The Role of Vagal Afferents in the Reflex Control of the Left Ventricular Refractory Period in the Cat

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SUMMARY We examined the reflex change in refractory period (RP) of the left ventricle produced by stimulation of the central end of the caudovagal nerve (CVS). RP was recorded in the region of distribution of the left anterior descending coronary artery. During the determination of RP, hearts were paced at cycle lengths between 244 and 315 msec. Initially, the tonic effects of removing vagal and sympathetic influences were determined. Neither right nor left vagotomy nor cardiac sympathectomy (symx) affected RP; however, bilateral vagal block decreased RP by 3 msec, whereas bilateral symx increased RP by 7 msec. Atropine increased RP by 2 msec, probably via inhibition of muscarinic receptors in ganglia. After determination of each of the tonic influences, CVS was performed with pulses of 35–50 Hz, 0.6–1.0 msec in duration, and 1.6–4.0 V. CVS increased RP by 8 msec. Right vagal cold block abolished the response, but left vagal block had no effect. Left symx had no effect on the response, but right symx limited it to 6 msec. Bilateral symx was similar to right symx alone. Subsequent atropine administration blocked 4 msec of the remaining response. Atropine given before symx limited the increase in RP due to CVS to 4 msec. After subsequent right symx, the increase in RP was only 1 msec. Left symx after atropine decreased the response only 1 msec. Total symx after atropine abolished the response. The degree of initial sympathetic activity had no effect on the RP response. We conclude that: (1) the afferent limb of the reflex lies in the right vagus; (2) the dominant efferent reflex path lies in the vagi; (3) the sympathetics have a significant role only when the vagi are blocked; (4) when active, the efferent sympathetic paths course mostly through the right side; (5) the vagi do not require existing sympathetic activity to exert an effect. Circ Res 46: 378–386, 1980

IN 1940, Wiggers et al. showed that ventricular fibrillation threshold (VFT) could be used as a measure of cardiac electrical vulnerability. Since these pioneering experiments, many experiments have been done, not only in the study of the effects of various interventions upon VFT, but also in the development of methods to study refractory periods (RP), repetitive extrasystole (RE) thresholds, and other electrical properties of the heart. The ultimate goal in the majority of these studies has been to determine the role of the autonomic nervous system and cardiac ischemia in modifying either the vulnerability of the heart to fibrillation or cardiac refractoriness. In general, increases in sympathetic outflow to the heart have been shown to decrease RP and to increase vulnerability. For example, left stellate ganglion stimulation decreased RP and increased the temporal dispersion of RP in the left ventricle after vagotomy and decentralization of the stellate ganglia (Han et al., 1964). Several studies have related changes in sympathetic nerve activity to alterations in vulnerability of the heart due to coronary artery occlusion, suggesting that efferent sympathetic nerve activity enhances the deleterious effects of coronary artery occlusion (Wiggers et al. 1940; Han, 1968; Kliks et al., 1975; Corbalan et al., 1976; James et al., 1977). On the other hand, increases in vagal efferent activity have been shown to reduce vulnerability (Kent et al., 1973), although this effect may have been indirect through the antagonistic effect of acetylcholine on the adrenergic actions of catecholamines (Kolman et al., 1975, 1976; Yoon et al., 1977). However, in each of the studies cited above, some afferent and/or efferent autonomic pathway was interrupted before the experiments were performed.

More recently, Brooks et al. (1978) demonstrated that interruption of the vagus in atropinized dogs resulted in a significant decrease in RE threshold, suggesting that tonic vagal afferent activity may exert a protective effect on ventricular vulnerability by inhibiting cardiac sympathetic nerve activity. Furthermore, the protective effect of stelllectomy was evident only after bilateral vagotomy. Tonic vagal efferent activity did not appear to alter RE threshold. Thus, the major interaction between the vagal and sympathetic nerves on cardiac vulnerability appeared to be through the tonic inhibitory influence of vagal afferents on sympathetic outflow. Additionally, Schwartz et al. (1977) demonstrated that both vagal afferents and efferents had a tonic influence on ventricular refractoriness in the presence of an intact sympathetic nervous system. Although a role for tonic sympathetic nerve activity...
in the control of refractoriness was also shown, this role was examined only after the vagi had been sectioned. In summary, recent studies have begun to suggest that vagal afferents have a role in modulating ventricular refractoriness and vulnerability.

The purpose of the present study was to determine whether activation of cardiac vagal afferents could elicit reflex alterations in the refractoriness of the feline heart. Since the reflex effect of vagal afferent stimulation may depend on the sympathetic outflow, studies were performed when sympathetic outflow was altered. We also examined the relative contribution of efferent vagal and sympathetic influences on the cardiac RP. The results indicated that electrical activation of vagal afferents produce a reflex increase in RP mediated predominantly by increases in efferent vagal activity. Reflex changes in RP mediated by decreases in sympathetic activity were apparent only after vagal efferent blockade with atropine.

Methods

Surgical Procedures

Forty-one cats weighing 1.8–5.2 kg were anesthetized by the intraperitoneal administration of sodium pentobarbital (30 mg/kg). A catheter was inserted into the femoral vein for the administration of additional anesthetic or other drugs. Arterial blood pressure was recorded by a pressure transducer (Statham P23Db) connected to a catheter passed retrograde via the femoral artery to the descending aorta. Mean arterial pressure (MAP) was obtained electronically. The vagi and carotid arteries were isolated in the neck and were looped with suture for future identification. To eliminate the possibility that the reflexes studied traveled via the aortic or cervical sympathetic nerves, these nerves were cut. The trachea was cannulated so that artificial ventilation could be provided by a Harvard apparatus respirator (model 665). The stroke of the pump was adjusted to eliminate spontaneous respiration and to maintain Po2 and pH within normal values. The thorax was opened via a sternal approach between the 5th and 6th ribs, and the 3rd, 4th, and 5th ribs were removed bilaterally. A small incision was made in the pericardium to expose the heart in the region of distribution of the left anterior descending (LAD) coronary artery on the left ventricle. Pairs of stimulating and recording Teflon-coated stainless steel electrodes were inserted into the myocardium at this site, the stimulating electrodes more distal (that is, toward the apex) than the recording electrodes. The four electrodes were spaced 1–2 mm apart and were inserted approximately 3 mm into the ventricle. This 3-mm portion of the electrodes was stripped of its coating. A second incision in the pericardium was made over the right atrium for the placement of a pair of pacing electrodes on the right atrium. The thoracic branches of the vagus nerve, known as the caudovagal nerves, (Mizeres, 1955) were isolated. These nerves leave the vagus ventrically and are rostral or dorsal to the axygos vein (Fig. 1). The nerves course toward the right atrium. In cats that had multiple caudovagal nerves, the largest one was selected for study. In most cases, the caudovagal nerve selected for study exited the vagus 5–15 mm rostral to the axygos vein (Fig. 1B). In a few cases, the nerve selected was dorsal to the axygos vein (Fig. 1C). Finally, the stellate ganglia and thoracic sympathetic chains were isolated bilaterally for subsequent extirpation. Arterial pressure and heart rate (HR) were recorded on a Beckman type R411 dynograph recorder.

Measurement of Refractory Period

The stimulator was a Grass model S88. The S1 portion of the stimulator was connected to the pacing electrodes on the right atrium. Additionally, the output pulse of the S1 was routed through a delay circuit to trigger the S2 portion of the stimulator, which was connected (with an intervening Grass stimulation isolation unit, or SIU) to the stimulating electrodes placed in the vicinity of the LAD. The recording electrodes were connected to a Grass P15 AC preamplifier. The amplified signal then was recorded on a Tektronix dual beam storage oscilloscope and on the pen recorder.

FIGURE 1 Anatomy of the area containing the caudovagal nerve. X = right vagus nerve, CV = caudovagal nerve(s), AZ = axygos vein, SVC = superior vena cava, IVC = inferior vena cava, RA = right atrium, AO = aorta, PA = pulmonary artery, LA = left atrium. Panel A: General anatomical location of the caudovagal nerve on the right side of the cat. Dashed area is enlarged in panels B and C. Panel B: Most common orientation of the CV. This configuration produced the largest responses (see text). Panel C: Variations in anatomy of CV. Sometimes the CV appeared as two separate nerves traveling together. In these cases, the largest one was selected for stimulation. These nerves were not as large as the single nerve illustrated in panel B. In a few cases, one or more CV exited the vagus dorsal to the axygos vein. In general, responses to afferent CVS were not as large when nerves were in configurations shown in panel C.
The recording procedure for obtaining the cardiac electrogram and RP during pacing was as follows. The pacing stimulus was a rectangular pulse of 2 msec duration and 2-4 V intensity. The pacing frequency was set to obtain a HR 10-25 beats per minute (bpm) greater than the intrinsic HR. The initial pacing interval varied between 244 and 315 msec (246 and 190 bpm) depending on the cat.

The pacing artifact (S1) and the left ventricular electrogram resulting from the paced beat (R1), were recorded on the oscilloscope and paper recorder. The time from the onset of S1 to the onset of R1, was the atrioventricular conduction time. For the determination of diastolic threshold, the delay circuit was set to deliver a premature impulse (S2) late in diastole (approximately 30-50 msec before the onset of the next ventricular potential) via the ventricular stimulating electrodes. The voltage required to initiate a premature response was determined, and this intensity was the diastolic threshold. The intensity was then doubled for the subsequent measurement of RP.

The RP of the myocardium at the site of the recording electrodes was determined as follows. Initially, the S2 pulse was delayed in 10-msec increments until a premature response was obtained. Then the delay was decreased to the value preceding that which caused the premature impulse, and the S2 pulses then were delayed in 1-msec increments until the premature impulse was again obtained. This process was repeated several times, with at least 10 beats between trials (Russell and Oliver, 1978) to obtain a reproducible delay which would cause a premature impulse to appear. The R1 to S2 interval which produced a premature response at least two out of three times with an S2 stimulus duration of 2 msec and intensity of twice diastolic threshold was defined to be the RP. The delay circuit of the S2 portion of the S88 coupled with the outside (non-S88) delay circuit allowed RP to be determined to the nearest millisecond. Since the accuracy was 1 msec, all RP values reported in the results were rounded to the nearest msec.

**Experimental Protocol**

The caudovagal nerve was selected for study for the following reasons. (1) It possesses afferent nerve fibers which originate from the left (Oberg and Thorén, 1972) and the right (Armour, 1973) ventricles and which later course through the right vagus (Jones, 1953; Oberg and Thorén, 1972, 1973). (2) It produces depressant responses upon stimulation of C-fibers (Oberg and Thorén, 1973) or administration of veratridine, a drug which activates the Bezold-Jarisch effect (Jones, 1953). We felt that if a reflex alteration in RP could be elicited, a likely candidate for stimulation would be the caudovagal nerve.

The characterization of the reflex change in RP involved the ablation of autonomic pathways by means of surgery and/or drugs. Therefore, it was necessary to determine the effect of such interventions on RP. Thus, RP was measured before and after each intervention described below was performed.

Initially the effect of cutting the caudovagal nerve on RP, mean arterial pressure (MAP), and HR was determined. The control effects on RP, MAP, and HR of stimulating the central end of the nerve were ascertained. Such stimulations were repeated 2-4 times in each cat to ensure reproducibility of results; the values obtained were averaged for each parameter in each cat. Stimulation parameters consisted of 35-50 Hz, 1.6-4.0 V, and 0.6-1.0 msec in duration. These parameters produce depressant effects due to unmyelinated C-fiber activation (Oberg and Thorén, 1973), The frequency was fixed for each cat, and the intensity and duration were altered to obtain a 40-60 mm Hg decrease in MAP. Thus, stimulation of the nerve was not supramaximal. Preliminary experiments showed that a large change in RP was obtained with the degree of stimulation described above. Furthermore, supramaximal stimulation was found to decrease MAP virtually to zero, and it was felt that stimulation of this magnitude might produce equivocal results.

To determine the afferent autonomic pathway for the reflex change in RP, the following maneuvers were performed. The central end of the caudovagal nerve was stimulated before and during right or left vagal cold block. Additionally, bilateral vagal cold block was performed. Reversible block was accomplished by placing the cervical vagi in contact with U-shaped hollow stainless steel tubing through which antifreeze at $-10^\circ$C was circulated. The U-shaped tubing was suspended above the cervical incision so that only the vagi were cooled. Vagal blockade occurred when the vagal temperature reached $0-2^\circ$C (Shimizu et al., 1978). At these temperatures, conduction of evoked responses over the cooled portion of the vagi was blocked.

The efferent arc of the reflex was determined in the following manner. Four groups of cats were used to determine the relative importance of the activation of vagal efferents vs. the withdrawal of sympathetic efferents. In one group of cats, afferent caudovagal nerve stimulation (CVS) was performed after each of the following: (1) atropine administration (0.2 mg of the salt per kg), (2) right cardiac sympathectomy (section of the right stellate ganglion plus thoracic rami T1-T5, abbreviated right symx), and (3) left cardiac sympathectomy (section of the left stellate ganglion plus thoracic rami T1-T4, abbreviated left symx). An interval of at least 15 minutes elapsed after each unilateral symx before measurements were resumed. In the other three groups of cats, different combinations of the above interventions were performed. The sequences for the other groups were the following: (1) atropine, left symx, right symx; (2) right symx, left symx,
atropine; and (3) left symx, right symx, atropine. In a few cats, autonomic blockade as described above did not abolish the effect of CVS on RP. In these cats, propranolol (1 mg of the salt per kg) then was administered and the effect of CVS again determined.

To ascertain the effects of various degrees of sympathetic outflow on the reflex, we evaluated carotid occlusion and propranolol administration. The central end of the caudovagal nerve was stimulated before and during carotid occlusion, as well as before and after propranolol administration. For this series of experiments, the propranolol was injected with all autonomic efferent neural pathways intact.

Conceivably, the decrease in blood pressure produced by CVS could have produced the change in RP. To examine this possibility we determined the effects of hemorrhage on RP. A sufficient amount of blood was removed to decrease MAP to the same extent as CVS. The hemorrhages were performed at various points in the protocol, so that different portions of the autonomic nervous system were intact. For example, hemorrhage was performed with all nerves (except the caudovagal nerve) intact, after atropine administration with or without symx, etc. In a given cat, however, hemorrhage was performed only once.

Statistical comparisons were made with the t-test for paired data (Batson, 1956). Differences were considered significant if \( p < 0.05 \). All data in the Results are presented as mean ± standard error.

Results

Effects of Vagal Blockade and Atropine on RP

Figure 2 illustrates the effects of selective vagal cold block and atropine administration on the RP of the left ventricle. Neither right vagal cold block (RVB) alone nor left vagal cold block (LVB) alone had a significant effect on RP. However, blocking both vagi (BVB) produced a significant decrease in RP. The change in RP obtained after atropine administration depended upon whether it was given before or after bilateral symx. If injected before the symx, atropine produced a small but statistically significant increase in RP, but if administered following the symx, there was no change in RP.

Effects of Symx on RP

The changes in RP due to selective symx are shown in Figure 3. Neither right nor left symx alone, regardless of the presence or absence of atropine, had a significant effect on RP. Bilateral symx, however, produced a significant increase in RP of 7 msec if performed with the efferent vagi intact and of 10 msec if performed after vagal efferent blockade with atropine.
1 to 16 msec. Most of the cats (27 of 39) exhibiting an increase in RP fell in the range of 6-10 msec. In the two cats not responding with an increased RP, MAP and HR were significantly decreased by CVS.

For the investigation of possible neural arcs involved in the reflex, cats with responses to CVS ranging from 1 to 4 msec were not included since interpretation of the data would have been equivocal. As a result, the control increases in RP reported below may be greater than that shown in Figure 4.

Effects of Interrupting Cardiac Autonomic Pathways on the Reflex Change in RP

The data in Figure 5 show the effects of vagal blockade and atropine administration on the reflex change in RP. RVB greatly attenuated the increase in RP observed with CVS; in two cats, the original increase in RP was converted to a decrease. However, LVB was without significant effect on the change in RP. Atropine alone significantly reduced the reflex change in RP. Similarly, atropine injection after the bilateral surgical symx significantly attenuated, but did not abolish, the reflex alteration of RP when the eight cats examined were considered together. However, in six cats, the RP response was abolished; the other two cats exhibited only slight reductions in the RP response to CVS after symx and atropine. These two cats were given propranolol, as described below.

Figure 5 illustrates the effects of selective symx on the reflex change in RP. Right symx alone produced a slight nonsignificant decrease in the RP change due to CVS. However, right symx did significantly attenuate the RP response if atropine had been given before the symx. On the other hand, left symx had no effect on the RP response either alone or after atropine administration. Bilateral symx decreased the RP response by 2 msec, although the change was not statistically significant. Additionally, after atropine had been given, bilateral symx attenuated, but did not abolish, the RP response when all eight cats tested were considered together. However, in five of the eight cats, the RP response was only slightly altered. The possibility existed that adrenal release of catecholamines could have occurred after bilateral symx, and the catecholamines may have affected the RP response. To test this hypothesis, propranolol was administered to the five cats that still exhibited a reflex RP response after cardiac efferent autonomic denervation. Propranolol significantly attenuated the remaining RP response in these five cats.

In five of the 16 cats that received atropine before the sympathectomies, the RP response was abolished. In these cats, a subsequent symx was not performed. Similarly, right symx after atropine abolished the RP response in four of six cats, and in two of these, a subsequent left symx was not performed.

To examine the effects of varying the initial sympathetic outflow on RP, carotid occlusions were performed, and propranolol was administered. Figure 7A illustrates the effects of the carotid occlusions on RP, MAP, and the response to CVS. The left panel shows that carotid occlusion decreased RP by 4 msec and increased MAP by 43 mm Hg, indicating that sympathetic activity was increased. The right panel shows that the increased sympathetic discharge had no effect on the change in RP due to CVS, although the decrease in MAP was
FIGURE 7  Effects of carotid occlusion and propranolol on tonic and CVS-induced changes in RP, HR, and MAP. Panel A: Effects of carotid occlusion. Left side—tonic effects on RP and MAP. Right side—effects on changes in RP and MAP induced by CVS. Panel B: Effects of propranolol. Left side—tonic effects on HR and MAP. Right side—effects on changes in RP and MAP induced by CVS.

Effects of Hemorrhage on RP

In nine cats, hemorrhage sufficient to lower MAP to an extent similar to that of CVS (-62 ± 3.4 mm Hg with CVS vs. -54 ± 4.5 mm Hg with hemorrhage P > 0.05) produced a slight nonsignificant decrease of 2 msec in RP (167 ± 6.7 to 165 ± 7.7 msec). Thus, the decrease in MAP due to CVS was not responsible for the increase in RP.

Discussion

The data presented provide the first demonstration of a reflex neural pathway which can alter the refractoriness of the heart. Most studies examining neural effects on cardiac electrical activity have ablated the central projections of autonomic nerves to clarify efferent neural effects on the parameters measured. Cutting the central end of autonomic nerves abolishes any reflex mechanisms that may be operative; as a result, some potential neural influences are not present, and the description of autonomic nervous effects must necessarily be incomplete. Recently, however, Brooks et al. (1978) have suggested that vagal afferents could influence ventricular vulnerability. They demonstrated that atropine had no effect on vulnerability but that vagotomy increased it; furthermore, unilateral stellate ganglionectomy did not alter vulnerability unless vagotomy had been performed. These observations suggested that vagal afferents had a protective effect on cardiac vulnerability by reflex inhibition of sympathetic efferent activity. In addition, Schwartz et al. (1977) demonstrated that vagal afferents had a tonic influence on right ventricular refractoriness.

The present data extend the observations of Brooks et al. (1978) and Schwartz et al. (1977) to the definition of a specific reflex arc which can alter cardiac RP. The reflex was predominately vagal-vagal in nature; that is, the afferents coursed in the right vagus nerve and vagal efferents were responsible for most of the increased RP. However, the withdrawal of cardiac sympathetic efferents also contributed to the response and was primarily evident when the vagi were blocked.

The caudovagal nerve contains both inhibitory and stimulatory afferent fibers (Armour, 1973; Oberg and Thorén, 1972, 1973). With the stimulation parameters used in the present study, the predominant effect of CVS is a Bezold-Jarisch-like response (Krayer, 1961; Oberg and Thorén, 1973). Thus, large decreases in MAP and HR are observed upon CVS. However, there is some variability in the magnitude of the RP response. The variability probably is a function of anatomy. Figure 1 illustrates the different configurations of caudovagal nerves noted in this study. Those cats that exhibited large increases in RP (≥ 6 msec) possessed a single predominant caudovagal nerve (Figure 1B), although small fibers coming off the vagus frequently were present. Conversely, cats exhibiting smaller increases in RP had more diffuse caudovagal nerves; that is, two or three smaller nerves of similar size exited the vagus rather than a single large nerve (Fig. 1C). It is possible that had all these smaller nerves been stimulated simultaneously, the change in RP would have been greater. The caudovagal nerve also contains stimulatory afferents, although their effects were masked. In a few cats, however, a decrease in RP upon CVS was noted if the pathway of the inhibitory afferents was blocked (e.g., RVB), indicating that stimulatory afferents are present and that they can have a small (≤ 2 msec) influence on RP with the stimulation parameters used here. These afferents must have coursed partially in non-vagal pathways (e.g., via stellate ganglia) in order to exert any effect, inasmuch as the cervical right vagus was blocked.

Section of the caudovagal nerve produced a decrease in HR and an increase in RP, responses that would be expected if cardiac sympathetic inputs were removed. The caudovagal nerve contains both
sympathetic and parasympathetic efferent nerve fibers, the latter predominating (Armour et al., 1975; Armour, 1973). In the present study, cardiac sympathetic outflow was high due to the pentobarbital anesthesia; hence, it is reasonable to assume that the sympathetic efferent fibers initially were more active than the parasympathetic fibers. Furthermore, neither RVB nor LVB affected RP, indicating that caudovagal efferent tonic nerve activity was predominantly sympathetic. Thus, cutting the caudovagal nerve would appear to diminish sympathetic outflow despite the fact that more parasympathetic fibers were present in the nerve.

Neither right nor left symx nor vagal cold block had an effect on RP; however, bilateral cardiac sympathectomy increased whereas bilateral vgal cold block decreased RP. Furthermore, bilateral symx had a greater effect on RP if vagal efferent activity was blocked. These observations suggest that vagal and sympathetic efferents overlap in their innervation of the heart, such that if one neural input is ablated, then others may assume an apparently greater role. For example, if the right vagus was cut, then the left vagus and the cardiac sympathetics could compensate for the loss of that input, preventing a measurable change in RP. However, compensation sufficient to prevent a change in RP could not occur if both vagi or both sympathetic influences were eliminated. Furthermore, efferent vagal activity antagonizes the effect of the sympathetics since section of the cardiac sympathetics had a greater effect on RP if vagal efferents were blocked by atropine. A similar effect of vagal efferent restraint on the sympathetic influence on electrical vulnerability (Kolman et al., 1975, 1976) or refractoriness (Schwartz et al., 1977) has been suggested previously.

Atropine administration produced a small but statistically significant increase in RP. Initially, this effect was surprising, since it was expected that the removal of vagal efferent activity to the heart would produce a decrease in RP. However, BVB did produce a decreased RP. Taken together, these responses suggested that atropine was having an effect in addition to its blockade of vagal efferents. A likely possibility was that atropine was blocking muscarinic receptors in cardiac sympathetic ganglia. Muscarinic receptors have been shown to be present in sympathetic ganglia (Jones, 1963; Brown, 1967; Flacke and Gillis, 1968), and blockade of these receptors would be expected to increase RP when sympathetic outflow was relatively high. Additional evidence to support this hypothesis is the observation that atropine did not produce the increase in RP if cardiac sympathectomy had been performed. Thus, it is reasonable to assume that atropine produced an increase in RP by blocking muscarinic receptors in cardiac sympathetic gangia.

The observations that (1) RVB blocked the reflex RP response, (2) LVB produced no significant effect, and (3) efferent vagal blockade with atropine diminished, but did not abolish, the reflex RP response indicate that the blockade of right vagal afferents was the significant effect of RVB which prevented an RP change upon CVS. These data demonstrate that the efferent limb of the reflex is wholly in the right vagus nerve. This result is in agreement with studies which showed that the effects of afferent stimulation of the caudovagal nerve could be blocked by cooling the right vagus nerve (Jones, 1953; Öberg and Thoren, 1973). Both reflex vagal activation and sympathetic withdrawal accounted for the efferent pathway, the former predominating. Thus, the vagi could compensate for the lack of sympathetic activity, but the reverse was not true. Blockade of vgal efferents by administering atropine attenuated the RP response regardless of whether the sympathetic nerves were intact. On the other hand, neither right nor left symx had an effect on the RP response if vgal efferents were intact, although bilateral symx produced a slight blockade. Once the vgal efferents were eliminated, however, the effect of withdrawing sympathetic activity became more evident. Approximately 75% of the response remaining after atropine could be ascribed to withdrawal of the cardiac sympathetic nerves on the right side, whereas the left side contributed 25%. In a few cats, atropine and cardiac sympathectomy did not block all of the RP response. The administration of propranolol to these animals did abolish the remaining response. This observation suggests that circulating catecholamines could have contributed to the response; more specifically, the caudovagal afferents may have inhibited the release of adrenal catecholamines. This effect is probably more likely to occur as a compensatory mechanism after cardiac sympathetic denervation. That the vagus may inhibit adrenal release of catecholamines has been shown previously (Kaindl and von Euler, 1951).

Previous work studying the effects of efferent vagal activation vs. the efferent cardiac sympathetics on electrical parameters of the heart has produced contradictory results. Most studies have suggested that the efferent vagi have no effect on cardiac vulnerability or refractoriness unless sympathetic activity is present (Kolman et al., 1975, 1976; Yoon et al., 1977; James et al., 1977), although Kent et al. (1973) showed that efferent vagal stimulation could increase VFT, and Schwartz et al. (1977) demonstrated that both vgal afferents and efferents could tonically influence refractoriness. The results presented herein suggest that changes in vgal efferent activity can have an effect on RP regardless of the initial sympathetic activity. Thus, increasing the sympathetic activity by carotid occlusion had no effect on the RP response. Eliminating cardiac sympathetic activity by propranolol produced only a slight attenuation of the RP response to CVS; if the efferent vagi had no effect in the absence of sympathetic activity, propranolol should have abolished the RP response. Therefore, the
present study suggests that the vagi do not require sympathetic activity to alter refractoriness. Reasons for the differences reported in the contribution of the vagi to the control of electrical properties of the heart may include the following. (1) All neural pathways were intact in the present study but were not in the studies cited above. Thus, afferent effects could not be examined in the previous studies. The possibility exists that the vagi could play a larger role in the control of VFT if they were intact. That intact vagal afferents can influence VFT (Brooks et al., 1978) or refractoriness (Schwartz et al., 1977) has been demonstrated. (2) The parameter measured may influence the results obtained. RP and VFT are not measurements of the same physiological phenomenon, although they may be related. The measurement of RP from a single site, as performed in the present study, does not provide an index of cardiac vulnerability, although the dispersion of refractory periods from several sites does provide such an index (Han and Moe, 1964; Merx et al., 1977; Russell and Oliver, 1978). On the other hand, tonic autonomic influences on both parameters are similar; that is, sympathetic activity decreases VFT and RP, but vagal activity increases them (Kent et al., 1973; Kolman et al., 1975, 1976; Yoon et al., 1977; James et al., 1977; Schwartz et al., 1977). Furthermore, as discussed previously, tonic vagal afferent activity can influence both parameters. Thus, the quantitative differences in the results obtained herein and those reported in other studies probably do not relate to the difference in the measured parameter. However, efferent vagal fibers may contribute quantitatively more to the control of RP than VFT. (3) The previous studies used dogs, whereas the present study used cats. Perhaps the species difference could account for the differences in results. However, species differences probably would be responsible for only quantitative, rather than qualitative, differences. (4) Pentobarbital was the anesthetic used here, but chloralose was used in most other studies. Since pentobarbital produces a lower vagal tone than chloralose, perhaps the present data are skewed toward sympathetic domination. This possibility is unlikely, since our results show an overall vagal dominance which could only be expected to become more pronounced if chloralose had been used. Had our results been skewed toward sympathetic domination of the reflex, they probably would have agreed closely with the earlier studies. To summarize, the most significant difference between the protocols used in the present study and those used in most of the other studies involves the integrity of the nervous system (possibility 1). The vagi probably have a greater role in influencing cardiac refractoriness or vulnerability when all reflex neural pathways are intact.

In relation to the sympathetic efferent portion of the reflex RP response, the right sympathetic nerves were dominant in the present study. Thus, right symx inhibited the RP response to a greater extent than did left symx. These observations are in contrast with results of several studies which showed the left side sympathetic nerves to have a greater effect on cardiac vulnerability. Left but not right stelllectomy after vagotomy has been shown to increase vulnerability (Kliks et al., 1975; Schwartz et al., 1976a; Brooks et al., 1978); subsequent coronary artery occlusion produced a smaller decrease in VFT than it did before left stelllectomy (Kliks et al., 1975). Schwartz et al. (1976b) demonstrated that right stelllectomy increased but left stelllectomy decreased the arrhythmias associated with either left anterior descending or circumflex coronary artery occlusion. The determination of the relative dominance of the right vs. the left sympathetic nerves on cardiac vulnerability or refractoriness may depend on the recording sites. The studies cited above, except for Kliks et al. (1975), measured VFT from the endocardial apex of the right ventricle. Kliks et al. (1975) placed one electrode in the borderline ischemic zone and the other in the right ventricle. In the present study, we recorded from the anterior surface of the left ventricle in the distribution of the LAD coronary artery. These areas may have different innervation patterns. Several studies have demonstrated that the right side sympathetic nerves innervate the anterior ventricular surface primarily, whereas the left side sympathetics innervate the posterior surface, although there is a considerable amount of overlapping innervation (Rogers et al., 1973; Kralios et al., 1975; Yanowitz et al., 1966; Haws and Burgess, 1978). Thus, the results that one obtains on ablating or stimulating the sympathetics may depend on the recording site, since recording from different sites would mean recording from different peripheral nerve fields. As discussed previously, observations may depend on the parameter measured or the species studied. However, the recording site is probably the most important factor due to the discreteness of autonomic innervation. Thus, our results relate to a small area of the feline left ventricle in the region of distribution of the LAD coronary artery and should not necessarily be extrapolated to other sites on the heart.

The present study has demonstrated a cardiocardiac reflex arc, predominately vagal-vagal but also vagal-sympathetic, which can alter the refractoriness of the heart. Other investigators have demonstrated cardiocardiac reflexes elicited by coronary artery occlusion (Malliani et al., 1968; Gillis, 1971; Peterson et al., 1973; Thorén, 1976). Similarly, afferent sympathetic fibers have been shown to inhibit vagal afferents and to facilitate sympathetic efferents; opposite effects on efferents were noted on stimulation of vagal afferents (Schwartz et al., 1973). The caudovagal nerve, as well as other cardiac nerves, probably mediates part of these reflexes. For example, the caudovagal nerve carries some of the fibers responsible for the Bezold-Jarisch effect (Jones, 1953). Since reflexes have been shown to contribute to the deleterious effects of coronary
occlusion, and may have a role in the sudden death syndrome, it would be prudent for future investigators to obtain additional information on the role of cardiovascular reflexes in affecting the electrical properties of the heart.

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