Power spectral analysis of respiratory responses to pharyngeal stimulation in cats: comparisons with eupnoea and gasping

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1. Based on similarities between properties of gasping and the aspiration reflex, we hypothesized that this reflex activates the central pattern generator for gasping. To evaluate this hypothesis, we have analysed high-frequency oscillations in phrenic and hypoglossal neural activities. These oscillations, analysed by power and coherence spectra, are considered as signatures of the central pattern generators for automatic ventilatory activity.

2. In decerebrate, vagotomized, paralysed and ventilated cats, the aspiration reflex was elicited in eupnoea and gasping by mechanical stimulation of the pharynx and electrical stimulation of the glossopharyngeal nerve.

3. Compared with eupnoeic values, the peaks in the power spectra occurred at higher frequencies in spontaneous gasping. Peaks in the coherence spectra showed identical changes.

4. Power and coherence spectra of inspiratory neural activities during the aspiration reflex differed markedly from those of eupnoea, but were similar to those in gasping.

5. We conclude that mechanical stimulation of the pharynx or electrical stimulation of the glossopharyngeal nerve activates a reflex by which the central pattern generator for eupnoea is depressed, and that for gasping is activated. Our results also support the concept that separate brainstem mechanisms generate ventilatory activity in eupnoea and gasping.

As characterized by Lumsden in this Journal in 1923, the automatic ventilatory patterns of eupnoea, apneusis and gasping can be generated by brainstem mechanisms inherent to the pons and medulla. The entire pons and medulla appear to be necessary for eupnoeic ventilatory activity since, following ablation of the rostral pontile pneumotaxic centre, apneusis is obtained. This apneusis is replaced by gasping following a complete isolation of medulla from pons. In addition to physical ablations, the ventilatory pattern is sequentially altered from eupnoea to apneusis and then gasping upon exposure to extreme hypoxia (Lumsden, 1923, 1924; St John, 1990).

There is evidence that multiple potential sites for ventilatory neurogenesis exist within the pons and medulla. Thus, following midsagittal sections of the brainstem, cranial and spinal nerves on each side acquire different respiratory rhythms (Gromysz & Karczewski, 1981; St John, 1983). Moreover, the respiratory-modulated activities of pontile and medullary motoneurons, which are linked in eupnoea, become independent after separation of pons from medulla (St John & Bledsoe, 1985; Huang & St John, 1988). Finally, activity of neurons within a region of the lateral tegmental field of the medulla is critical for the neurogenesis of gasping, yet appears to play no role in eupnoea (St John, Bledsoe & Sokol, 1984; St John, Bledsoe & Tenney, 1985). Since ablation of these neurons eliminates gasping but does not alter the eupnoeic rhythm, it appears that different patterns of automatic ventilatory activity may be generated at different sites and/or by different mechanisms within the brainstem. This possibility is also supported by findings concerning high-frequency oscillations in neural activities in eupnoea, apneusis and gasping.

By definition, respiratory-modulated neural activities are characterized by cyclical variations in magnitude in phase with the respiratory cycle. For nerves having discharges during the inspiratory phase, high-frequency oscillatory waves of activity have also been observed (e.g. Cohen, 1973; Richardson & Mitchell, 1982; Bruce, 1986, 1988).

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While the neuronal source is undefined, these high-frequency oscillations are considered to be a signature of the basic mechanisms underlying the phasic inspiratory activity. Another term for such basic neuronal mechanisms which generate and shape the inspiratory discharge is central pattern generator.

The concept that high-frequency oscillations are a signature of central pattern generators is of considerable interest, since the peak frequencies of these oscillations differ greatly in eupnoea, apneusis and gasping (Richardson & Mitchell, 1982; Richardson, 1986). Thus, in eupnoea, peak frequencies range from 70 to 90 Hz. With a change to apneusis, frequencies decline. In contrast, during gasping, much higher frequencies than those of eupnoea are recorded. These different peaks have been taken to imply different central pattern generators. Different pattern generators for eupnoea and gasping are consistent with the observation, noted above, that medullary mechanisms which are critical for the neurogenesis of gasping, play no role in the neurogenesis of eupnoea.

In a recent report in this Journal, we have presented evidence that the medullary mechanism for gasping may be released by the 'aspiration reflex' in eupnoea (Fung, St John & Tomori, 1994). Specifically, mechanical stimulation of the pharynx causes cessation of the eupnoeic rhythm and elicitation of a series of gasps. The characteristics of these gasps are the same as those appearing spontaneously during anoxia. Moreover, following ablation of neurons in the lateral tegmental field of the medulla, phrenic activity of eupnoea is unaltered by pharyngeal stimulation and gasps cannot be induced by anoxia. Hence the aspiration reflex from pharyngeal stimulation may activate the central pattern generator for gasping.

If both the aspiration reflex and gasp share the same central pattern generator, it would be hypothesized that the high-frequency oscillations in neural signals should be the same during both. We have evaluated this hypothesis using power spectral analyses. The concept that pharyngeal stimulation releases the central pattern generator for gasping is supported. Results also support the conclusion that mechanisms responsible for the neurogenesis of gasping differ from those for eupnoea.

METHODS

General experimental preparation

Twenty adult cats of either sex were used. The surgical preparation has been described in detail previously (St John *et al.* 1984, 1985; Fung *et al.* 1994). Animals were initially anaesthetized with 4·0% halothane in oxygen. Following cannulation of the trachea, the halothane concentration was reduced to 2·0%. Catheters were placed in the femoral artery and femoral vein. The vagi were sectioned bilaterally at the midcervical level. The animals were mounted in a stereotaxic apparatus and the brainstem was transected at the midcollicular level. All neural tissue rostral to the transection was removed (Kirsten & St John, 1978). Halothane anaesthesia was then discontinued and the animals were placed supine.

The animals were paralysed with gallamine triethiodide (5·0 mg kg^{-1} initially and approximately 2·5 mg kg^{-1} every 30 min thereafter). Artificial ventilation with a hyperoxic gas mixture was delivered. End-tidal fractional concentrations of CO_2 and O_2 were continuously monitored and the animals were maintained in normocapnic hyperoxia. Normocapnia was considered as an end-tidal fractional concentration of CO_2 of approximately 0·05. Rectal temperature was maintained at 37–39 °C. Arterial blood pressure was a minimum of 80 mmHg and intravenous infusions of a metaraminol–dextran solution were delivered, if required.

C_5 or C_6 rootlets of the phrenic nerve were exposed and sectioned in all animals. The hypoglossal nerve was also sectioned in eight cats. Also, by a ventral approach, the glossopharyngeal nerve was identified close to its exit from the skull and traced laterally. Distal to the carotid sinus nerve, the glossopharyngeal nerve was freed from surrounding tissue for approximately 1 cm; the nerve was not sectioned.

Elicitation of the aspiration reflex

As described previously (Tomori, 1979), a ventrolateral pharyngostomy was performed to allow visualization of the pharynx. This region was mechanically stimulated by touching the mucosa with an elastic nylon fibre.

In addition to this mechanical stimulation, we also attempted to elicit the aspiration reflex by electrical stimulation of the glossopharyngeal nerve, as described by Nail, Sterling & Widdicombe (1972). Hence the glossopharyngeal nerve was placed upon a bipolar electrode. Trains of stimuli, of a minimum duration of 400 ms, were delivered. The duration of individual pulses was 0·1 ms and these were delivered at 20–50 Hz. The stimulation current was 150 mA.

Recordings of neural activities

Monophasic recordings of activities of both the phrenic and hypoglossal nerves were obtained. For detection of high-frequency oscillations, such monophasic recordings are required (Cohen, 1973; Richardson, 1986). The nerves were placed upon a bipolar electrode and crushed between the poles. Activities were recorded in two manners. For power spectral analysis, activities were amplified, filtered from 0·1 Hz to 20 kHz and recorded on magnetic tape (DC 1250 Hz). For determination of durations and rates of rise, activities were amplified, filtered at 0·6–6·0 kHz, and recorded on tape. These activities were also integrated by R–C circuits (i.e. 'leaky integrator'; time constants: 0·02 s 'on' and 0·04 s 'off'). These two time constants were used so that rapid rises of inspiratory activity could be accurately reproduced and yet have some smoothing of the signal (St John & Knuth, 1981).

Alterations of the pattern of neural respiration

The pattern of activity of the phrenic nerve can be reversibly altered from eupnoea to apneusis and then gasping by ventilating the experimental animal with a gas mixture containing 1% carbon monoxide (CO) in air or 100% nitrogen (Zhou, Wasicko, Hu & St John, 1991; Fung *et al.* 1994). Approximately 10–15 min are required for gasping to be produced with CO; less than 5 min are required for N_2. Replacement of the CO mixture or N_2 by oxygen results in the reverse pattern of changes with gasping being replaced by apneusis and then eupnoea. This sequence can be repeated several times. Arterial pressure was allowed to decline to hypotensive levels during the exposure to CO or N_2.

Experimental protocol

Recordings were obtained at normocapnia during eupnoea. The 'aspiration reflex' was elicited numerous times during these control recordings by mechanical stimulation of the pharynx and by electrical stimulations of the glossopharyngeal nerve.

Ventilation with carbon monoxide or nitrogen was then begun. Mechanical stimulations of the pharynx and electrical stimulation of the glossopharyngeal nerve were repeated periodically. These stimulations were also performed during apneusis and gasping and after ventilation with oxygen had recommenced.

Measurement of variables

Timing and rates of rise. For integrated activity of the phrenic nerve, the following were determined: duration of the burst from onset to rapid decline (neural inspiration, t_I), period to the start of the next burst (neural expiration, t_E), peak height and mean rate of rise of activity. The rate of rise was determined over the linear phase of activity, i.e. from time of onset to a level approximating 90% of the peak value.

In eupnoea, gasping and during the aspiration reflex, the above variables were defined for a minimum of six respiratory cycles and the average obtained. Statistical evaluations of data were by analysis of variance. Probabilities less than 0·05 were considered statistically significant.

Power spectra. In order to avoid problems with aliasing (e.g. Oppenheim & Schafer, 1975), recordings of phrenic and hypoglossal activities were filtered again, from 1 to 500 Hz. The resulting signals were digitized at 1 kHz. The power spectra analysis, using a Fast Fourier Transform, was in either the Data-Pac II (RUN Technologies, Laguna Niguel, CA, USA) or the Matlab systems (Mathworks, Inc., South Natick, MA, USA). Briefly, synchronized with the start of the phrenic burst, windows of 256 ms of data were taken from a minimum of five respiratory cycles. Prior to the Fast Fourier Transform, data were de-meaned. Thus the mean value of voltage in each data window was determined and subtracted from the voltage of each datum point. The result is a new mean value of 0 V. Also, a Hanning window cosine tapering function was used. This function, which is applied to the entire data window, tapers off the voltage values of data points at the beginning and end of the window. Thus the amplitude of values at the end-points of the data window are forced into equality.

The power spectra of windows from individual respiratory cycles were averaged and the result smoothed by a five-point moving average. The peak frequency was defined from this averaged power spectrum. These peak frequencies were averaged for all experimental animals.

For those eight experiments in which activity of the hypoglossal nerve was recorded, coherence spectra between its activity and that of the phrenic nerve were computed. Thus cross-spectra were obtained from the Fast Fourier Transforms of each neural activity. As for the power spectra noted above, these cross-spectra were generated for 256 ms of data and represented a frequency range of 30–190 Hz. Frequencies below and above this range were not considered since peak frequencies for eupnoea, apneusis and gasping lay within this range (Cohen, 1973; Richardson & Mitchell, 1982; Richardson, 1986). Data for individual respiratory cycles were averaged. The maximum correlation of frequency components of phrenic and hypoglossal signals was represented by the peak in the coherence spectra. Peaks were determined by the 95% confidence interval for a null hypothesis of zero coherence.

RESULTS

Elicitation of the aspiration reflex in eupnoea, apneusis and gasping

As illustrated in Fig. 1, mechanical stimulation of the pharynx during eupnoea caused a marked change in the pattern of phrenic and hypoglossal activities. Thus the

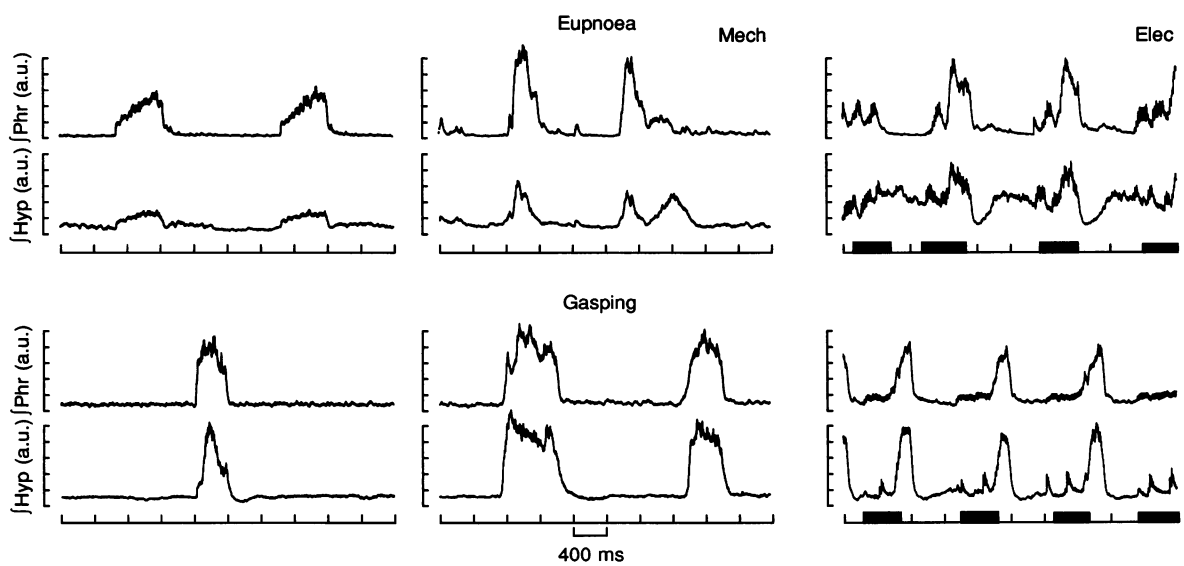

Figure 1. Alterations of inspiratory neural activities during mechanical stimulation of the pharynx and electrical stimulation of the glossopharyngeal nerve

The upper and lower panels show integrated phrenic and hypoglossal activities in eupnoea and gasping. Mech, mechanical stimulation; Elec, electrical stimulation; Phr, phrenic; Hyp, hypoglossal; a.u., arbitrary units. Bars below right-hand panels designate periods of stimulation.

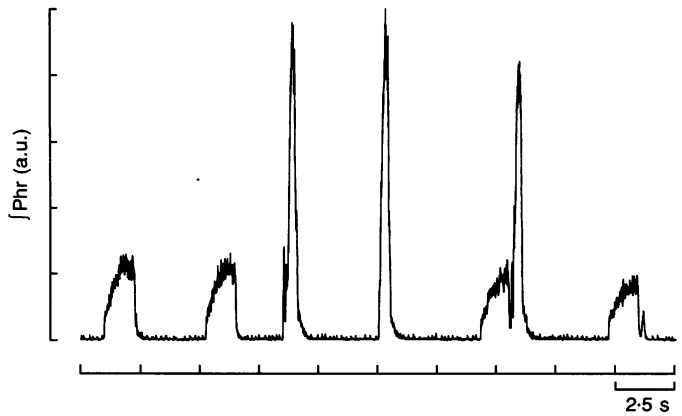

Figure 2. Elicitation of the aspiration reflex throughout the respiratory cycle
Records of integrated phrenic activity showing that mechanical stimulation of the pharynx induced gasps, even after a eupnoeic inspiration had begun.

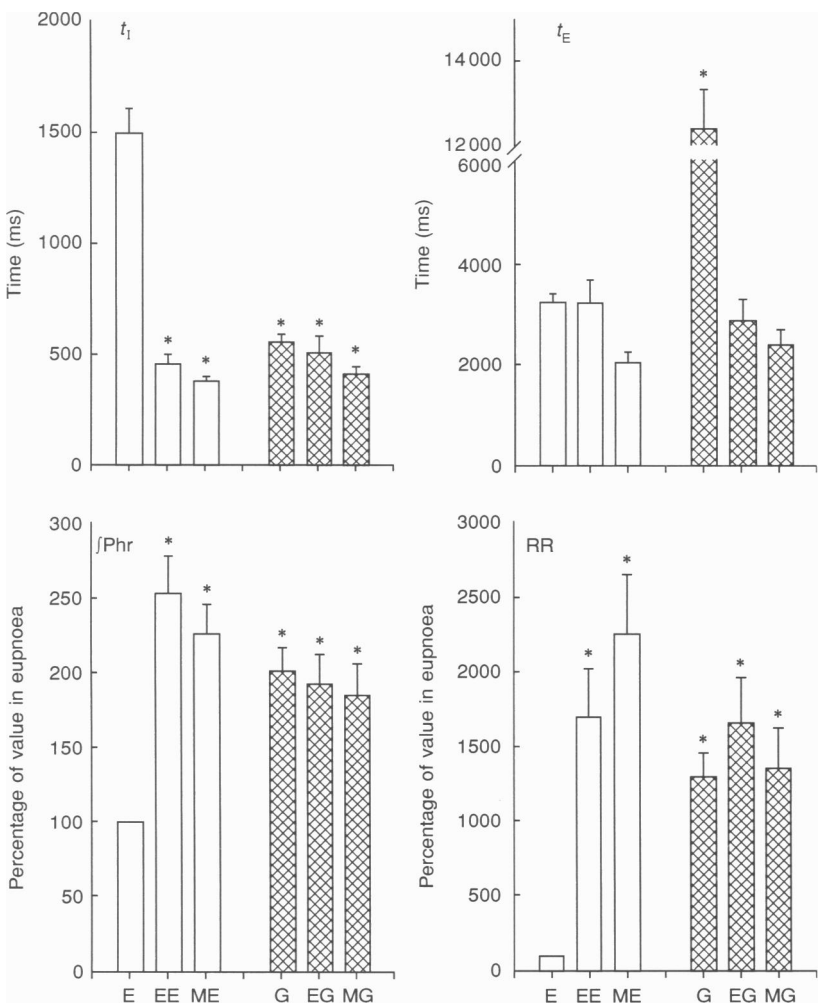

Figure 3. Variables of phrenic activity during eupnoea, gasping and the aspiration reflex
The histograms show mean values (+ S.E.M.) of the following: duration of the burst (neural inspiration, t_I), the period between bursts (neural expiration, t_E), peak integrated activity (∫Phr) and rate of rise (RR). The last two variables are expressed as percentages of values in eupnoea. E, eupnoea; EE, aspiration reflex elicited by electrical stimulation in eupnoea; ME, aspiration reflex elicited by mechanical stimulation in eupnoea; G, gasping; EG, aspiration reflex elicited by electrical stimulation in gasping; MG, aspiration reflex elicited by mechanical stimulation in gasping. * $P < 0{\cdot}05$ compared with the value in eupnoea.

'aspiration reflex' was elicited, with the ramp-like rise of phrenic activity being replaced by a rapid rise to a level close to the peak value. The latter pattern is characteristic of gasping. A similar rapid rise was also elicited for the hypoglossal activity.

It is important to note that the aspiration reflex could be elicited throughout neural inspiration and expiration. Hence pharyngeal stimulation in expiration resulted in premature bursts of phrenic and hypoglossal activities. If delivered after phrenic activity had begun, the stimulation resulted in the superimposition of the gasp upon the eupnoeic burst (Figs 1 and 2). We have not included these fused or mixed eupnoeic and gasping inspiratory discharges in the analyses reported here.

Also shown in Fig. 1 are responses to electrical stimulation of the glossopharyngeal nerve. These stimulations caused changes similar to those of the mechanical stimulation. However, as is also evident from this figure, electrical artifacts from stimulation were considerable in some recordings of hypoglossal activities. We have taken the start of the aspiration reflex as the concomitant rapid rises of phrenic and hypoglossal activities.

The consistency with which the respiratory pattern was altered by electrical stimulation was less than that by mechanical stimulation. A gasp-like burst typically followed each mechanical distortion of the pharynx. For electrical stimulation, the gasps resulted only during a limited number of stimulus trains (Fig. 1). Moreover, the current required to alter the respiratory pattern was variable between animals. Even in the same animal, augmentations in the current were sometimes required to elicit the aspiration reflex in repeated trials.

Exposure to carbon monoxide or nitrogen resulted in a change in ventilatory pattern to apneusis and, then, gasping. Arterial blood pressure declined during these exposures. Concerning apneusis, this pattern changed progressively with the durations of neural inspiration and expiration, first increasing and then declining. These changes occurred very rapidly during exposure to nitrogen. Under all conditions, the aspiration reflex could be elicited by both mechanical stimulation of the pharynx and electrical stimulation of the glossopharyngeal nerve. However, because of the constantly changing pattern of apneusis, spectral analysis of the apneustic pattern and of the aspiration reflex elicited during apneusis did not seem reasonable. Hence no data concerning apneusis will be reported here.

When spontaneous gasping was established, the aspiration reflex more consistently occurred during stimulus trains than had occurred in eupnoea, as noted above (Fig. 1). Mechanical stimulation of the pharynx also regularly elicited the aspiration reflex in gasping.

Characterization of phrenic activity during eupnoea, gasping and the aspiration reflex

The duration of neural inspiration, peak phrenic height and the rate of rise of phrenic activity differed significantly during the aspiration reflex compared with the eupnoeic ventilatory cycle. Values of these indices did not differ for reflexes induced by mechanical stimulation of the pharynx compared with electrical stimulation of the glossopharyngeal nerve (Fig. 3).

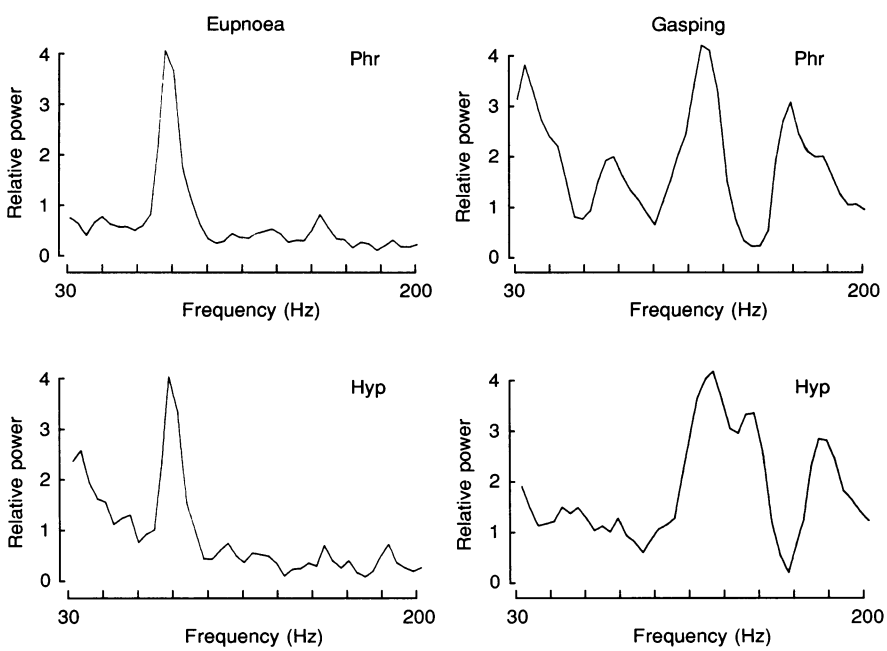

Figure 4. Examples of the power spectra of phrenic and hypoglossal activities in eupnoea and gasping

Phr, phrenic; Hyp, hypoglossal.

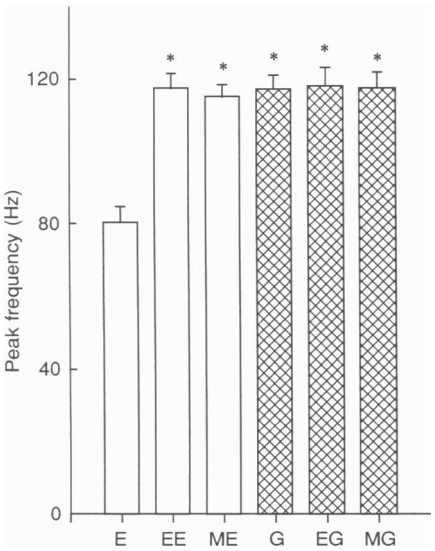

Figure 5. Peak frequency in power spectra of phrenic activity in eupnoea, gasping and during the aspiration reflex

Values presented are means (+ S.E.M.) from 20 experimental animals. E, eupnoea; EE, aspiration reflex elicited by electrical stimulation in eupnoea; ME, aspiration reflex elicited by mechanical stimulation in eupnoea; G, gasping; EG, aspiration reflex elicited by electrical stimulation in gasping; MG, aspiration reflex elicited by mechanical stimulation in gasping. * $P < 0.05$ compared with the value in eupnoea.

Compared with values during spontaneous eupnoeic ventilatory cycles, the duration of neural inspiration was shorter and expiration was longer in spontaneous gasping. Peak phrenic activity and its rate of rise were significantly greater in gasping (Fig. 3).

As opposed to the generalized differences from values during eupnoea, values during spontaneous gasping and the aspiration reflex were the same with the exception of the duration of neural expiration. By definition, this value must be shorter during the reflex since premature gasps were elicited in neural expiration (Fig. 3).

Power spectra of phrenic and hypoglossal activities in eupnoea and gasping

In Fig. 4, power spectra are shown for one animal. In eupnoea, peak values were 79 and 81 Hz for phrenic and hypoglossal activities, respectively. In gasping, peaks were found at 122 Hz for phrenic and 124 Hz for hypoglossal activity.

For all twenty animals, the peak of the power spectra of phrenic activity was significantly elevated from a mean of 80·4 Hz in eupnoea to a mean of 117·1 Hz in spontaneous gasping (Fig. 5). Very similar shifts in the peak of the power spectra with the change from eupnoea to gasping were obtained when the coherence between the power spectra of hypoglossal and phrenic activities was evaluated (Fig. 6). Hence in the eight cats in which hypoglossal activity was recorded, the maximum coherence occurred at a mean of 88·6 Hz in eupnoea and 115·0 Hz in gasping.

Power spectra during the aspiration reflex

Upon mechanical stimulation of the pharynx in eupnoea, the power spectra of phrenic and hypoglossal activities were shifted to higher frequencies. Electrical stimulation of

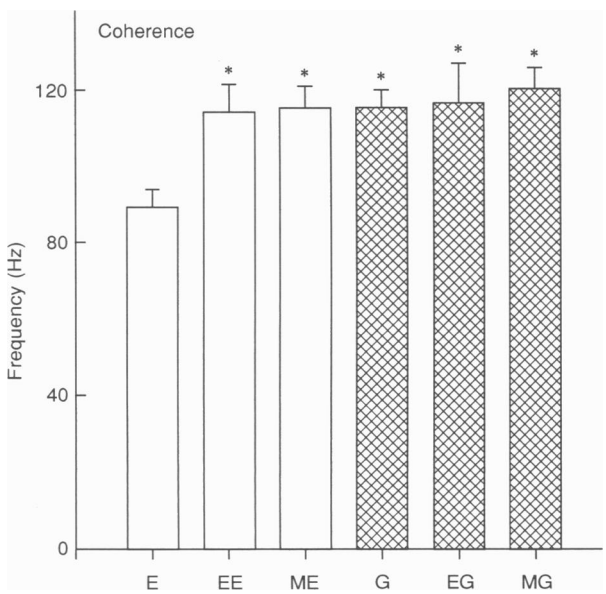

Figure 6. Peak of coherence spectra between hypoglossal and phrenic activities in eupnoea, gasping and the aspiration reflex

Values presented are means (+ S.E.M.) from 8 experimental animals. E, eupnoea; EE, aspiration reflex elicited by electrical stimulation in eupnoea; ME, aspiration reflex elicited by mechanical stimulation in eupnoea; G, gasping; EG, aspiration reflex elicited by electrical stimulation in gasping; MG, aspiration reflex elicited by mechanical stimulation in gasping. * $P < 0.05$ compared with the value in eupnoea.

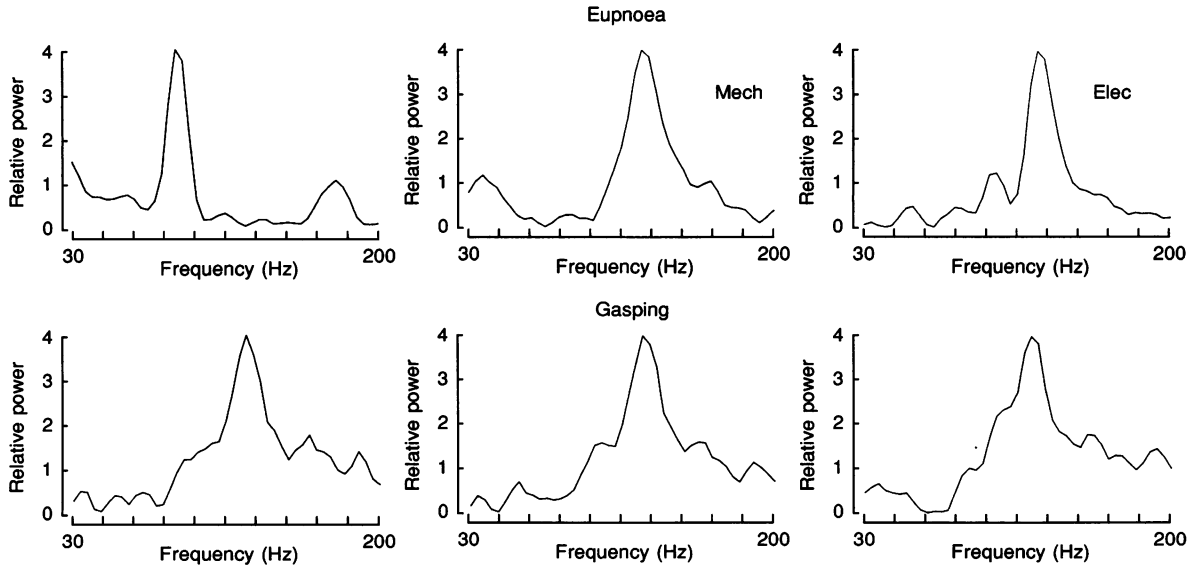

Figure 7. Examples of power spectra of phrenic activity during elicitation of the aspiration reflex in eupnoea and gasping

Mech, mechanical stimulation of pharynx; Elec, electrical stimulation of glossopharyngeal nerve.

the glossopharyngeal nerve produced similar shifts (Figs 5, 6 and 7). The mean of the peak of power spectra of phrenic activity during electrical stimulation was 117·5 Hz, and 115·0 Hz during mechanical stimulation (Fig. 5). The coherence between spectra of phrenic and hypoglossal activities yielded similar peaks, averaging 113·8 Hz for electrical stimulation and 115·3 Hz for mechanical stimulation (Fig. 6).

The similarities in shifts of the power spectra during electrical and mechanical stimulation (e.g. Fig. 7) diminishes the possibility that artifacts during the former significantly influenced the spectra. As noted above, stimulus artifacts were present to variable degrees in recordings of phrenic and hypoglossal activities.

As opposed to changes during eupnoea, elicitation of the aspiration reflex during gasping caused little change in the power spectra of either phrenic or hypoglossal activities (Figs 5, 6 and 7). Hence the mean values of peak frequencies were 117·1 Hz in gasping, 118·2 Hz during electrical stimulation and 117·4 Hz during mechanical stimulation (Fig. 5). The comparable values for the coherence of hypoglossal and phrenic activities were 115·0, 116·0 and 120·0 Hz, respectively (Fig. 6).

An obvious conclusion from the above evaluations is that power spectra of phrenic and hypoglossal activities differed greatly during eupnoea compared with the aspiration reflex, recruited either during eupnoea or gasping. On the other hand, power spectra of activities in gasping were very similar to those during the aspiration reflex, regardless of the basic ventilatory pattern during elicitation of this reflex.

DISCUSSION

The major conclusion of this study is that the central pattern generator underlying the neurogenesis of gasping is also responsible for production of the inspiratory discharges of the aspiration reflex. Furthermore, our results provide support for the concept that eupnoea and gasping are generated by different brainstem mechanisms.

As noted in the introduction, high-frequency oscillations in inspiratory neural activities are considered as signatures of the central pattern generator for rhythmic activity. We have used power spectral analysis to characterize these high-frequency oscillations and have two indices of the power spectra of inspiratory neural activities. These indices are the peaks of the spectra and the coherence between phrenic and hypoglossal activities. Both of these indices were markedly and significantly different for comparisons of eupnoeic inspiratory activities and activities of the aspiration reflex. In contrast, both were the same for spontaneous gasping and the aspiration reflex. These indices were also almost the same regardless of whether the aspiration reflex was elicited during eupnoea or gasping. Elicitation of the aspiration reflex by mechanical stimulation of the pharynx or electrical stimulation of the glossopharyngeal nerve yielded very similar power spectra.

The great similarity of power spectra resulting from electrical stimulation of the glossopharyngeal nerve and mechanical stimulation of the pharynx obviously implies that gasping is induced by both. This finding confirms the observations of Nail *et al.* (1972) that either stimulation resulted in similar alterations in phrenic and intercostal motoneuronal activities. However, mechanical and electrical

stimulations were not equally effective in inducing gasping during eupnoea.

In eupnoea, a gasp typically followed each mechanical distortion of the pharynx, but only a limited percentage of stimulus trains elicited gasps. This difference may represent the simultaneous activation of multiple cranial nerves by mechanical stimulation. In addition to the glossopharyngeal nerve, the naso- and oropharynx is innervated by the trigeminal and intermediate branch of the facial nerve (Tomori & Widdicombe, 1969; Tomori, 1979). It is well recognized that activation of these afferents, especially the former, causes significant alterations in ventilatory activity, including apnoea (e.g. Angell James & de Burgh Daly, 1972; Widdicombe, 1986).

Interestingly, as opposed to eupnoea, premature gasps were consistently recruited by electrical, as well as mechanical stimulation, once spontaneous gasping was established. Such consistency is hypothesized to result from a removal of the necessity for depression of the central pattern generator for eupnoea before activation of the medullary mechanisms for gasping (Fung *et al.* 1994).

Despite these differences in the efficiency of mechanical and electrical stimulation, it is clear that the aspiration reflex terminates on-going ventilatory activity and induces gasping. The accuracy of this conclusion depends upon the assumption that the high-frequency oscillations in neural activities during inspiration may reasonably be considered as signatures of the central pattern generator. However, these oscillations may be altered by numerous experimental perturbations and, indeed, 'are not essential for the generation of inspiratory discharge' (Cohen, 1973).

During eupnoea, the amplitude of the high-frequency peak in the power spectra of phrenic activity augments throughout the inspiratory phase. The frequency at which the peak occurs may also shift. This peak occurs at higher frequencies with a change from normocapnia to hypercapnia or normoxia to hypoxia (Cohen, 1973; Richardson & Mitchell, 1982; Bruce, 1986, 1988; Cohen, See, Christakos & Sica, 1987; Richardson, 1988). Similarly, in animals having intact vagi, this peak frequency shifts upwards during cycles in which lung inflations are delivered (Richardson & Mitchell, 1982; Richardson, 1988). Reductions in body temperature cause a reduction in the peak frequency of 5·0 Hz $°C^{-1}$ (Richardson & Mitchell, 1982).

Anaesthesia is found to have a profound influence on the high-frequency oscillations in inspiratory activity. Thus the peak in the power spectra is reduced and ultimately eliminated with augmentations in anaesthesia (Cohen, 1973). The high-frequency oscillations are also eliminated by lesions in the region of the nucleus tractus solitarii of the medulla (Richardson & Mitchell, 1982) or midsagittal medullary sections (Davies, Kirkwood, Romaniuk & Sears, 1986).

In spite of these numerous factors which may alter the high-frequency oscillations, it is improbable that an uncontrolled physiological variable was responsible for the similar shifts in the power spectra in the aspiration reflex and gasping. Hence animals were normotensive, normocapnic and hyperoxic during elicitation of the reflex in eupnoea, whereas gasping occurred under conditions of hypotension, hypoxia and, probably, tissue hypercapnia.

The peak frequencies of the high-frequency oscillations of inspiratory neural activities in eupnoea and gasping reported here overlap with comparable measurements by other investigators. In this context, we have only analysed the major peaks in the spectra; secondary peaks, which differ among the neural activities, have also been found. However, as opposed to the major peaks, these secondary peaks can be variably altered, depending upon the specific neuronal activity which is recorded (Richardson & Mitchell, 1982; Bruce, 1986, 1988; Richardson, 1986; Cohen *et al.* 1987).

In summary, the similarity of our results to those of other laboratories supports the concept that the high-frequency oscillations may serve as signatures of the central pattern generators for eupnoea and gasping. The markedly different pattern of these high-frequency oscillations is compatible with different sites and/or mechanisms for the neurogenesis of these patterns of automatic ventilatory activity. Finally, stimulation of pharyngeal afferents activates a potent reflex by which the central pattern generators for eupnoea or apneusis are suppressed, and that for gasping is activated.

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