fibers capable of spontaneous diastolic depolarization, it is possible that stable ectopic atrial rhythms might arise from these fibers in the chronic absence of the SAN.

Our study chronically examines the ectopic rhythms produced by removal of the SAN and a large section of the crista terminalis. Since the autonomic nervous system plays an important role in modulating pacemaker function, we tested the response of the subsidiary pacemakers to atropine, propranolol, and treadmill exercise. We also evaluated the susceptibility of the subsidiary pacemakers to overdrive suppression.
Materials and Methods

We experimented on 25 adult mongrel dogs weighing 12–18 kg. The dogs were brought into the laboratory three or four times before surgery, and resting ECGs (lead II) and pneumograms were recorded. The pneumograms were recorded by attaching an expandable rubber diaphragm around the dog’s rib cage. The dogs were also trained to run on an exercise treadmill. After control recordings and exercise training were completed, the dogs were anesthetized with sodium pentobarbital (30 mg/kg). Under aseptic conditions, a right thoracotomy was performed in the fourth intercostal space while the dogs were maintained under positive pressure ventilation with 40% oxygen. After construction of a pericardial cradle, the sulcus terminalis was lifted with forceps and held in a Satinsky clamp. In 11 of the dogs, we made a single excision 3.5–4 cm long and 1–1.5 cm wide. In five dogs, two smaller overlapping excisions were made (2–2.5 cm by 1–1.5 cm). To ensure complete removal of the SAN, the excisions were started a few millimeters proximal to the cavoauricular junction and were centered around the SAN artery. An ECG (lead II) was continuously monitored during the excisions. Nine of the 25 dogs served as controls — the SAN and crista terminalis were identified but not excised.

Figure 1, a schematic diagram of the right atrium and vena cava, shows the extent of tissue excised in each dog. The excised tissue, shown by the striped area, usually extended beyond the interatrial groove to include some of the junction between the inferior vena cava and right atrium. To avoid interference with coronary sinus flow, the excision was kept at least 1 cm away from the mouth of the coronary sinus.

In 10 dogs whose SAN was excised and six of the controls, a bipolar plaque electrode was sutured to either the right or left atrial appendage for overdrive pacing. The electrode wires were tunneled subcutaneously and connected through a cutaneous stab wound over the second or third thoracic vertebra.

Electrocardiograms and pneumograms were recorded while the dogs stood quietly in the laboratory on the first day after surgery and at 2-day intervals during the first week. Thereafter, recordings were made at 1–3-week intervals until the dogs were sacrificed. The response of the conscious dogs to autonomic blockade was determined at various times after surgery by intravenous administration of atropine (0.3 mg/kg) or propranolol (0.5 mg/kg). Treadmill exercise was resumed in the third week after surgery. In order to monitor arterial blood pressure, surgery was again performed in four dogs 4–12 weeks after the initial surgery. Under aseptic conditions, a polyvinyl chloride catheter was inserted into the aorta via the omocervical artery, then tunneled subcutaneously and passed through a stab wound in the back of the neck.

Statistical analysis of the data was performed using the t test for both paired and unpaired samples. Results are expressed as the mean ± SEM. Differences between means were considered significant when p < 0.05.

Results

In all 16 of the dogs that underwent excision, a JR developed at the time of clamping or immediately after excision of the SAN and crista terminalis. In 15 dogs, we monitored the JR for 60–90 minutes until the ECG leads were removed. In one dog, an EAR with an inverted P wave returned within 30 minutes after the excision. During the first week after surgery, P waves (upright in 10 dogs, inverted in five) returned in all but one of the dogs that had shown a stable JR on the operating table; this dog remained in a JR until sacrificed in the fifth month after surgery.

Before surgery, all dogs displayed respiratory sinus arrhythmia. The average heart rate of the dogs while standing quietly in the laboratory was 94 ± 5 beats/min and the average P-R interval was 101 ± 4 msec. The JR which appeared after tissue excision had an average heart rate of 95 ± 5 beats/min. With the return of a P wave, the average heart rate fell to 63 ± 3 beats/min, which was significantly slower than both the preoperative sinus rhythm (p < 0.001) and the JR under anesthesia (p < 0.001). The average P-R interval of the atrial rhythms was 75 ± 3 msec which
was significantly shorter than the preoperative P-R interval ($p < 0.001$).

Figure 2 shows typical rhythm strips from one dog before and after excision of the SAN and crista terminalis. Panel A shows a sinus arrhythmia with an average heart rate of 90 beats/min recorded 2 days before surgery. The sinus rate under pentobarbital immediately before excision was 150 beats/min. Panel B shows a JR with an average heart rate of 115 beats/min 1 hour after excision. Panel C, recorded 65 days after surgery, shows 3–5-second asystoles which recur at intervals of 12–16 seconds. The average heart rate over several minutes was 38 beats/min. A faster trace of a single cycle of the arrhythmia is shown in panel D. A small, upright P wave can be seen beneath the arrows in the three beats just preceding a 5-second asystole. The idioventricular escape beat is followed by a JR before the cycle repeats. Panel E was recorded 3 minutes after intravenous administration of atropine. Parasympathetic blockade in this dog increased the heart rate to 70 beats/min, eliminated the asystoles, and produced a stable, biphasic P wave that is different from the one shown in panel C.

In the 15 dogs in which a P wave returned after removal of the SAN and crista terminalis, periodic episodes of asystole similar to those shown in figure 2 were observed. The asystoles lasted 1.5–6 seconds and recurred at intervals of 4–20 seconds. The arrhythmias appeared within 2 weeks after surgery, except in two dogs that had atrial flutter for 3 weeks after surgery. In these two dogs, periodic asystoles appeared after spontaneous termination of the flutter. In two of the 15 dogs, the periodic asystoles lasted only a few days and were replaced by a permanent, stable EAR. In four of the 15 dogs, the arrhythmias tended to subside with time only when the dogs were brought into the laboratory. When rhythm strips were recorded with the dogs lying undisturbed in their cages, the periodic asystoles were still prominent. In the remain-

FIGURE 2. Rhythm strips (lead II) in an animal which developed transient arrhythmias after excision of the sinoatrial node (SAN) and crista terminalis (CT). A) Sinus arrhythmia with a heart rate of 90 beats/min recorded 2 days after surgery. B) Junctional rhythm with an average rate of 150 beats/min recorded 1 hour after excision of the SAN and crista terminalis. C) Ectopic atrial arrhythmia with an average heart rate of 38 beats/min recorded 65 days after surgery. D) Faster trace of the rhythm in panel C; arrows indicate P waves. E) A rhythm strip obtained 10 minutes after administration of atropine (0.3 mg/kg). The heart rate accelerated to 70 beats/min and the arrhythmia disappeared.
increase and decrease of efferent vagal tone which is synchronized to the respiratory cycle. To determine if the instability of the ectopic atrial pacemakers could be accounted for by respiratory-associated oscillations in autonomic tone, pneumograms were recorded during bouts of spontaneous arrhythmia. Figure 4 shows a pneumogram, ECG, and aortic blood pressure trace taken from a dog 90 days after excision of the SAN and crista terminalis. In the slow trace of the spontaneous arrhythmia in the upper left portion of the figure, the average heart rate is 37 beats/min and the time between successive inspirations averages 1.7 seconds (36 beats/min). The 2-second asystoles which recur about every 10 seconds are accompanied by large oscillations in blood pressure with diastolic pressure falling to 25 mm Hg. A faster trace on the right shows that the asystoles span both inspiratory and expiratory cycles. Furthermore, from analysis of multiple cycles of this arrhythmia, the onset of an asystolic period did not appear to be confined to any particular portion of the respiratory cycle. In the bottom half of figure 4, the left atrium was paced through chronically implanted electrodes at a rate of 150 beats/min. The slower trace at the left shows the presence of ventricular slowing which is synchronized to the respiratory cycle. The faster trace on the right shows atrioventricular (AV) block during expiration with 1:1 AV conduction during inspiration. Atropine eliminated both the spontaneous and pacing-induced arrhythmias. In 12 of the 15 dogs which had unstable EAR, no phase relationship could be found between the arrhythmia and the respiratory cycle. In three dogs, there was a phase relationship with tachycardia during inspiration and bradycardia during expiration. Rapid atrial pacing (150–200 beats/min) in the 10 dogs with chronically implanted electrodes consistently produced respiratory-associated episodes of AV block which were eliminated by atropine. In six control dogs, rapid atrial pacing (150–200 beats/min) resulted in similar vagal-modulated episodes of AV block. Rapid atrial pacing also used to determine the susceptibility of the ectopic pacemakers to overdrive suppression. We subjected 16 dogs to pacing for 60 seconds at 2–3 times their average spontaneous rate. The corrected recovery time (CRT) was determined by subtracting the average control cycle length from the longest cycle within the first few cycles after termination of the pace. Two weeks after surgery, we began overdrive pacing studies which continued until the dogs were sacrificed. The average CRT for each dog was determined from three or more overdrive trials on at least 2 separate days. The average CRT for 10 of the dogs with unstable EAR was 3.8 ± 0.3 seconds. The CRT for six of the control dogs was 0.2 ± 0.1 seconds (p < 0.001). Administration of atropine (0.3 mg/kg) significantly shortened the CRT of the dogs which had unstable EAR, to 1.9 ± 0.6 seconds (p < 0.001). Administration of propranolol (10–15 minutes after atropine) to the dogs without SAN and crista terminalis lengthened the CRT to 6.5 ± 2 seconds (p < 0.001). In five dogs, propranolol resulted in post-drive pauses longer than 8 seconds which were accompanied by syncope.

Figure 5 shows the response of a dog to overdrive pacing 32 days after excision of the SAN and crista terminalis. Panel A shows an ECG (lead II) and an aortic blood pressure trace. The average heart rate was 57 beats/min and spontaneous oscillations in blood pressure and heart rate were evident. Panel B was recorded 20 seconds after starting a 1-minute period of left atrial drive at 200 beats/min. The dropped ventricular beats during the pace were due to vagally induced episodes of AV block. Termination of
the pace (arrow) was followed by a 5-second asystole, which was followed by marked secondary oscillations in blood pressure and heart rate. Although not shown in the figure, administration of atropine (0.3 mg/kg) increased the heart rate to 90 beats/min, shortened the post-drive pause to 3 seconds, and markedly attenuated the secondary oscillations. Ten minutes after atropine, propranolol (0.5 mg/kg) was administered and the overdrive repeated. As shown in panel C, termination of the pace was followed by a 10-second asystole with a gradual return to a new resting heart rate of 45 beats/min. Secondary oscillations in blood pressure and heart rate after the asystole (fig. 5B) were absent.

Discussion

The SAN is generally considered the normal site of origin of the heartbeat in the mammalian heart, although the pacemaker location after suppression or destruction of the SAN is controversial. After perfusing the SAN artery with eserine or acetylcholine, Urthaler and co-workers concluded that the AV junction is the only supraventricular secondary pacemaker.

however, atrial rhythms have been observed after suppression of the SAN by other methods. The distribution of the SAN artery has been mapped using both dye and radioactive microspheres, and has been shown to perfuse much more of the right atrium than just the SAN. Thus, perfusion of the SAN artery with vagomimetic substances probably suppresses ectopic atrial pacemakers in addition to the SAN.

Surgical removal of a short segment of the sulcus terminalis containing the SAN (histologically verified) results in an immediate, stable EAR with little change in P-wave morphology or P-R interval. In the present study, removing a large section of the crista terminalis as well as the SAN invariably resulted in an immediate JR. However, ectopic atrial pacemakers with significantly shorter P-R intervals appeared within 1 week after surgery in 94% of the dogs. Although the inability to maintain a permanent JR in the absence of the SAN has been reported previously, the mechanism responsible for the return of an atrial pacemaker remains unknown. The altered levels of sympathetic and parasympathetic tone during surgery or the direct effects of anesthesia on pacemaker func-
tion may be important for the continued maintenance of a JR; or removal of the SAN may traumatize atrial pacemaking sites, which may require variable amounts of time to recover function.

We do not know the precise location of the atrial pacemakers observed in the conscious dogs in the present study. The variable P-wave morphology suggests that there may be several pacemaking sites. Several studies using stationary epicardial electrodes have indicated that the earliest site of negativity is at the coronary sinus after permanent destruction of the SAN. However, the recent experiments of Jones et al. failed to confirm the return of a coronary sinus pacemaker after excision of a 3-4 cm section of the sulcus terminalis, including the SAN. In that study, extensive epicardial mapping with a movable suction electrode located the site of earliest negativity on the distal border of the inferior vena cava-right atrial junction in 80% of the dogs with EAR. Furthermore, isoproterenol infusion shifted the apparent pacemaker location to Bachman’s bundle in 70% of the dogs mapped.

The spontaneous arrhythmias observed in the present study, as shown in figures 2-5, consisted primarily of periodic episodes of severe bradycardia and asystole. The mechanism responsible for the asystoles may be either a true pacemaker arrest or an exit block out of the pacemaking site. Asystoles resembling pacemaker exit block were only observed in four of the 15 dogs. In the remaining dogs, exit blocks might have occurred, but they could not be identified due to pacemaker shifts or spontaneous variations in cycle length.

The rapid disappearance of the asystoles after administration of atropine (fig. 2) or during treadmill exercise (fig. 3) suggests that vagal tone plays a key role in pacemaker instability. Whether the periodic asystoles result from oscillations in vagal firing rate or whether they represent intrinsic pacemaker oscillations in the presence of tonic vagal discharge cannot be determined from our experiments. Spontaneous, repetitive activity followed by quiescence has been observed in rabbit atrial fibers demonstrating oscillatory afterpotentials. However, the depressant effects of acetylcholine and the enhancing effects of catecholamines on afterpotentials are not consistent with the effects of atropine and propranolol on the arrhythmias observed in the present study. Atropine eliminated the asystoles, but the blockade of adrenergic input with propranolol, while leaving cholinergic input intact, consistently enhanced the duration of the asystoles.

The appearance of a transitory period of pacemaker instability after destruction or removal of the SAN has been reported previously. Borman and Meek observed atrial pauses which they interpreted as sinoauricular block for several days after radon seeds were implanted in the SAN. Sealy et al. observed periods of atrial asystole, pacemaker shifts, and tachycardias for 3 weeks in some animals after surgical exclusion of SAN from the remainder of the right atrium. In both of these studies, the arrhythmias dis-
appeared as a permanently stable atrial rhythm was established. In the present study, the arrhythmias which appeared soon after surgery were not transient, but were repeatedly observed for several months in most of the dogs. In only two dogs were the arrhythmias replaced by a permanently stable atrial rhythm. Furthermore, the arrhythmias observed in the present study appear to be more severe than the arrhythmias observed after excision of just the SAN.10 In the present study, surgical intervention may have damaged the atrial pacemakers, making them more sensitive to the depressant effects of acetylcholine. If atrial pacemakers are concentrated within the crista terminalis then removal or destruction of just the SAN may not damage the ectopic pacemakers sufficiently to create permanent arrhythmogenic foci. Alternatively, the pacemakers which assumed dominance in the present experiments may be exposed to higher local concentrations of acetylcholine or have a greater intrinsic sensitivity to acetylcholine than either the SAN or the stable ectopic pacemakers which are dominant after removal of just the SAN.

Lange has shown that, in addition to a slower automaticity, ectopic atrial pacemakers in acute experiments are more sensitive to overdrive suppression than the SAN.20 The present study has extended those findings to the conscious, unanesthetized dog. In the dogs with ectopic pacemakers, overdrive pauses of 3 seconds or more were consistently observed (fig. 6), while in the control dogs, pauses greater than 1 second were never obtained. Although the mechanism for overdrive suppression of supraventricular pacemakers is not completely clear, mechanisms involving a local release of acetylcholine from nerve terminals or a buildup of extracellular potassium by drive stimuli have been proposed.20 Overdrive pacing may activate an electrogenic sodium pump in atrial pacemakers similar to the one which is responsible for overdrive suppression in Purkinje fibers.21 A 50% reduction of the CRT after administration of atropine indicates the importance of acetylcholine in mediating the suppression. Furthermore, the effect of atropine on the CRT was consistent in eliminating the spontaneous arrhythmias. The administration of propranolol after atropine resulted in an average prolongation of the CRT by 360%, with five dogs developing syncope when their post-drive pauses exceeded 8 seconds. The increase in susceptibility of the ectopic pacemakers to overdrive after propranolol was relatively large with respect to the slowing of the spontaneous rate, and indicates that stability of some ectopic atrial pacemakers is highly dependent on adrenergic input.

The increase and decrease of heart rate in the normal dog (sinus arrhythmia) is thought to be generated by a powerful central inhibition of vagal tone during inspiration.22 In 80% of the dogs with ectopic arrhythmias there was no relationship between the arrhythmia and the respiratory cycle. However, it was possible to induce respiratory variations in AV nodal conduction in three dogs by rapid atrial pacing, as demonstrated in figure 4. This is consistent with the observation that the normal, conscious dog has a high degree of vagal control over AV nodal conduction.23 We do not know why there is no phase relationship between the respiratory cycle and spontaneous periodic asystoles. The marked oscillations in blood pressure that accompany the spontaneous arrhythmia (fig. 4) and the secondary pauses following overdrive (fig. 5) should be accompanied by large oscillations in arterial baroreceptor activity. The baroreceptor oscillations could result in vagal oscillations to the ectopic atrial pacemakers which could perpetuate the arrhythmia.

The arrhythmias described in the present study may have some relevance to the spontaneous episodes of bradycardia and asystole that have been reported in patients with the sick sinus syndrome.24 The secondary pauses observed following overdrive pacing (fig. 5) are very similar to the post-pacing secondary pauses reported by Benditt et al. in patients with sinus node dysfunction.25 It has not been determined in these patients whether the pacemaker instability is caused by a malfunctioning SAN, or whether the SAN is so suppressed that an unstable ectopic atrial pacemaker assumes dominance. A normal P-wave morphology and P-R interval in a patient with symptomatic arrhythmia may not indicate a pacemaker of sinus origin. Extensive atrial pacing studies in both man and experimental animals have demonstrated that normal P waves and P-R intervals can be obtained from many atrial ectopic locations.26-28

Although asystoles are commonly observed in patients with symptomatic pacemaker dysfunction, the asystoles do not demonstrate the periodicity characteristic of the spontaneous asystoles observed in the present experiments. This difference may be the result of a greater level of resting vagal tone in the dog, or to a species difference in the relative levels of cardiac sympathetic and parasympathetic tone.29 Abnormal vagal control mechanisms have been demonstrated in many patients with symptomatic pacemaker dysfunction during carotid sinus massage.30,31 In these patients, carotid sinus massage resulted in prolonged asystoles (3–6 seconds) which were eliminated after administration of atropine.30,31 The role of both parasympathetic and sympathetic tone in the genesis of the spontaneous episodes of asystole in the patient with symptomatic sinus node dysfunction requires further investigation.

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