Rhythmic variations in peak left ventricular pressure were often observed in recent studies upon innervated, isovolumetric, paced, left ventricle preparations. The frequency of these pressure fluctuations coincided with that of the movements of the rib cage, although the lungs were collapsed, the hili were securely ligated, and the perfusion pressure for the coronary circulation and the cephalic portion of the animal was rigorously maintained at a constant level. Under such conditions, the rhythmic modulation of peak left ventricular pressure in an isovolumetric preparation must have represented phasic variations in cardiac autonomic activity, originating from neurons located in the respiratory centers or from neurons which discharge synchronously with those in the respiratory centers. This paper deals with a more detailed description of these respiratory fluctuations in left ventricular performance, and with the interrelationships between such “contractility waves” in the paced heart and the respiratory variations in heart rate in the unpaced heart. Some of the data included in this paper were extracted from the previously conducted experiments.

Methods

In each experiment, the donor dogs were anesthetized with thiamylal sodium (Surital, Parke Davis). The dogs from which the innervated, isovolumetric left ventricles were prepared were anesthetized with morphine sulfate, followed by chloralose and urethane, as described previously. The hili of both lungs were securely ligated. The coronary and cephalic perfusion pressures were maintained constant by means of overflow reservoirs which were continuously filled by pump-oxygenators. A latex balloon and a drain (Thebesian drainage) were inserted into the left ventricle through an apical incision. A small volume of saline was introduced into the balloon, and left ventricular pressure was registered from the balloon by a strain gauge. Blood oxygen saturation was recorded with a Gilford cuvette densitometer, and blood pH was registered with a Radiometer pH meter. In order to gauge the activity of the respiratory center, rib cage movements were recorded by stretching an elastic string from a force transducer to a point on the rib cage showing maximal excursions. These variables were all registered on a Sanborn direct-writing recorder and stored by tape recorder (Honeywell, model LAR 7400).

Heart rate was obtained from the ventricular tracing by one of two types of tachometers. For most experiments, an “averaging tachometer” was employed (e.g., fig. 8). The phase lag and attenuation of this tachometer were determined by modulating a sinusoidal signal possessing a frequency approximating that of the mean heart rate with signals which covered the entire range of respiratory frequencies observed in these experiments. In some experiments, heart rate was registered by means of a “cycle duration meter” (e.g., figs. 1 and 2), in which a voltage ramp of constant slope was reset by the peak of each left ventricular pressure pulse. This type of tachometer requires no corrections for phase lag or attenuation. In those experiments in which both types of tachometers were employed simultaneously, the values obtained with the cycle duration meter corresponded closely with the corrected values obtained with the averaging tachometer. To measure precisely the phase differences among the respiratory movements, the heart rate, and the peak ventricular pressure, the signals from the tape recorder were played back to the direct-writing recorder at appropriate paper speeds (usually 2.5 mm/sec).
Results

Respiratory Effects Upon Heart Rate

A. Vagi Intact

Observations were made before pacing the heart in order to determine the amplitude and phase relationships of the heart rate oscillations which occur at the frequency of the respiratory movements. Also, the effects of various stimuli, such as hypoxia of the carotid chemoreceptors, were ascertained. A record from a representative experiment in which the vagus nerves were intact is shown in figure 1. During the control period at the left side of the tracing, the carotid chemoreceptor region was perfused with fully oxygenated blood. Heart rate varied from a minimum of 120 to a maximum of 135 min⁻¹. Analysis of tracings recorded at faster paper speeds revealed that the heart rate began to accelerate slightly before the beginning of each respiratory movement, and peak rate was attained at approximately the midpoint of each respiratory cycle. During the bradycardia which was evoked by hypoxia of the carotid chemoreceptor region, the amplitude of the heart rate fluctuations was augmented considerably.

In nine experiments in which the vagi were intact, during control conditions the mean heart rate was 155 min⁻¹, and the mean amplitude of the fluctuations of heart rate (difference between maximum and minimum heart rates) was 26.4 min⁻¹ (table 1). Cardiac acceleration consistently began before the beginning of the inspiratory movements. However, the rate of increase was usually slight during the expiratory phase, and the acceleration became much more pronounced with the actual onset of inspiratory activity. The peak heart rate was attained at a point in time which was 32.3% of the respiratory period (reciprocal of the frequency), measured from the beginning of inspiration.

B. Vagi Sectioned

In many experiments, observations were

![Diagram](attachment:image)

**FIGURE 1**

Heart rate and respiratory movements in a representative experiment before, during and after hypoxia of an isolated carotid sinus. The densitometer tracing (bottom) shows the oxygen saturation of the blood perfusing the isolated carotid sinus. Vagi intact, Heart rate recorded with a "cycle duration meter." In the middle tracing, inspiration is downward.

**TABLE 1**

<table>
<thead>
<tr>
<th>Heart Rate and Contractility Variations at the Frequency of Respiratory Movements, Before and After Bilateral Vagotomy *</th>
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<tbody>
<tr>
<td><strong>Heart Rate</strong></td>
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*All values represent mean ± standard error.
RESPIRATORY CENTER ACTIVITY AND THE HEART

FIGURE 2
Respiratory variations in left ventricular pressure and heart rate (cycle duration meter) in a representative experiment shortly after bilateral vagotomy. Left half of figure, heart beating spontaneously; right half, heart paced at 211 min⁻¹. Bottom tracing represents movements of the rib cage (inspiration upward).

Repeated after bilateral vagotomy, in an attempt to assess the relative roles of the two divisions of the autonomic nervous system. The respiratory cardiac arrhythmia was often still detectable after vagotomy, although the amplitude of the fluctuations was considerably reduced. An example is displayed in the left half of figure 2. In four experiments after vagotomy, the mean heart rate was 184 min⁻¹ during control conditions (table 1). The amplitude of the heart rate waves was 8.5 min⁻¹, which was significantly less than that observed with the vagi intact (P = 0.01). Cardiac acceleration began synchronously with the onset of the respiratory movements, and the peak rate was attained at 33.7% of the respiratory period from the beginning of the respiratory cycle. This percentage is not significantly different from that which prevailed prior to vagotomy. However, since the respiratory period was almost twice as long as after vagotomy, the actual time from the beginning of inspiration to the peak of the heart rate wave was proportionately greater than that observed before vagotomy.

FIGURE 3
Changes in left ventricular pressure in a paced heart after bilateral vagotomy, after the respiratory centers were depressed by the administration of additional anesthetic. Inspiration downward.

RESPIRATORY EFFECTS ON VENTRICULAR CONTRACTILITY

A. General Characteristics of Contractility Fluctuations

When the heart is paced at a constant rate, changes of peak pressure in the isovolumetric left ventricle preparation reflect alterations of myocardial contractility.² Prominent rhythmic modulation of ventricular contractility (hereafter referred to as contractility waves) at the frequency of the respiratory movements was often observed both before and after vagotomy. Hence, such contractility waves serve as an index of the variations in nervous activity affecting the ventricular myocardium.

From experiments in which regular respiratory movements prevail, it is not possible to ascertain whether the contractility waves, which are usually sinusoidal, represent oscillations above, below, or about a base line level of left ventricular systolic pressure. The experiment illustrated in figure 3 reveals that in the vagotomized animal, the contractility waves represent a periodic enhancement of left ventricular pressure. In this experiment, a few minutes before the tracing in figure 3 was recorded, additional anesthetic was given in order to depress the respiratory center. With each of the sporadic respiratory movements seen in the figure, the left ventricular systolic pressure increased by 17 mm Hg from a base line level of 47 mm Hg.

That the contractility waves are independent of the actual respiratory movements of
Changes in left ventricular pressure (heart paced) and respiratory movements (inspiration downward) in a vagotomized preparation as the pH of the blood perfusing the brachiocephalic arterial bed was lowered by enriching the oxygenator gas mixture with additional CO₂. A separate oxygenator was used for the coronary circulation; the coronary arterial CO₂ content was constant throughout this experiment. Succinylcholine was administered to paralyze respiratory movements in the interval between the registration of the left and right panels.

The timing of the contractility waves was compared with the timing of the heart rate waves observed prior to pacing. Also, the timing of the contractility waves was compared before and after bilateral cervical vagotomy. The phase relationships between the heart rate fluctuations and the contractility waves in a representative experiment are illustrated in figure 2. In the unpaced heart (left half), cardiac acceleration began with the onset of inspiration, and the peak heart rate was attained at 31.7% of the respiratory period. When the heart was paced at a constant frequency of 211 min⁻¹, the minima and maxima of the contractility waves occurred at points in time which were 17.6 and 63.3%, respectively, of the duration of the respiratory period, measured from the beginning of the inspiratory movement. Each value represents an average of five respiratory cycles, which were measured on tracings made at much greater paper speeds than that employed in recording figure 2.

As the composite data included in table 1 show, the phase relationships of the contractility waves were significantly different from those of the cardiac arrhythmia. The minima for the heart rate waves occurred before or synchronous with the onset of inspiration. The minima for the contractility waves occurred at approximately one-third of the respiratory period, which was significantly later than for the heart rate waves (P < 0.001 and P = 0.01 before and after vagotomy, respectively). The maxima of the contractility waves also occurred later in time than the maxima of the heart rate waves (P < 0.001 both before and after vagotomy).

The phase relationships (expressed in terms of...
Variations in left ventricular pressure and rib cage movements (inspiration downward) in an experiment with vagi intact and with heart paced. Several minutes before this record was made, the brachiocephalic arterial bed was perfused for 90 sec with anoxic blood. The two panels at the right show tracings at faster paper speed, the left during expiration, the right during inspiration.

before and after bilateral cervical vagotomy during steady state conditions (table 1). The minima of the contractility waves occurred at 39.5 and 28.8% of the respiratory period before and after vagotomy, respectively ($P = 0.3$). The corresponding maxima were at 75.1 and 74.8% of the respiratory period, respectively. When expressed in absolute units of time, however, the maxima occurred at slightly greater time intervals after the onset of inspiration after vagotomy than before vagotomy, because the respiratory cycles were longer.

C. Influence of Respiratory Frequency

Changes of respiratory frequency occurred under a variety of experimental conditions; an inverse correlation between respiratory frequency and the amplitude of the contractility waves was noted consistently. Examples are presented in figure 5, and also in figure 2 of an earlier paper. In the experiment recorded in figure 5, while the cephalic portion of the animal was being perfused with fully oxygenated blood after a brief period of cephalic hypoxia, respiratory frequency decreased progressively from 17.6 to 5.2 min$^{-1}$. As the Bode diagram for this experiment reveals (fig. 6), there was a concomitant, progressive increase in the amplitude of the contractility waves from 1 to 13% of the peak pressure generated by the left ventricle.

The regression lines of contractility wave amplitude as a function of the respiratory
period are presented in figure 7 for this experiment (line C) and for three other experiments. Line A represents an experiment in which respiratory frequency changed during hypoxia of the carotid chemoreceptors; line B, an experiment in which respiratory frequency changed during cephalic hypoxia (fig. 2 of reference 2); and line D, an experiment in which respiratory frequency changed after transection of the carotid sinus nerves. The ordinates represent the amplitudes of the contractility waves, expressed as a percentage of left ventricular systolic pressure, measured at the trough of the individual waves. The slopes of these regression lines indicate increments of contractility ranging from 0.48 to 1.43% per second increase in respiratory period. The correlation coefficients vary from 0.75 to 0.87, and all are statistically significant \( P \leq 0.001 \) for each coefficient.

The contractility wave phase lag, when expressed as a fraction of the duration of the respiratory period, also varies with the frequency of respiration. In the experiment depicted in figure 5, respiratory frequency decreased progressively from 17.6 to 5.2 min\(^{-1}\). As the Bode diagram in figure 6 shows, the phase lag from the onset of inspiration to the peak of the contractility wave decreased progressively from 382° to 149° (where 360° represents the total duration of each respiratory period). For the composite data for all experiments included in table 1, the phase lag, \( \phi \), to the peaks was correlated significantly but inversely \( (r = -0.572; P = 0.025) \) with the magnitude of the respiratory period, \( T \). The regression equation is \( \phi = 100.9 - 2.91T \), where \( \phi \) is expressed as per cent of the respiratory period, \( T \); and where \( T \) is expressed in seconds.

When the lag is expressed, however, in terms of absolute units of time, the intervals from the onset of inspiration to the minima and maxima of each wave remain remarkably constant, despite large variations in the respiratory period. For example, in the experiment represented by line A of figure 7, the respiratory period varied from 6.4 to 32.6 sec. The lags to the minima of the contractility waves varied randomly between 5.5 and 7.0 sec, and to the maxima, between 17 and 20 sec, with no apparent relationship to the duration of the respiratory period. In the experiment depicted in figures 5 and 6, the respiratory period varied from 3.4 to 11.6 sec. The time from the onset of inspiration to the minima of contractility waves varied randomly between 5.5 and 7.0 sec, and to the maxima, between 17 and 20 sec, with no apparent relationship to the duration of the respiratory period. In the experiment depicted in figures 5 and 6, the respiratory period varied from 3.4 to 11.6 sec. The time from the onset of inspiration to the minima of contractility waves varied randomly between 1.4 and 1.8 sec. The time to the contractility wave peaks did increase progressively, but only slightly, with the duration of the respiratory periods; for the shortest periods, the time to the peaks was 3.8 sec, while for the longest periods, the time was 4.6 sec.

**FIGURE 7**

Variations of left ventricular contractility as a function of the respiratory period for four representative experiments in which appreciable changes in respiratory frequency occurred. Ordinates represent the amplitude of the contractility waves, expressed as a percentage of left ventricular systolic pressure. Line A \( (Y = 1.005X + 1.559; r = 0.87; P < 0.001) \) represents the response to carotid chemoreceptor hypoxia. Regression line B \( (Y = 1.433X - 9.195; r = 0.76; P < 0.001) \) represents the experiment depicted in figure 2 of a previous article.\(^*\) Line C \( (Y = 1.054X - 0.779; r = 0.75; P = 0.001) \) represents the experiment displayed in figure 5. Line D \( (Y = 0.477X + 0.806; r = 0.75; P < 0.001) \) represents an experiment in which respiratory frequency changed after transection of the carotid sinus nerves.

**TIMING OF HEART RATE AND CONTRACTILITY CHANGES DURING RIGHT STELLATE GANGLION STIMULATION**

The right stellate ganglion was stimulated.
Effects of stimulation of the right stellate ganglion on heart rate (averaging tachometer) and on left ventricular pressure with the heart beating spontaneously (segments A-C) and paced (segments D-G). Each deflection of the event marker represents a train of stimuli of 1 sec duration, at a frequency of 20 cycles/sec. The trains of stimuli were delivered at a frequency of 1/10 sec for segments A and D, 1/20 sec for B and E, and 1/30 sec for C and F. Segment G is a continuation of segment F, but at a faster paper speed, in order to display the configuration of the left ventricular pressure curves.

rhythmically in both paced and unpaced hearts, to determine the extent to which central or peripheral factors account for the phase differences between the contractility and the heart rate waves that are manifest in table 1. In each experiment, stimuli were applied repetitively at rates of once per 10, 20, and 30 sec. Each stimulus consisted of a 1 sec train of impulses of 1 v intensity, 5 msec duration, and 20 pulses/sec frequency. Records from a typical experiment are shown in figure 8. These same tracings were stored on tape, and were replayed to the direct-writing recorder at paper speeds of 2.5 mm/sec (10 times that used to register fig. 8) in order to permit more precise measurements of the phase relationships.

A total of six similar experiments was done and the composite results are presented graphically in figure 9. It is apparent that, at each frequency, the times from the beginning of stimulation to the peaks (total height of each bar) and to the troughs (horizontal line within each bar) are appreciably greater for the contractility waves than for the heart rate waves. For the contractility waves, the mean times to the troughs vary from 2.40 to 2.43 sec; for heart rate, 1.65 to 1.92 sec. The mean times to the peaks vary from 7.23 to 8.30 sec for the contractility waves, and from 4.37 to 5.63 for the heart rate waves. At all frequencies, the differences between the timing for the contractility and heart rate waves were statistically significant, both for the minima and for the maxima (P ≤ 0.01).

Discussion

RESPIRATORY CARDIAC ARRHYTHMIA

Multiple factors have been implicated in the genesis of respiratory cardiac arrhythmia;
namely, the venous return to the right atrium, the pressure gradient in the venous system, the baroreceptors, inflation of the lungs, and interactions between the respiratory center and the cardiac autonomic center in the central nervous system. Although several or all of these factors may operate to produce the arrhythmia in the intact subject, it is apparent that only the last factor was involved in the present study. In these experiments the venous return did not vary during the respiratory cycle, the right atrium was continuously drained by gravity, the arterial pressure was held constant by means of one or more overflow reservoirs, the lungs were collapsed throughout each experiment, and the pulmonary hili were securely ligated.

Both divisions of the autonomic nervous system must have conducted the impulses which produced the arrhythmia, although the influence of the parasympathetic system predominated. With the vagi intact, the mean amplitude of the heart rate oscillations was 26.4 min⁻¹; after bilateral vagotomy, the mean amplitude was only 8.5 min⁻¹. Koepchen et al. also noted the persistence of slight respiratory cardiac arrhythmia after bilateral vagotomy. In other studies, sectioning or cooling the vagi caused the respiratory cardiac arrhythmia to disappear. In one of these studies, Anrep et al. were able to demonstrate under such conditions that rhythmic activity of the cardiac sympathetic nerves still persisted, however. By applying a repetitive stimulus to the cardiac ends of the sectioned vagi of sufficient intensity to return heart rate to the prevagotomy level, a slight respiratory cardiac arrhythmia appeared again; this must have been mediated via sympathetic pathways. Other investigators have confirmed the persistence of rhythmic electrical activity synchronous with respiration in the cardiac sympathetic nerves after bilateral vagotomy.

The magnitude of respiratory cardiac arrhythmia has been shown to vary with the extent of vagal tone. Stimulation of the carotid body chemoreceptors accentuates vagal tone markedly when pulmonary ventilation is controlled. This undoubtedly accounts for the pronounced exaggeration of the respiratory cardiac arrhythmia which was observed consistently during hypoxic stimulation of the isolated carotid sinus (fig. 1). A similar mechanism probably explains the augmentation of the arrhythmia when the head was perfused with hypercapnic blood in the experiments of Anrep et al.

With respect to the timing of the cardiac arrhythmia, when the vagi were intact, gradual cardiac acceleration began prior to the onset of detectable respiratory muscular activity (table 1). However, whether the vagi were intact or sectioned, appreciable cardiac acceleration began approximately synchronously with the onset of inspiratory activity, and the peak heart rate was attained at one-third of the interval toward the next inspiratory effort (table 1). In absolute units of time, however, the peak heart rate was reached appreciably later after vagotomy, since the respiratory period was almost twice as great. The nervous factors which determine these time relationships are complex. Reduced vagal activity is largely confined to the inspiratory phase of the respiratory cycle, whereas enhanced sympathetic activity may occur during the last half of inspiration, and during the early or entire portion of expiration. The latent period for the effect of vagal stimulation upon heart rate is considerably less than for that induced by sympathetic activation. Furthermore, after cessation of stimulation, the effects of sympathetic stimulation decay much more gradually than do those of vagal activation. The latent period for cardiac deceleration after a single shock to the cervical vagus is 240 to 300 msec in the dog, and 100 to 160 msec in the cat. With sympathetic stimulation, cardiac acceleration first appeared after 2.5 to 8 sec in the experiments conducted by Samaan. In our experiments the latent period for right stellate stimulation was regularly slightly less than 2 sec (fig. 9).

RESPIRATORY FLUCTUATIONS OF VENTRICULAR CONTRACTILITY

In the present study, the rhythmic modulation of ventricular contractility occurring at
the same frequency as the respiratory movements was undoubtedly a consequence of fluctuations in cardiac autonomic nervous activity. Since the variations in contractility were evident in the bilaterally vagotomized animal, the sympathetic nerves were certainly involved. Indeed, the contractility waves were more pronounced after vagotomy, probably because of the associated reduction in frequency of the respiratory movements (probably secondary to aortic chemoreceptor denervation). The vagi have recently been shown to exert a negative inotropic effect upon ventricular contractility. It is likely therefore, that the contractility waves in animals with vagi intact were partly ascribable to parasympathetic activity as well, although it appears likely that sympathetic influences predominated under the conditions of this study.

The mechanism responsible for the rhythmic fluctuations in cardiac autonomic nervous activity is probably identical to that which evokes the respiratory cardiac arrhythmia of the unpaced hearts in the present study. The lungs themselves do not serve as a source of periodic afferent activity, since they are collapsed and securely ligated. The baroreceptors and chemoreceptors do not generate periodic afferent activity, since the receptor zones are perfused at a constant pressure with blood of constant gas composition during control observations. The rib cage itself probably does not give rise to relevant afferent discharges synchronous with the respiratory movements, since the contractility waves are equally prominent after paralysis with succinylcholine (fig. 4). This evidence also rules out the possibility that the rhythmic fluctuations in peak left ventricular pressure may represent artifacts due to displacements of the heart associated with the movements of the rib cage. By exclusion, therefore, the most likely explanations are (a) that the contractility waves represent radiation of nervous activity from the respiratory centers to the cardiac autonomic centers within the central nervous system, or (b) that similar central rhythms originate simultaneously within the cardiac and respiratory centers, to parallel the recent hypothesis of Weidinger and Leschhorn relative to the vasomotor center. This does not deny the possibility, however, that in the intact subject, reflex effects from the lungs, the baroreceptors, and the chemoreceptors may have important contributory actions. Furthermore, the rhythmic fluctuations in cardiac contractility must now be included among the list of factors responsible for the respiratory variations which are usually observed in the arterial blood pressure.

The present data do not afford a full explanation for the differences in phase relationships between the respiratory cardiac arrhythmia and the contractility waves (table 1). Electroneurographic studies have revealed rhythmic changes in activity at the frequency of respiration in both divisions of the autonomic nervous system. It has not been determined whether there are different nervous pathways to the pacemaker cells and to the ventricular myocardial cells, with disparate time relationships and conduction velocities. When both divisions of the autonomic nervous system are intact, such a mechanism would probably be involved, since the heart rate changes are mediated primarily via the vagus nerves, and the contractility waves are probably mediated predominantly via the sympathetic nerves. In vagotomized animals, however, the phase differences still exist (table 1). The studies of Randall and his associates suggest that cardiac sympathetic augmentor and accelerator fibers do not follow anatomically separate pathways from the spinal cord to the heart. Instead, the response appears to depend on the location of the nerve terminations within the heart itself.

The experiments in which the right stellate ganglion was stimulated periodically (fig. 8) demonstrate that peripheral factors account for an important fraction of the differences in the phase relationships between the contractility and heart rate waves, at least after vagal transection. Figure 9 shows that the peaks and troughs of the heart rate waves occur significantly earlier than those of the contrac-
tility waves, when each is measured from the beginning of stimulation. These differences may be related to disparities between conduction times in the sympathetic fibers to the sino-atrial node and to the ventricular myocardium. However, it is much more likely that the discrepancies are related to factors operating within the heart itself, at the terminations of the fibers near the pacemaker and myocardial cells, at the cell membranes, or within the cells themselves.

The variations in amplitude and phase of the contractility waves as a function of respiratory frequency also cannot be explained fully on the basis of available information. The variations of respiratory frequency that were observed in the present study were associated with a rather constant duration of inspiration, complemented by appropriate changes in the duration of expiration. When the intervals from the onset of inspiration to the peaks and troughs of the contractility waves were expressed in absolute units of time, then the intervals remained quite constant over the frequency ranges which prevailed in these experiments. Therefore, when the phase lags were expressed as a fraction of the total duration of the respiratory cycle, the phase lags varied directly with the respiratory frequency. These findings parallel the electroneurographic data obtained by Tang et al. Over a considerable range of respiratory frequencies, discharges in the splanchnic nerves followed those appearing in the phrenic nerves by a constant interval of approximately 1 sec.

The changes in amplitude of the contractility waves as a function of respiratory frequency (Figs. 6 and 7) were probably dependent upon both central and peripheral mechanisms. Peripherally, in the ventricular myocardium, the facilitatory effect of a brief burst of sympathetic activity would decay with a finite time constant. This is apparent at the end of each series of stimuli in segments D, E, and F of figure 8. With decreasing respiratory periods below a certain limit, the stimulatory effect of each subsequent respiration would occur at a progressively earlier point in the decline from the preceding effect. This would result in diminishing wave amplitudes, analogous to the manner in which the wave amplitudes in segment D, figure 8, are less than those in segments E or F. Bronk and his coworkers reported similar findings for heart rate fluctuations during rhythmic stimulation of the cardiac sympathetic nerves; at frequencies greater than 1/5 sec, the heart rate waves fused. Centrally, if the impulses from the respiratory centers induced reverberation in neuron pools in the cardiac autonomic centers, and if this reverberation decayed with a finite time constant, then in a similar fashion there would be a progressively more complete fusion as respiratory frequency increased. Elucidation of the quantitative roles of these central and peripheral factors must await further investigation.

**Summary**

Rhythmic fluctuations in heart rate and ventricular contractility at the frequency of the respiratory movements were observed in innervated, isovolumetric, canine, left ventricle preparations. The heart rate and contractility waves probably represent the radiation of activity from the respiratory centers to the cardiac autonomic centers within the central nervous system. In spontaneously beating hearts, the respiratory cardiac arrhythmia is mediated via the vagi predominantly, although a slight arrhythmia is still evident after bilateral vagotomy. The greater the vagal tone, the greater is the amplitude of the arrhythmia.

In paced hearts, the contractility waves exhibit significantly greater phase lags than do the heart rate waves in unpaced beats. The magnitude of the contractility waves varies inversely with the respiratory frequency. These waves are more prominent after bilateral vagotomy. Therefore, sympathetic influences appear to predominate in the mediation of the contractility waves, although the change in wave amplitude after vagotomy must be ascribed partly to the deceleration of respiratory frequency which occurs after vagotomy. The contractility waves represent rhyth-
mic augmentations of contractility above a base line level after vagal section.

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Effects of Respiratory Center Activity on the Heart
Matthew N. Levy, Hilaire DeGeest, Harrison Zieske and Donald Levy

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