High-frequency oscillations of phrenic activity in eupnea and gasping of in situ rat: influence of temperature

Walter M. St.-John and J. C. Leiter
Department of Physiology, Dartmouth Medical School, Dartmouth-Hitchcock Medical Center, Lebanon, New Hampshire 03756

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St.-John, Walter M., and J. C. Leiter. High-frequency oscillations of phrenic activity in eupnea and gasping of in situ rat: influence of temperature. Am J Physiol Regul Integr Comp Physiol 285: R404–R412, 2003. First published April 3, 2003; 10.1152/ajpregu.00599.2002.—We hypothesized that the in situ perfused preparation of the juvenile rat exhibits patterns of ventilatory activity comparable to eupnea and gasping in vivo. To evaluate this hypothesis, we examined high-frequency oscillations of activity of the phrenic nerve at 27–34°C. The peak frequency of these high-frequency oscillations was defined from power spectral analysis. In situ, recordings were obtained in hyperoxic normocapnia, during ventilatory cycles in which the peak of integrated phrenic activity was achieved late in the burst, as in eupnea in vivo. Recordings were also obtained in hypoxic hypercapnia, when the peak of integrated phrenic activity occurred in the first half of the burst, as in gasping in vivo. In situ, peak frequencies in the power spectra were significantly higher in gasping than during eupnea. Frequencies during eupnea and gasping were progressively elevated as the temperature of the in situ preparation was increased. The shift in peak frequencies between eupnea and gasping and the temperature sensitivity of frequencies in situ were the same as in vivo. Results provide additional support for the conclusion that the in situ preparation demonstrates distinctly different patterns of automatic ventilatory activity, comparable to eupnea and gasping in vivo.

in situ preparation; power spectra; peak frequency

IN A SERIES OF STUDIES IN 1923 and 1924, Lumsden characterized “gasing,” which followed transection of the brain stem at the pontomedullary junction or exposure to severe hypoxia or ischemia (13, 14). A primary characteristic of gasping was a “more sudden beginning” than that observed with a normal or eupneic inspiration. Numerous studies have confirmed this essential characteristic, with the rate of rise of phrenic activity being much higher in gasping than during eupnea (see Refs. 29–31 for review).

For examinations in vivo at normothermia, the duration of the phrenic burst is shorter and the peak height is greater in gasping than during eupnea (29–31). The period between bursts is longer in gasping; hence, the respiratory frequency is less than during eupnea (29–31). In addition, activities during neural expiration are greatly reduced with the change from eupnea to gasping (29–31, 35). Reflecting the inspiratory character of the gasp is the finding that the onset of activities of cranial nerves, which may precede that of the phrenic nerve in eupnea, occurs at approximately the same time as the phrenic burst in gasping (29–31, 35, 36).

Many of these differences between eupnea and gasping, found in vivo, have also been reported in an in situ perfused preparation of the juvenile rat (32–35). In this preparation, the augmenting pattern of phrenic activity, typical of eupnea in vivo, is observed if the perfusate is equilibrated with a hyperoxic gas mixture. After equilibration with a hypoxic-hypercapnic mixture or production of ischemia by termination of perfusion, phrenic discharge is changed to a decrementing pattern, typical of gasping in vivo. Parenthetically, gasping can be elicited in situ by perfusates equilibrated with hypoxic gases, regardless of the concentration of CO₂ (34). Equilibration of the perfusate with a hypoxic-hypercapnic mixture is used in situ to reproduce the conditions resulting from exposure to severe hypoxia or anoxia in vivo. In spontaneously breathing in vivo preparations, a period of apnea and, thus, hypercapnia precedes the onset of gasping (29–31).

Other changes in activities of cranial and spinal nerves of the in situ preparation are also similar to those observed in vivo during eupnea and gasping (29–31). Thus activities during neural expiration of the in situ preparation are reduced in gasping (35). Activity of cranial and phrenic nerves also commences at approximately the same time (35). Transection of the brain stem at the pontomedullary junction of the in situ preparation reproduces the changes in phrenic activity that follow exposure to hypoxia or ischemia (35). Hence, after this transection, phrenic activity is altered from an incrementing to a decrementing pattern (35).

Some characteristics of gasping differ between in vivo and in situ preparations. Specifically, in vivo, the period between phrenic bursts is significantly longer in gasping than during eupnea, whereas these periods are the same in the perfused preparation (32–34). However, this difference between in vivo and in situ find-
ings reflected examination of the perfused preparations in hypothermia. When the in situ preparation was studied at temperatures that were close to normothermia in vivo, the frequency of gasping was significantly less than the frequency of eupnea (28). These differences, present under normothermic but not hypothermic conditions, reflect a differential influence of brain stem temperature on eupnea and gasping. This differential influence of temperature is consistent with the concept that different neurophysiological mechanisms underlie the genesis of eupnea and gasping (see Discussion in Ref. 28).

Supporting the concept of different mechanisms for the genesis of eupnea and gasping is the finding that high-frequency oscillations in neural activities differ significantly in eupnea and gasping (9, 19, 39). Such oscillations, characterized by power spectral analyses, are considered signatures of the brain stem mechanisms underlying respiratory rhythm generation (3, 4, 6, 7, 19–21, 39).

During eupnea in vivo, the peak frequency in the power spectra of inspiratory neural activity falls to lower frequencies with reductions in temperature of the preparation (9, 19–21). Although such peak frequency in the power spectra occurs at significantly higher frequencies in gasping, the temperature dependence has not been evaluated. Moreover, whether such high-frequency oscillations in inspiratory neural activities can be recorded in situ has not been established.

In the present studies, we hypothesized that different peak frequencies in the power spectra of activity of the phrenic nerve will be evident during eupnea and gasping in the perfused, in situ preparation. Moreover, we hypothesize that these peak frequencies will be altered by a change in the temperature of the preparation. Results provide further support for the concept that the perfused juvenile rat preparation exhibits distinctly different patterns of ventilatory activity that are comparable to eupnea and gasping in vivo.

**METHODS**

**Preparation.** Fifty-three perfused preparations of the juvenile rat were used. Procedures were performed in accordance with the guidelines established by the National Institutes of Health. The preparation was identical to that described previously (32–35). Under halothane anesthesia, the portion of the body caudal to the diaphragm was removed. Halothane anesthesia was discontinued, and the preparation was immersed in ice-cold mock cerebrospinal fluid and decerebrated at a precocilical level. The descending aorta was cannulated, and perfusion was commenced. The composition of the perfusate in distilled water was as follows (in mM): 1.25 MgSO₄, 1.25 KH₂PO₄, 5.0 KCl, 25 NaHCO₃, 125 NaCl, 2.5 CaCl₂, 10 dextrose, and 0.1785 Ficoll 70.

Control conditions were established with the perfusate equilibrated with 95% O₂-5% CO₂ at 27, 31, and 34°C. The number of observations under control conditions (i.e., in eupnea) at these various temperatures is given in Table 1. This number of observations includes four preparations that were examined at 31 and 27°C. In each of these preparations, recordings were initially made at the higher temperature. All other preparations were evaluated at only one temperature.

Table 1. Number of observations in eupnea and/or gasping at various temperatures

<table>
<thead>
<tr>
<th></th>
<th>28°C</th>
<th>31°C</th>
<th>34°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eupnea</td>
<td>11</td>
<td>34</td>
<td>11</td>
</tr>
<tr>
<td>Gasping</td>
<td>10</td>
<td>27</td>
<td>9</td>
</tr>
<tr>
<td>Both</td>
<td>9</td>
<td>27</td>
<td>7</td>
</tr>
</tbody>
</table>

The temperature of the perfusate was measured at the point at which it entered the cannula in the aorta. For this measurement, a thermistor probe was placed in one arm of a “Y” tube, with the tip of the probe in contact with the perfusate. Temperature was also measured by another thermistor “needle” probe inserted into the ventricle. The temperatures in the cannula and in the ventricle were the same. The temperature of the perfusate was regulated by a servo-controlled heat exchanger.

Efferent activity of the phrenic nerve was recorded with a suction electrode. In 10 preparations, activity of both phrenic nerves was recorded. In each of the 53 preparations, phrenic activity was amplified and filtered in two different manners simultaneously. To characterize the ventilatory cycle, activity was filtered at 0.6–6.0 Hz and integrated (50-ms time constant). For power spectral analysis, activity was amplified and filtered at 1–500 Hz. In some studies, this activity was further processed by an adaptive filter (HumBug, Quest Scientific). Data were digitized at 1 kHz and stored on disk. The filtering for power spectral analysis is identical to that of previous studies and is necessary to avoid aliasing (39). The filtering used to characterize the ventilatory cycle was selected to reproduce conditions in previous studies (28–36).

**Experimental protocol.** After perfusion was established, the preparation was allowed to equilibrate for ~30–60 min. Activity was then recorded in eupnea, with the perfusate equilibrated with 95% O₂-5% CO₂. Gassing was elicited by a perfusate that was equilibrated with a hypoxic-hypercapnic mixture (8.0–9.5% O₂-7.5–9.0% CO₂). Within ~1 min, the incrementing pattern of eupnea was replaced by the decrementing pattern of gasping. After a minimum of five gasps were recorded, the perfusate was returned to that equilibrated with the hyperoxic mixture. In hyperoxia, the eupneic pattern was gradually reestablished. After ~10 min, the preparation was again exposed to hypoxic hypercapnia and gasping was recorded. Three to five of these alterations from eupnea to gasping were produced in each preparation. Hence, 15–25 gasps were recorded from any given preparation and used for analyses.

The number of preparations that were examined in gasping at the various temperatures is given in Table 1. Table 1 also shows the number of preparations in which eupnea and gasping were recorded at the same temperature.

**Analyses of data.** Integrated phrenic activity was analyzed as to the duration of the burst (neural inspiratory, Tᵢ), period between bursts (Tₑ), peak integrated height, and rate of rise. As in previous studies (32–35), the time to reach peak integrated height, divided by the duration of neural inspiration, was taken as an index of the rate of rise.

Data for gasping were chosen after the “decrementing pattern” was clearly established (see Fig. 2). By definition, such a decrementing pattern is consonant with a greater rate of rise of phrenic activity than during eupnea. Indeed, a primary characteristic of gasping is that peak phrenic activity is achieved in the first half of the phrenic bursts, whereas the peak of the augmenting eupneic burst is achieved in the last half of neural inspiration (32–35).
More than 50 eupneic ventilatory cycles and 15–25 gasping ventilatory cycles were used for analysis of characteristics of integrated phrenic activity and analysis of power spectra. In each experiment, there were multiple repetitive cycles of hyperoxia (eupnea) and hypoxia (gasing). The ventilatory cycles that were used for spectral analyses were chosen throughout each experiment and spanned multiple periods of hyperoxia and hypoxia. The individual power spectra from each type of ventilatory pattern (i.e., eupnea vs. gasping) did not differ systematically over the course of each experiment.

Power spectra were computed using a fast Fourier transform, as described previously (39). As noted above, phrenic activity was filtered at 1–500 Hz and digitized at 1 kHz to avoid aliasing. We analyzed 256 ms of data commencing at the start of the phrenic burst in eupnea or gasping. Choosing data from the start of the phrenic burst, rather than from the entire burst, was necessary to obtain consistent spectra among preparations. This choice was based on two criteria: 1) fast Fourier transforms can only be performed on segments of data that are powers of 2 (3, 39), and 2) in some preparations, including the decerebrate rat, the amplitude at the peak frequency and/or the peak frequency falls late in the eupneic phrenic burst (3, 5, 15). In a subset of trial data, we found a fall in peak frequency during eupnea, comparing the initial and final portions of the phrenic burst (Fig. 1). Hence, we consistently analyzed the first 256 ms of Ti, inasmuch as these include most of the phrenic burst in gasping and a portion of the phrenic burst in eupnea at which peak frequency in the power spectra is relatively constant.

Data were taken from multiple cycles and were averaged to establish the peak frequency in the power spectra in eupnea and gasping. As a control for possible contamination by electrical interference, power spectra were computed for data recorded during the first 256 ms of neural expiration, after the termination of the phrenic burst. The power spectra of individual respiratory cycles were averaged and smoothed with a five-point moving average. Such averaging is similar to that performed in many previous studies (3, 20, 21, 39) and was necessary to diminish the variability in individual ventilatory cycles and obtain an overall index of the power spectra in eupnea or gasping. The peak frequency between 30 and 180 Hz was defined from this averaged power spectrum in each preparation. A numerical value for this peak frequency was provided by the program used for computation of the power spectra (DATAPAC, Run Technologies).

For those 10 preparations in which activities of both phrenic nerves were recorded, cross-spectral density and coherence between these activities were computed. Cross spectra were obtained from the fast Fourier transforms of each neural activity. We calculated the average coherence at the peak frequency in the power spectra of each phrenic nerve. Coherence has values between 0.0 and 1.0, representing no coherence and complete coherence, respectively.

**Statistical evaluations.** We compared the average peak frequency in the power spectra of eupnea and gasping at three temperatures using a two-way analysis of variance. The pattern of ventilatory activity (i.e., eupnea or gasping) was a repeated within-subjects factor. The temperature at which each preparation was studied was a between-subjects factor. Linear regression was used to characterize the relation between the peak frequency in the power spectrum and the temperature of the preparation during eupnea and gasping using the GLM procedure in SYSTAT (SPSS Science, Chicago, IL). A similar linear regression analysis was used for defining characteristics of integrated phrenic activity in eupnea and gasping. Values are means ± SE, *P < 0.05* was considered significant.

To determine statistical significance for coherence spectra, the 95% confidence intervals were calculated. When the 95% confidence intervals did not include zero, the coherence was considered statistically significant (*P < 0.05*), indicating that the two phrenic signals were not related by chance.

**RESULTS**

**Patterns of phrenic activity in eupnea and gasping.** With the perfusate equilibrated with 95% O2-5% CO2, a eupneic pattern of phrenic activity was recorded. This pattern was characterized by a sudden onset of discharge and then a ramplike rise to reach a peak integrated level close to the end of the burst (Fig. 2). This pattern was similar at the three temperatures examined. For all preparations, these temperatures averaged 27.6 ± 0.15, 30.6 ± 0.08, and 33.6 ± 0.17°C.

On switching to the perfusate equilibrated with a hypoxic-hypercapnic mixture, the amplitude of integrated phrenic activity initially rose and then ceased. Activity then returned, but with a gasping pattern. In gasping, the peak of integrated phrenic activity is achieved soon after the onset of discharge; activity then typically decrements throughout the rest of neural inspiration (Fig. 2, Table 2). This gasping pattern was similar at the three temperatures.

Variables of eupnea and gasping at the three temperatures were similar to those described in detail previously (24) (Table 2). For eupnea and gasping, regression analysis indicated that Ti and Te fell significantly and frequency rose significantly as the temperature increased. Although Ti was less in gasping than during eupnea, the patterns of influence of temperature on Ti, Te, and frequency were similar in eupnea and gasping (there was no interaction between temperature and the pattern of breathing). Rates of rise of
phrenic activity in eupnea and gasping were not altered with the change in temperature.

At all temperatures, the duration of the phrenic burst in gasping was significantly less than during eupnea, whereas the period between bursts and the frequency were not significantly different (Table 2). The peak integrated height of the gasp and the rate of rise of activity were significantly greater than those of the eupneic burst at all three temperatures ($P < 0.002$).

**Coherence between high-frequency oscillations in phrenic activities.** Figure 3 illustrates the power spectra that were computed from activities of both phrenic nerves during eupnea. All 10 preparations in which phrenic activities were recorded simultaneously were maintained at 31°C. Also shown in Fig. 3 are power spectra that were computed for the first 256 ms of neural expiration. This computation provides an estimate of any contribution of nonspecific electronic noise to the power spectra that were computed during the period of neuronal activity. Results of Fig. 3 were typical for most recordings, in that the peak in the power spectra during inspiratory neural activity was many-fold higher than activity during neural expiration. Such a comparison between power spectra during the period of neural activity and inactivity was routinely performed if peaks were in the range of 60 Hz or some multiple thereof. Data were rejected if similar peaks were found during neural inspiration and expiration and if the spectral power during expiration was more than half of that during inspiration. For recordings of activities of two phrenic nerves, such problems in one or both recordings caused a rejection of data from 1 of 10 preparations in eupnea and 3 of 10 preparations in gasping. A similar problem of nonspecific noise caused data to be discarded from ~10% of the preparations in which activity of a single phrenic nerve was monitored (see Comparison of peaks in the power spectra of phrenic activity in eupnea and gasping).

For all nine preparations in which activities for both phrenic nerves were successfully recorded, the mean temperature of the preparations was 30.8 ± 0.2°C. Peaks in the power spectra during eupnea were similar in the two phrenic nerves, averaging 75.5 ± 6.0 and 77.0 ± 8.0 Hz, respectively. There was greater variability in gasping, with values averaging 126 ± 12 and 104 ± 16 Hz; these values were not significantly different.

As shown in Fig. 3, the activities of the two phrenic nerves were highly coherent. Coherence was assessed with each of the two phrenic activities serving as the basis for comparison. Hence, two values of coherence were obtained. In eupnea, the coherence at the peak frequency of the power spectra of each phrenic nerve averaged 0.498 ± 0.047 and 0.490 ± 0.029. For gasping, the coherence was 0.514 ± 0.046 and 0.484 ± 0.038. These values were not significantly different.

**Table 2. Variables of phrenic activity in eupnea and gasping**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Ti, s</th>
<th>Te, s</th>
<th>Frequency, l/min</th>
<th>Rate of Rise, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eupnea</td>
<td>Gasping</td>
<td>Eupnea</td>
<td>Gasping</td>
</tr>
<tr>
<td>38°C</td>
<td>0.54 ± 0.03</td>
<td>0.70 ± 0.04</td>
<td>4.97 ± 0.51</td>
<td>5.26 ± 0.8</td>
</tr>
<tr>
<td>31°C</td>
<td>0.54 ± 0.04</td>
<td>0.61 ± 0.02</td>
<td>4.84 ± 0.44</td>
<td>5.47 ± 0.76</td>
</tr>
<tr>
<td>34°C</td>
<td>0.52 ± 0.02</td>
<td>0.39 ± 0.04</td>
<td>3.84 ± 0.40</td>
<td>3.34 ± 1.7</td>
</tr>
</tbody>
</table>

Values are means ± SE. Ti, duration of phrenic burst; Te, duration between bursts; rate of rise, time to reach peak of integrated phrenic activity/Ti. Ti was significantly less in gasping than during eupnea when considered at all temperatures ($P < 0.05$). Ti and Te of eupnea and gasping fell and frequency rose significantly as temperature rose ($P < 0.05$). Rate of rise of gasping was greater than that of eupnea at all temperatures.
Fig. 3. A: power spectra of activities of 2 phrenic nerves recorded simultaneously during eupnea in a preparation maintained at 31°C. Solid lines, spectra computed for the first 256 ms of the phrenic burst; spectra represent averages of multiple ventilatory cycles. Dashed lines, spectra for the first 256 ms of phrenic activity during neural expiration. Peaks in the spectra for activities of 2 phrenic nerves were similar. Values for power, in arbitrary units, have been normalized to maxima recorded in the preparation. B: coherence between activities of the 2 phrenic nerves, with each nerve (Phr 1 and Phr 2) serving as control. Peaks in coherence at ~0.6 were statistically significant.

The coherence during eupnea was not significantly different from that in gasping.

In Fig. 3, peaks of lower frequency, termed “medium-frequency” oscillations (3, 4, 15), were also recorded. However, these medium-frequency peaks were not correlated between activities of the two phrenic nerves (Fig. 3) and were difficult to define in many recordings (Fig. 4). Hence, these medium-frequency peaks were not systematically examined in the present study.

Comparison of peaks in the power spectra of phrenic activity in eupnea and gasping. Different peaks in the power spectra of phrenic activity during eupnea and gasping were recorded at the three temperatures. Examples of average spectra at each temperature are shown in Fig. 4. In each of these three preparations, the peak frequency increased with the change from eupnea to gasping. Also the total power in the spectra at the peak frequency was higher in gasping in two preparations but was the same as that during eupnea in one preparation. These results were typical for all preparations in which total power at the peak frequency was greater in gasping than during eupnea in 70% of the preparations, the same in gasping and eupnea in 14% of the preparations, and less in gasping than during eupnea in 16% of the preparations.

The average peak frequency for all studies at each temperature is shown in Fig. 5. For the paired data of Fig. 5, the peak frequency was significantly higher in gasping than during eupnea at all temperatures (P < 0.001). Also inherent to Fig. 5 is the observation that the peak frequency for the power spectra increased in eupnea and gasping as the temperature of the preparation was elevated.

In Fig. 6, peak frequencies in the power spectra are shown for all preparations that were examined in eupnea or gasping. The unpaired data of Fig. 6 were similar to the paired data of Fig. 5 and show a progressive increase in the peaks of the power spectra as the temperature increased. In this context, four preparations were examined at two temperatures in eupnea, and, in each of these preparations, peak frequencies in the power spectra were higher at the higher temperature.

The increases in peak frequency of the power spectra with increases in temperature were highly significant for eupnea and gasping (P < 0.0007). Linear regression analyses yielded slopes of 5.07 ± 1.16 and 7.2 ± 2.10 Hz/°C for eupnea and gasping, respectively. These slopes were significantly different from zero (P < 0.001) but were not significantly different from each other.

As a final point concerning the temperature dependency of the power spectra, it is evident from Figs. 5 and 6 that peak frequencies in the power spectra for eupnea and gasping were not unique. Thus, for example, the peak frequency of gasping at 27.6°C, although higher than the peak frequency of eupnea at 27.6°C, was approximately the same as the peak frequency of eupnea at 33.6°C.
DISCUSSION

Results of the present study provide additional support to the conclusion that the in situ perfused preparation exhibits distinctly different patterns of automatic ventilatory activity that are comparable to eupnea and gasping in vivo.

Comparison of in situ and in vivo findings. High-frequency peaks in the power spectra of phrenic activities in eupnea and gasping, the temperature dependence of these peaks, and the coherence between activities of the two phrenic nerves of the decerebrate in situ preparation were very similar to comparable data obtained from decerebrate in vivo preparations. Initially, numerical data from the in situ and in vivo preparations are not identical, because adult cats, rather than rats, have typically been examined in vivo (see Refs. 5 and 9 for discussion and review). In a recent study, peak frequencies in the power spectra of phrenic activity during eupnea in adult rats were much higher than those reported previously in adult cats (15). Also, comparison of results in situ with those from decerebrate in vivo preparations is essential, inasmuch as anesthesia reduces the peak frequency, reduces the power at this peak frequency, or completely eliminates a peak frequency in the power spectra (see Refs. 5 and 9 for discussion and review).

The values of the peak frequencies in the power spectra during eupnea in situ were lower than those of adult decerebrate rats in vivo (15). Such a difference would be expected, because peak frequencies in the...

Fig. 4. Power spectra of phrenic activity recorded in 3 different preparations (27, 30, and 34°C) in eupnea and gasping. Peaks in the power spectra were higher in gasping than during eupnea at each of the 3 temperatures. Peak frequencies in the power spectra increased as the temperature was elevated in eupnea and gasping. Values for power, in arbitrary units, have been normalized to maxima recorded in the preparation. Hence, as shown for recordings at 27 and 30°C, total power during recordings in gasping was typically much in excess of that during eupnea.

Fig. 5. Peak frequencies in power spectra of activity of the phrenic nerve during eupnea and gasping. Values are means ± SE for paired observations during eupnea (open bars) and gasping (solid bars) at 27.6°C (n = 9), 30.6°C (n = 27), and 33.6°C (n = 7). Values in gasping were significantly higher than those during eupnea at all temperatures. *P < 0.001.

Fig. 6. Influence of elevations in temperature on peak frequencies in power spectra of activity of the phrenic nerve during eupnea and gasping. Values are means ± SE for observations in eupnea (open bars) at 27.6°C (n = 11), 30.6°C (n = 34), and 33.6°C (n = 11) and gasping (solid bars) at 27.6°C (n = 10), 30.6°C (n = 27), and 33.6°C (n = 9). Temperature of preparation had a significant influence on peak values during eupnea and gasping (P < 0.001). Linear regression analysis resulted in slopes for eupnea of 5.07 Hz/°C and gasping of 7.20 Hz/°C; each of these slopes was significantly different from zero (*P < 0.01), but slopes were not significantly different from each other.
power spectra have a strong dependency on temperature (9, 21). Indeed, the dependency of peak frequencies during eupnea in the present study, which averaged 5 Hz/°C, is identical to that previously reported for adult decerebrate cats (21). When values of peak frequencies at the various temperatures in situ were extrapolated to 37–39°C at which adult rats had been examined (15), identical frequencies were found for in vivo and in situ preparations. Hence, values for adult rats were 106–160 Hz (15), and extrapolated values for in situ preparations were 108–165 Hz.

As in adult decerebrate cats in vivo (19, 39), peak frequencies of the power spectra were shifted to significantly higher values after the alteration from eupnea to gasping in situ. Such a shift occurred at all temperatures examined. The magnitude of this shift was similar in situ and in vivo. Hence, in adult decerebrate cat preparations, the shift in peak frequency with the change from eupnea to gasping averaged 37–40 Hz. In the studies reported here, the magnitude of the shift varied from 21 to 43 Hz at the various temperatures, with the mean shift being 33 Hz. With the shift from eupnea to gasping, the total power at the peak frequency also increased in most, but not all, preparations. Such an increase in total power may imply a greater synchronization of motoneuronal activities at a given peak frequency in the power spectra may be a variant or kernel of eupnea in vivo (1, 12, 17).

In gasping, the temperature dependency of peak frequencies of the power spectra of the in situ preparation was the same as that during eupnea. This finding was somewhat surprising, inasmuch as we previously reported that the frequency of phrenic bursts during eupnea and gasping in vivo and in situ had different sensitivities to alterations in temperature (28). Hence, the frequency of eupnea was greater than that of gasping at >35°C, whereas the frequency of eupnea and gasping was the same at lower temperatures. Because, as shown in Table 2, the frequency of phrenic bursts per minute was the same in eupnea and gasping at 33.6°C; 35°C may represent a critical breakpoint for this temperature dependency. Higher temperatures were not attempted, because gasping of in situ preparations cannot be sustained at such temperatures, and the peak height of gasps falls after several cycles (see Fig. 6 and discussion in Ref. 28).

As for decerebrate preparations in vivo (3, 4, 15), significant coherence was found between high-frequency peaks in the activities of the two phrenic nerves. Such significant coherence was the same for evaluations in eupnea and gasping. Significant coherence between activities of the two phrenic nerves was expected on the basis of the finding that medullary premotor neurons have axons that are distributed bilaterally to the phrenic motoneuron pool (16, 38). Similar coherence values in eupnea and gasping are compatible with the concept that brain stem mechanisms responsible for the genesis of both patterns of automatic ventilatory activity impinge on the same medullary premotor neurons. A single premotor pool for eupnea and gasping is inherent to the “switching concept” for ventilatory neurogenesis (22, 23, 35). This switching concept holds that the discharge pattern of brain stem respiratory neurons in eupnea is defined by the pontomedullary neuronal circuit that generates the eupneic rhythm. In gasping, activities of the same brain stem respiratory neurons are altered, inasmuch as a medullary pacemaker system generates the gasp.

Comparison of in situ and neonatal in vivo and in vitro findings. An en bloc in vitro brain stem-spinal cord preparation of the neonatal rat has been used by a number of laboratories to examine neurophysiological mechanisms of respiratory rhythm generation (1, 2, 17). However, the relation between rhythmic activities in this preparation and automatic patterns of ventilatory activity in vivo has been controversial (1, 8, 17, 30). We have long maintained that results from this in vitro preparation are applicable to the neurogenesis of gasping, but not to eupnea in vivo (30). This conclusion is based on the similarity of in vitro discharges and the mechanisms underlying their neurogenesis to the neurogenesis of gasping in vivo (30–35). However, other investigators maintain that in vitro rhythms represent a variant or kernel of eupnea in vivo (1, 12, 17).

Power spectral analysis of discharges of in vitro preparations has been used to attempt to clarify whether these discharges are typical of eupnea or gasping. However, as shown here, the marked dependency on temperature of peaks in the power spectra of phrenic activity renders it impossible to use power spectra alone to categorize a respiratory pattern. Thus a given peak frequency in the power spectra may be characteristic of eupnea at one temperature and gasping at a lower temperature.

Peaks in the power spectra of en bloc in vitro neonatal rat preparations are 20–40 Hz (2, 9, 26). Because significant coherence between discharges of multiple nerves was found, these peaks have been considered comparable to “high-frequency” oscillations of in vivo preparations.

Because en bloc in vitro preparations are examined at 27°C, the possibility was raised that the lower value of the peaks in the power spectra than those at normothermia during eupnea in vivo reflected the hypothermia (9). However, as shown here, peaks during eupnea and gasping of in situ preparations, which were also evaluated at 27°C, are >20 Hz higher than those found for in vitro preparations.

In addition to hypothermia, developmental changes have also been invoked to explain the low frequencies for peaks in the power spectra of in vitro preparations (2, 9, 10, 11, 26). However, evaluations of neonatal preparations in vivo have been limited, and variable results have been obtained in different species. In a single study using “neonatal” rats, no high-frequency peaks in power spectra were found, but only medium-frequency peaks, with no correlation between the neural respiratory activities of different nerves in a single preparation (11). Thus the possibility was raised that these medium-frequency peaks, even though they were without correlation, were comparable to peaks having low frequency that were recorded from in vitro preparations (1, 26). However, pentobarbital-anesthetized
neonatal rats were used in this in vivo study. Such anesthesia is well recognized to reduce or eliminate high-frequency oscillations in adult animals in vivo (4–6, 9, 19–21). Moreover, some of the neonatal rats were of the same age (36 days) as some of the “juvenile” rats, having high-frequency oscillations in neural activities, which are reported here.

Results with other neonatal species do not provide additional insights into the interpretation of results from the in vitro neonatal rat preparations. Hence, in cats, power spectra of the newborn are dominated by medium-frequency peaks soon after birth, and high-frequency peaks become dominant later in development (24). Yet, in piglets, high- and medium-frequency frequency peaks become dominant later in development (25). For the brain stem respiratory control system, high-frequency oscillations of the in situ preparation exhibits patterns of automatic ventilatory activity that are comparable to eupnea and gasping in vivo (22, 23, 26). Such an identity would require that, in contrast to adults, neither anesthesia nor temperature of the preparation alters peaks in the power spectra of neonatal preparations.

Functional significance of high-frequency oscillations. For the brain stem respiratory control system, these high-frequency oscillations have long been considered “signatures” of the three patterns of automatic ventilatory activity: eupnea, apneusis, and gasping (3–6, 9, 21–23, 39). However, it has also been recognized that a multitude of factors, including temperature, chemoreceptor activation, mechanoreceptor activation, and anesthesia, can markedly alter these high-frequency oscillations. Perhaps, most dramatically, these oscillations in the power spectra of phrenic activity can be totally eliminated with little or no change in the pattern of ventilatory activity (see discussion in Ref. 7). Thus these oscillations are not critical for the genesis of ventilatory activity, and their functional role remains speculative, although perhaps it involves a synchronization of motoneuronal activities (2, 9).

When present, however, these high-frequency oscillations appear to provide an additional index of the pattern of ventilatory activity under examination. Hence, on the basis of previous results using the in situ preparation, we concluded that the alteration in the pattern of phrenic activity from incrementing to decrementing in hypoxia or ischemia demonstrated that this preparation could exhibit patterns of ventilatory activity comparable to eupnea and gasping in vivo (22, 23, 28, 32–35). This conclusion is strengthened by the present findings that the change in phrenic pattern from incrementing to decrementing in situ is also accompanied by a shift in the peak frequency of high-frequency oscillations in the spectra of the phrenic nerve. Again, such a shift is identical to that observed with the alteration from eupnea to gasping in vivo.

Also identical to in vivo findings is the temperature dependency of the peak frequency during eupnea in the high-frequency oscillations of the in situ preparation. We also found the same temperature dependency in gasping. These findings further support the conclusion that the in situ preparation exhibits patterns of automatic ventilatory activity that are comparable to eupnea and gasping in vivo.

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DISCLOSURES
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