

Response of the Canine Inspiratory Intercostal Muscles to Chest Wall Vibration

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High-frequency mechanical vibration of the rib cage reduces dyspnea, but the effect of this procedure on the respiratory muscles is largely unknown. In the present studies, we have initially assessed the electrical and mechanical response to vibration (40 Hz) of the canine parasternal and external intercostal muscles (third interspace) during hyperventilation-induced apnea. When the vibrator was applied to the segment investigated, prominent external intercostal activity was recorded in the seven animals studied, whereas low-amplitude parasternal intercostal activity was recorded in only four animals. Similarly, when the vibrator was applied to more rostral and more caudal interspaces, activity was recorded commonly from the external intercostal but only occasionally from the parasternal. The two muscles, however, showed similar changes in length. We next examined the response to vibration of the muscles in seven spontaneously breathing animals. Vibrating the rib cage during inspiration (in-phase) had no effect on parasternal intercostal inspiratory activity but induced a marked increase in neural drive to the external intercostals. For the animal group, peak external intercostal activity during the control, nonvibrated breaths averaged (mean \pm SE) $43.1 \pm 3.7\%$ of the activity recorded during the vibrated breaths ($p < 0.001$). External intercostal activity during vibration also occurred earlier at the onset of inspiration and commonly carried on after the cessation of parasternal intercostal activity. Yet tidal volume was unchanged. Vibrating the rib cage during expiration (out-of-phase) did not elicit any parasternal or external intercostal activity in six animals. These observations thus indicate that the external intercostals, with their larger spindle density, are much more sensitive to chest wall vibration than the parasternal intercostals. They also suggest that the impact of this procedure on the mechanical behavior of the respiratory system is relatively small. Leduc D, Brunko E, De Troyer A. Response of the canine inspiratory intercostal muscles to chest wall vibration.

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Although medical treatment of airflow obstruction has made significant progress, dyspnea remains a prominent symptom and a major cause of disability in many patients with chronic obstructive pulmonary disease (COPD). Studies, however, have shown that this symptom could be relieved by the application of high-frequency mechanical vibration to the parasternal region of the rib cage during inspiration (1, 2). The relief was observed not only during resting breathing (1) but also during CO₂-induced hyperpnea (2). Vibration of the parasternal region has also been shown to reduce the sense of effort in healthy subjects breathing CO₂-enriched gas mixtures or breathing against inspiratory resistive loads (3, 4). This beneficial effect has been primarily attributed to increased afferent information from the intercostal muscles (1-4), yet the actual response of the respiratory muscles to this procedure is still largely unknown.

Using concentric needle electrodes, Homma and coworkers (5) have previously reported that vibration of the parasternal region in normal subjects elicits an increase in parasternal intercostal activity. Mechanical vibration, however, when applied to the belly of a relaxed limb muscle or its tendon, is known to be a potent, relatively selective stimulus of muscle spindle primary endings (6, 7), and histological studies in cats have shown that the parasternal intercostal muscles are poorly supplied with muscle spindles (8). In contrast, the external intercostals have a high spindle content, and this difference in spindle density is a critical determinant of the response of the muscles to increased inspiratory mechanical loads. Thus, when inspiratory airflow resistance is suddenly increased in anesthetized cats (9, 10), rabbits (11), and dogs (12), or when the airway is occluded at end expiration for a single breath (13), the external intercostal muscles in the rostral interspaces exhibit a reflex increase in the rate of rise of activity; this facilitation is associated with an increase in afferent spindle activity (9) and is eliminated by section of the dorsal roots (9, 11, 13). On the other hand, increases in inspiratory airflow resistance and airway occlusion have little effect on the inspiratory activity recorded from the parasternal intercostals (12, 13). Similarly, when an external force is applied to the ribs to reduce their normal inspiratory cranial displacement, external intercostal inspiratory activity increases markedly but parasternal inter-

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costal activity remains unchanged (14). Therefore, one would expect that vibration of the rib cage would predominantly increase afferent inputs from the external intercostals, rather than the parasternal intercostals.

The present studies were designed to test this hypothesis. We thus initially set out to define the response of the relaxed inspiratory intercostal muscles to rib cage vibration in a group of anesthetized dogs. Vibration, applied during hyperventilation-induced apnea, induced only occasional, low-amplitude electrical activity in the parasternal intercostals. In contrast, the external intercostals consistently showed prominent activity, including when the vibrator was applied to distant areas of the rib cage. We therefore concluded, in agreement with the hypothesis, that the external intercostals are intrinsically more sensitive to vibration than the parasternal intercostals, and this prompted us to assess the response of the muscles to vibration in the different phases of the breathing cycle.

METHODS

The experiments were carried out on 14 adult mongrel dogs (13–25 kg) anesthetized with pentobarbital sodium (initial dose, 25 mg/kg intravenously). The animals were placed in the supine posture and intubated with a cuffed endotracheal tube, and a venous cannula was inserted in the forelimb to give maintenance doses of anesthetic. A catheter was also inserted in the femoral artery to monitor blood pressure and sample arterial blood periodically for blood gas analysis. The rib cage and intercostal muscles were then exposed on the right side of the chest from the first through the tenth rib by deflection of the skin and underlying muscle layers. Two experimental protocols were subsequently followed.

Experiment 1

The electrical and mechanical response to vibration of the relaxed parasternal and external intercostal muscles was studied in seven animals. The animals were connected to a mechanical ventilator (Harvard Apparatus, Holliston, MA), and the electromyograms and the length changes of both muscles were recorded in the third interspace. The electromyograms were obtained with pairs of silver hook electrodes spaced 3–4 mm apart, and the changes in muscle length were measured with pairs of piezoelectric crystals (2 mm diameter) implanted 6–10 mm apart in well-identified muscle bundles and connected to a sonomicrometer (Triton Technology, San Diego, CA). Detailed descriptions of this technique have appeared in previous reports (12, 15). The parasternal intercostal electrodes and crystals were inserted 10 mm apart in the portion of the muscle situated near the sternum, while the external intercostal electrodes and crystals were implanted midway between the angle of the ribs dorsally and the costochondral junctions ventrally. The two electromyographic (EMG) signals were processed with amplifiers (model 830/1; CWE, Ardmore, PA) and bandpass filtered below 100 and above 2,000 Hz.

The animals were allowed to recover for 30 min after instrumentation, after which the ventilator was set to deliver about the normal tidal volume (approximately 300 ml) at about twice the normal rate of breathing (i.e., 30 strokes/min). When the animal was disconnected from the ventilator, it was therefore apneic for 30 to 40 s. Trains of vibration of 2–3 s in duration were then applied at intervals to the parasternal intercostal muscle in the third right interspace, lateral to the site of implantation of the crystals and EMG electrodes. The vibrations were delivered by a commercially available vibrator (model V.101; LDS, Royston, UK), which was adjusted so that the amplitude of movement of its moving element and the frequency of vibration were 1.5 to 2.5 mm and 40 Hz, respectively. The vibrator was manually triggered and maintained in contact with the muscle via 30-cm-long Plexiglas tubing; this tubing, combined with the bandwidth selected for the EMG signals, essentially eliminated all vibration artifacts. The vibrator was held manually throughout, perpendicular to the muscle, so that the site and the force of application could be well controlled. The area of contact between the vibrator and the muscle was approximately 1.8 cm².

At least five trains of 40-Hz vibrations were obtained in each animal; three trials were also performed in which the frequencies of vi-

bration were set at 10 and 80 Hz. When this procedure was completed, 40-Hz vibrations were applied successively to (1) the parasternal intercostal muscle situated in each of the caudal (4 to 7) and rostral (1 and 2) interspaces, and (2) the external intercostal muscle in the third interspace. Vibrations to these muscles were also delivered during hyperventilation-induced apnea. EMG activity was constantly monitored on an oscilloscope and a loudspeaker during the experiment. Nevertheless, to make sure that the activity recorded from the external intercostal electrode was arising from the external intercostal muscle itself and not from the underlying internal intercostal (16, 17), the external intercostal nerve in the third right interspace was eventually sectioned about 2 cm ventral to the rib angle, and 40-Hz vibration of the parasternal and external intercostal muscles was repeated. Selective denervation of the parasternal intercostal in the third right interspace was also performed whenever parasternal activity was recorded during vibration (see RESULTS).

Experiment 2

The effects of vibration on the EMG activity of the parasternal and external intercostal muscles during spontaneous breathing were also studied in seven animals. The sites of electrode implantation and the procedures used to amplify and filter the EMG signals were similar to those described in Experiment 1. In two animals, however, no inspiratory activity could be recorded from the middle portion of the external intercostal muscle during resting, room air breathing. Electrode implantation in these animals was therefore made in the dorsal portion of the muscle close to the angle of the ribs, i.e., in the portion that receives the greatest inspiratory neural drive (17, 18). In addition, the two EMG signals were rectified before their passage through leaky integrators with a time constant of 0.2 s.

The animal was also allowed to recover for 30 min after instrumentation, after which it was connected to a heated Fleisch pneumotachograph and a differential pressure transducer (Validyne, Northridge, CA) for the measurement of lung volume. The animal was spontaneously breathing throughout, and every 5 to 10 breaths, 40-Hz vibrations were applied to the parasternal intercostal muscle in the third interspace. The investigator received continuous feedback of parasternal intercostal EMG activity via a loudspeaker, so that vibrations could be delivered either during inspiration (in-phase) or during expiration (out-of-phase). At least 10 breaths with in-phase vibration were obtained in each animal; vibration in these breaths was thus initiated shortly (≤ 1 s) before the onset of parasternal intercostal activity and was maintained until the onset of the expiratory pause. Ten breaths with out-of-phase vibration were also obtained, the vibration being then initiated after the onset of the expiratory pause and removed before the onset of the next parasternal inspiratory burst. Vibrations were subsequently applied during inspiration and expiration first to the parasternal intercostal muscle in the fourth interspace and then to the parasternal intercostal muscle in the second interspace.

The animals in both experiments were maintained under light surgical anesthesia throughout the measurements. Supplementary doses of anesthetic (1–2 mg/kg) were thus given at regular intervals to ensure that there was no spontaneous movement of the fore- or hindlimbs, no flexor withdrawal of the forelimbs, and no pupillary light reflex; the corneal reflex, however, was kept present. Rectal temperature was also kept constant between 36 and 38° C with infrared lamps. At the end of the experiment, the animal was given a lethal dose of anesthetic (30–40 mg/kg intravenously).

Data Analysis

The changes in parasternal and external intercostal muscle length induced by vibration during apnea (Experiment 1) were measured peak-to-peak and expressed in micrometers, while the electrical response of the muscles was evaluated qualitatively on the basis of the raw EMG traces. On the other hand, the effects of in-phase vibration on inspiratory EMG activity (Experiment 2) were quantified in two ways. First, activity during each vibrated breath was compared with the activity recorded during the immediately preceding nonvibrated (control) breath by measuring the peak height of the integrated EMG signal in arbitrary units. The duration of inspiration (inspiratory time, T_i), defined as the period beginning at the onset of the parasternal inspiratory burst and concluding with the peak parasternal activity, did

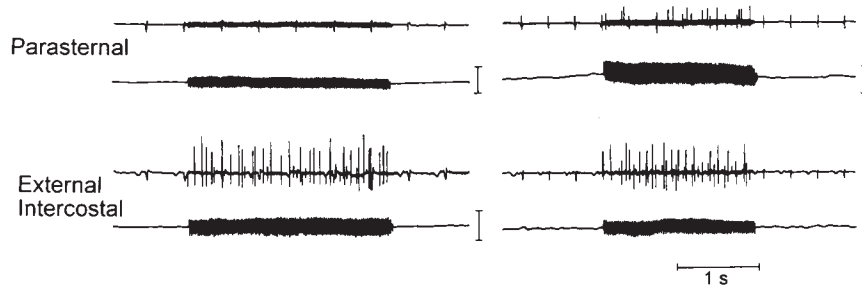


Figure 1. Responses of the parasternal and external intercostal muscles (third interspace) to vibration of the third interspace in two representative animals. The top trace for each muscle is the electromyogram and the bottom trace is the change in length (an upward deflection indicates muscle lengthening). Length calibration, 200 μm . The vibrator in both animals was applied to the parasternal intercostal and its frequency was set at 40 Hz.

not show any consistent alteration with vibration. The changes in peak activity seen during vibration were therefore independent of the changes in neural inspiratory time and chemical respiratory drive that might have occurred. One animal in the study, however, did not have any external intercostal inspiratory activity in the control breaths, even though the electrodes were inserted in the most dorsal portion of the muscle. To allow comparison between the two muscles in the different animals, the inspiratory EMG activity recorded during each control breath was consequently expressed as a percentage of the activity recorded during the subsequent vibrated breath.

Second, the raw EMG signals recorded during the same vibrated and control breaths were examined to determine the time difference between the onset of external intercostal inspiratory activity and the beginning of the parasternal intercostal activity. The time difference between the ending of parasternal intercostal activity and the cessation of activity in the external intercostal was measured as well. These values were calculated in seconds. By convention, positive values for onset and termination times indicate, respectively, that external intercostal activity occurred earlier than parasternal intercostal activity at the beginning of inspiration and persisted for a longer period of time at the end. In each animal, all of these measurements were averaged over the 10 trials.

Data were averaged for the animal group, and they are presented as means \pm SE. Statistical comparisons between the changes in parasternal and external intercostal muscle length during vibration and statistical assessments of the effects of in-phase vibration on inspiratory EMG activity, tidal volume, and T_I were made by using Student paired t tests; the criterion for significance was taken as $p < 0.05$.

RESULTS

Effects of Vibration During Apnea

Vibrating the parasternal intercostal muscle in the third interspace induced significant changes in length in both the parasternal intercostal and the external intercostal. With the frequency of vibration set at 40 Hz, the peak-to-peak amplitude of these changes thus averaged 80 ± 13 and 94 ± 16 μm , respectively. These length changes were not significantly different from each other, yet the two muscles had different EMG responses to vibration, as shown in Figure 1. All animals consistently demonstrated abundant EMG activity in the external intercostal. This activity started abruptly at the onset of vibration and remained constant for the duration of vibration, and in most trials it ceased abruptly on removal of the vibrator. On several occasions in two animals, external intercostal activity even continued for 3–5 s after the cessation of vibration. On the other hand, three of seven animals did not have any EMG activity in the parasternal intercostal (Figure 1, *left*), and in the four animals that did have parasternal intercostal activity, this activity consisted of only a few spikes (Figure 1, *right*). A similar difference between the external and parasternal intercostals was seen when the frequency of vibration was set at 10 and 80 Hz and also when the vibrator was applied to the external intercostal in the third interspace.

When the vibrator was applied to the parasternal intercostal muscle in more rostral or more caudal interspaces, the changes in muscle length decreased progressively ($p < 0.001$) as the site

of vibration became more distant from the third interspace (Figure 2) but the EMG response of the external intercostal was largely preserved (Figures 2 and 3). Thus vibrating the parasternal intercostal in the fifth or the first interspace still elicited a consistent external intercostal activity in six of seven animals (Figure 3b). Vibrating the parasternal intercostal in the seventh interspace also elicited a consistent, albeit smaller, external intercostal activity in five animals (Figure 3c). In contrast, parasternal intercostal activity was detected in only two animals during vibration of the first and fifth right interspaces and was never recorded during vibration of the seventh interspace.

Auditory feedback of the external intercostal activity indicated that the activity recorded during vibration was arising from motor units situated in the immediate vicinity of the EMG electrodes. And indeed, when the external intercostal nerve in the third interspace was sectioned, activity was no longer recorded during vibration in any animal (Figures 4a and 4b), thus indicating that the initial EMG response originated entirely from the external intercostal muscle itself. Similarly, in the four animals that showed parasternal activity during vibration, this activity was eliminated by section of the internal intercostal nerve at the costochondral junction (Figure 4c).

Effects of In-phase, Ipsisegmental Vibration

The animals of Experiment 2 had a mean arterial P_{CO_2} of 42.5 ± 1.3 mm Hg and a mean arterial P_{O_2} of 81.0 ± 4.6 mm Hg, and

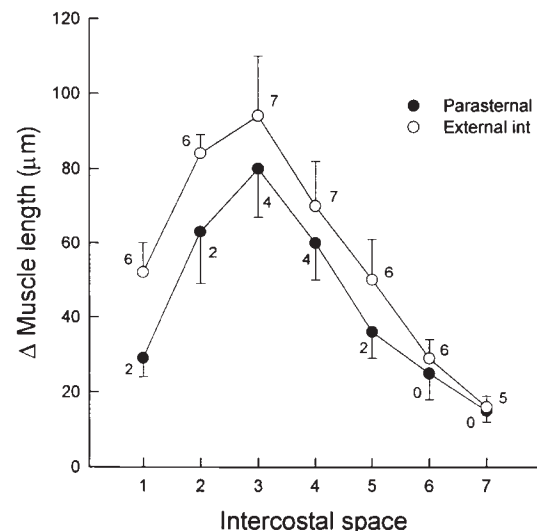


Figure 2. Changes in parasternal (closed circles) and external intercostal (open circles) muscle length in the third interspace during vibration of the parasternal intercostal muscle in interspaces 1 to 7. Values represent means \pm SE, obtained in seven animals. The numbers next to the circles indicate the number of animals in which EMG activity was induced by vibration.

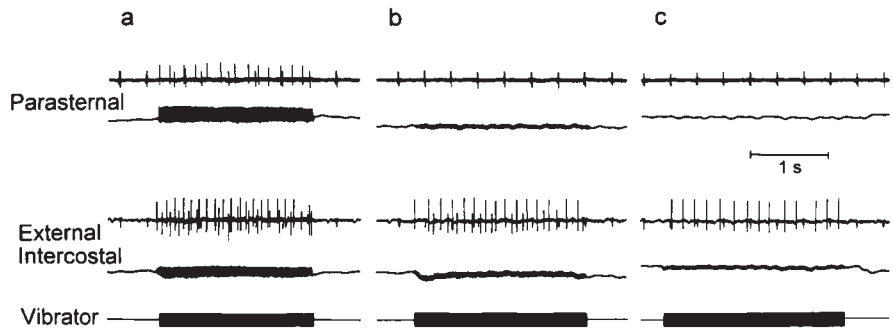


Figure 3. Response of the parasternal and external intercostal muscles (third interspace) to vibration of the parasternal intercostal in the third (a), fifth (b), and seventh (c) interspace in a representative animal. Same animal as in right panel of Figure 1. Length calibration, 200 μm .

Figure 5 shows representative records of parasternal and external intercostal EMG activity during resting, control breathing and during in-phase vibration of the parasternal intercostal muscle in the third interspace. Phasic inspiratory EMG activity in the external intercostal increased with each vibration in all animals; for the animal group, peak external intercostal activity in the control breaths was only $43.1 \pm 3.7\%$ of the peak activity recorded in the vibrated breaths ($p < 0.001$). Parasternal intercostal inspiratory activity, however, remained unchanged with vibration, such that peak activity in the control breaths averaged $105.0 \pm 7.4\%$ of the activity in the vibrated breaths (NS). Tidal volume (control, 364 ± 46 ml; vibration, 352 ± 43 ml; NS) and T_I (control, 1.14 ± 0.18 s; vibration, 1.15 ± 0.17 s; NS) also remained unchanged.

In-phase vibration of the parasternal intercostal in the third interspace induced not only an increase in peak external intercostal inspiratory activity but also a marked change in the timing of this activity (Figure 5). Specifically, external intercostal activity in the control breaths consistently appeared after the onset of parasternal intercostal activity in six of seven animals, whereas during vibration, the onset of external intercostal activity preceded the onset of parasternal intercostal activity in five animals. The lead time for the seven animals studied was thus reversed from -157 ± 105 to $+127 \pm 64$ ms ($p < 0.03$). In addition, in three animals, in-phase vibration also elicited marked prolongation of external intercostal activity at the end of inspiration; an example of this response is shown in Figure 6. For these three animals, postinspiratory activity in the external intercostal increased from $+134 \pm 72$ ms during control to $+663 \pm 149$ ms during vibration.

Effects of In-phase, Juxtasegmental Vibration

Vibrating the parasternal intercostal muscle in the fourth and second interspace during inspiration produced essentially similar alterations (Figure 7). Peak external intercostal inspiratory activity in the control breaths was only $38.2 \pm 13.0\%$ of

the activity recorded during in-phase vibration of the fourth interspace ($p < 0.004$). External intercostal activity during control also averaged $43.2 \pm 9.7\%$ of the activity recorded during in-phase vibration of the second interspace ($p < 0.002$). In contrast, peak parasternal intercostal inspiratory activity, tidal volume, and T_I remained unchanged throughout.

Effects of Out-of-phase Vibration

The response of the parasternal and external intercostal muscles to out-of-phase vibration is illustrated by the records of a representative animal in Figure 8. Whether the vibrator was applied to the third, the fourth, or the second interspace, no animal had any parasternal intercostal activity during out-of-phase vibration, and six of seven animals did not have any external intercostal activity either. In the remaining animal, external intercostal activity appeared with each vibration (Figure 9).

DISCUSSION

High-frequency mechanical vibration, when applied to the belly of a relaxed limb muscle or to its tendon, is well-known to produce an increased afferent input from spindle primary endings and to induce a reflex muscle contraction (6, 7). This muscle contraction is conventionally referred to as the "tonic vibration reflex" and abbreviated as TVR, and one of the main results of the present studies is the demonstration that vibration of the relaxed rib cage elicits more consistent and more prominent TVR in the external intercostal than the parasternal intercostal muscles. This difference was seen whether the vibrator was applied to the lateral or the ventral aspect of the segment of the rib cage being investigated and also when the vibrator was applied to more distant sites. Indeed, with the vibrator applied to more rostral or more caudal segments, a TVR was still induced commonly in the external intercostal but appeared only occasionally in the parasternal intercostal.

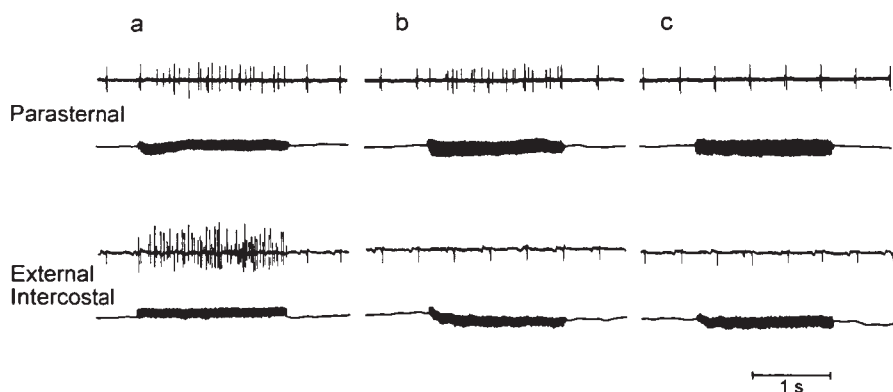


Figure 4. Response of the parasternal and external intercostal muscles (third interspace) to vibration of the parasternal intercostal muscle in the third interspace during control (a), after section of the external intercostal nerve (b), and after section of the internal intercostal nerve at the costochondral junction (c). Length calibration, 200 μm .

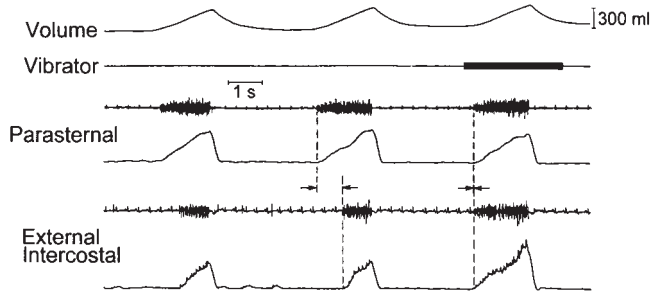


Figure 5. Electrical response of the parasternal and external intercostal muscles (third interspace) to in-phase vibration of the third interspace in a representative animal; raw and integrated EMG signals are shown for both muscles. During the control breaths, the parasternal and external intercostals were electrically active during the inspiratory phase of the breathing cycle, although the onset of external intercostal activity was delayed relative to the onset of parasternal intercostal activity (vertical dotted lines and arrows in second breath). During vibration, however, this delay was eliminated and external intercostal inspiratory activity was markedly increased. Vibration frequency, 40 Hz.

The parasternal intercostal muscles differ from the external intercostals with respect to their insertions. Specifically, whereas the fibers of the external intercostal in a given segment connect bony ribs, the fibers of the parasternal intercostal originate from the sternum and the medial aspect of the costal cartilage above to insert into the lateral aspect of the costal cartilage below. To the extent that the amplitude of displacement of the lateral aspect of the bony ribs during passive inflation is greater than that of the sternum and the medial aspect of the costal cartilages (19), mechanical vibration of the rib cage might have yielded greater changes in external intercostal than in parasternal intercostal length. The measurements summarized in Figure 2, however, demonstrated that vibration induced similar length changes in the two muscles, thus indicating that the stimulus applied to them was about the same. In agreement with our hypothesis, therefore, the conclusion can be drawn that the external intercostals are intrinsically more sensitive to chest wall vibration than the parasternal intercostals.

During spontaneous breathing, however, the intercostal α -motoneurons are subjected to slow rhythmic fluctuations of their membrane potential; these fluctuations are of central origin and have, accordingly, been called “central respira-

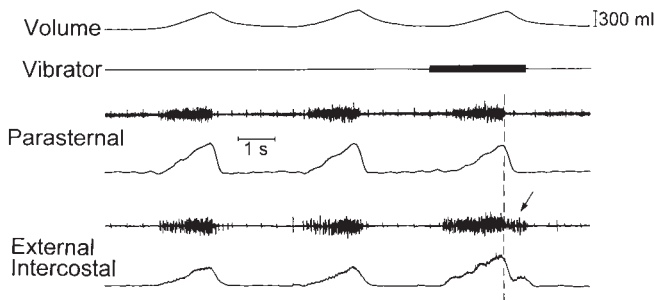


Figure 6. Example of the change in external intercostal postinspiratory activity during in-phase vibration. During the control breaths, the activity recorded from the external intercostal terminated almost simultaneously with the cessation of parasternal activity. During the vibrated breath, however, external intercostal activity carried on well after the end of parasternal intercostal activity (vertical dotted line).

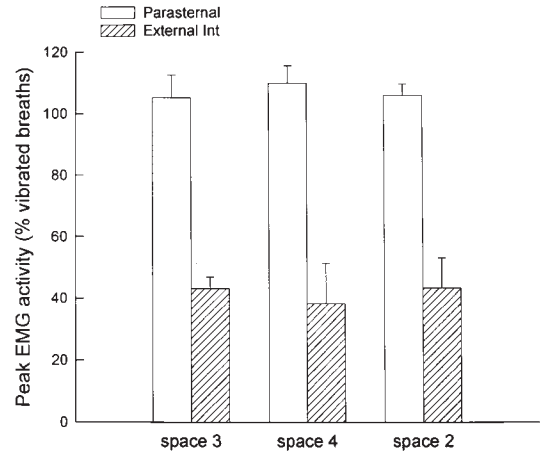


Figure 7. Response of the parasternal and external intercostal muscles (third interspace) to in-phase vibration of the parasternal intercostal in the fourth and second interspace. The response of the muscles to in-phase vibration of the third interspace is shown for comparison. Data represent means \pm SE, obtained from seven animals. Parasternal and external intercostal inspiratory activities during the control breaths are expressed as percentages of the activities recorded during the vibrated breaths.

tory drive potentials” or CRDPs (20, 21). Specifically, during a normal respiratory cycle, the parasternal and external intercostal α -motoneurons depolarize during inspiration to reach the threshold of activation and send efferent impulses to the corresponding muscles. Activating muscle spindles by rib cage vibration at this stage should therefore induce additional, depolarizing changes in membrane potential in both sets of α -motoneurons to increase the discharge frequency of active motoneurons and to recruit others into activity. Furthermore, the fusimotor neurons innervating the muscle spindles in the inspiratory intercostals also depolarize during inspiration (21, 22). These neurons, in fact, are subjected to similar CRDPs as the α -motoneurons, and studies on limb muscles in cats (6) and in humans (23) have clearly established that stimulation of fusimotor fibers increases the responsiveness to vibration of spindle primary endings. Consequently, vibrating the rib cage during inspiration might cause a substantial increase in both parasternal and external intercostal inspiratory EMG activity.

On the other hand, the parasternal intercostals and the external intercostals in the rostral interspaces rhythmically shorten during inspiration (12, 24), and studies on relaxed

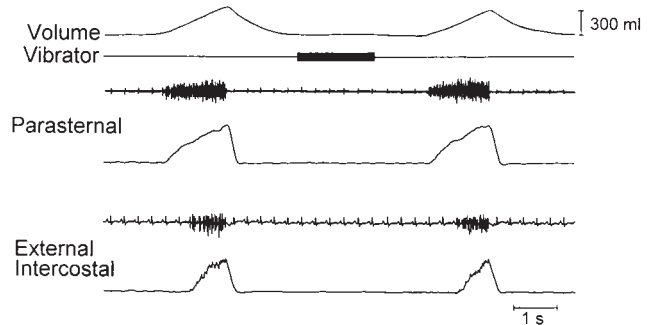


Figure 8. Response of the parasternal and external intercostal muscles (third interspace) to out-of-phase vibration of the third interspace in a representative animal. Same animal as in Figure 5. Note the absence of activity during vibration.

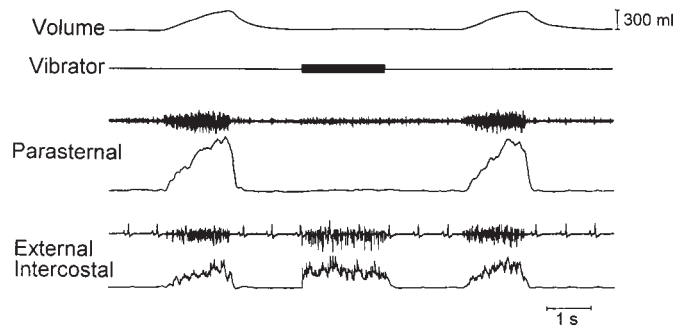


Figure 9. Traces of parasternal and external intercostal EMG activity in the animal that had external intercostal activity during out-of-phase vibration.

limb muscles in cats (6, 25) and in humans (7) have shown that the sensitivity to vibration of spindle primary endings increases during muscle stretch and decreases during muscle shortening. Similar observations have been made on isolated cat muscle spindles (26). Activation of α -motor fibers also reduces the sensitivity to vibration of the spindle primary endings, even when muscle length is maintained constant and the fusimotor fibers are simultaneously activated (6, 23). In addition, whereas vibration of a relaxed muscle in cats stimulates exclusively or predominantly the spindle primary endings, it also stimulates the Golgi tendon organs when applied to a contracting muscle (6). The increased responsiveness of tendon organs, combined with the decreased responsiveness of spindle primary endings, should add to the effect of muscle shortening to reduce, via spinal pathways, the increased parasternal and external intercostal activity that rib cage vibration during inspiration should produce otherwise. Finally, recordings from medullary inspiratory neurons and phrenic motor fibers in cats by Bolser and colleagues (27) have shown that stimulation of Golgi tendon organs in the external and internal intercostal muscles causes inhibition of inspiratory activities via supraspinal pathways. For all these reasons, in-phase vibration of the rib cage might therefore result in a net decrease, rather than an increase, in parasternal and external intercostal inspiratory activity.

With in-phase vibration, all animals consistently demonstrated a substantial increase in the amount of external intercostal activity at peak inspiration. External intercostal activity also occurred earlier at the onset of inspiration. In fact, external intercostal activity during vibration preceded parasternal intercostal activity in many animals, whereas in the absence of vibration, it usually appeared after the onset of parasternal activity. Furthermore, vibration caused the external intercostals to fire longer at the end of inspiration and commonly made external intercostal activity persist after the cessation of parasternal activity. Thus, even though the muscle shortening, the α -motor activation, and the increased tendon organ responsiveness during inspiration may have attenuated the response of the external intercostal muscles to vibration, neural drive to these muscles was definitely increased.

The inspiratory EMG activity recorded from the parasternal intercostals, however, was unchanged with respect to both its magnitude and its timing, and this amplifies the conclusion that in the dog, the sensitivity to vibration of these muscles is much smaller than that of the external intercostals. Also, this finding confirms our previous contention that the canine parasternal intercostals are primarily governed by central control mechanisms (13, 14), and it further suggests that the vibrations

used in this study had little or no supraspinal effect. Indeed, Bolser and coworkers (27, 28) have previously shown in cats that a vibration amplitude of 90–100 μm causes exclusive or predominant activation of intercostal muscle spindles and does not affect medullary inspiratory activity. However, since vibration during apnea did elicit low-amplitude parasternal EMG activity in several animals (Figures 1 and 4), the absence of increased neural drive to these muscles during in-phase vibration cannot be exclusively attributed to the small vibration amplitude and the small density in muscle spindles (8). It must, therefore, involve other factors. A number of studies using sonomicrometry have shown that in anesthetized dogs breathing at rest, the parasternal intercostal muscles shorten by 7 to 9% of their relaxation length during inspiration whereas the external intercostals in the rostral interspaces shorten by only 2% (12, 24). Furthermore, in our previous studies of the topographical distribution of EMG activity among the canine inspiratory intercostals, it was shown that at peak inspiration, the amount of activity in the medial portion of the parasternal intercostal in the third interspace is, on average, 55–60% of the maximal amount of activity (29). In contrast, the amount of external intercostal inspiratory activity in the third interspace was only 10–20% of maximum (17). The greater α -motor activation and greater shortening of the parasternal intercostals during inspiration might lead to a greater reduction in the responsiveness to vibration of the spindle primary endings in these muscles (6, 7, 25, 26).

Although the external intercostals are more sensitive to vibration than the parasternal intercostals, it is notable that six of seven animals did not have any external or parasternal intercostal activity with out-of-phase vibration. Thus, the response of these muscles to vibration during expiration was substantially smaller than during apnea, and this confirms the previous suggestion by Sears (21) and Aminoff and Sears (30) that the repolarization of the inspiratory intercostal α -motoneurons during expiration involves an (active) inhibitory synaptic drive. In other words, the membrane potential of the parasternal and external intercostal α -motoneurons would be further away from the activation threshold (i.e., more negative) during the expiratory phase of the breathing cycle than during hyperventilation-induced apnea. As a result, the excitatory postsynaptic potentials (EPSPs) resulting from vibration might allow the α -motoneurons to reach the activation threshold during apnea, whereas similar or greater EPSPs during expiration might be insufficient to do so.

It is difficult to reconcile the current findings with the previous observation by Homma and coworkers (5) that vibration of upper intercostal spaces in normal humans causes marked increases in parasternal intercostal activity during both inspiration and expiration. However, besides a species difference, two factors must be considered. First, the subjects studied by Homma and coworkers (5) were awake, whereas the animals of this study were anesthetized. It is well known that anesthesia, in particular barbiturate anesthesia, may depress spindle reflexes (11), so the possibility exists that the sensitivity to vibration of the parasternal intercostals in our animals was inadvertently reduced. Anesthesia, however, cannot account for the observation that in contrast to the parasternal intercostals, the external intercostals in these animals consistently showed a prominent EMG activity during apnea and an increased neural drive during in-phase vibration. In addition, it is particularly striking that Homma and coworkers (5) observed greater increases in parasternal activity during expiration (i.e., when the α -motoneurons were hyperpolarized) than during inspiration (see Figure 2 in Reference 5), and this suggests that the perception of vibration in the rib cage may have been a

key factor in these subjects. In the current study, all potential conscious reactions to vibration were eliminated.

The second important difference between the study of Homma and coworkers (5) and the current studies relates to the technique of electromyography. Specifically, because our animals were anesthetized, the electrodes were implanted into the muscles under direct vision, and the muscles overlying the rib cage were deflected. Selective intercostal muscle denervations further allowed all cross-contaminations to be identified. On the other hand, Homma and coworkers (5) implanted concentric needle electrodes transcutaneously. The parasternal electrodes therefore passed through the pectoralis major, and when the vibrator was applied to the skin over the parasternal area, a TVR may have been induced in this muscle as well. Thus the activity recorded from the parasternal intercostals may have originated, in fact, from the pectoralis major.

A final issue deserves some consideration. In the dog, the external intercostals in the rostral interspaces cause a cranial displacement of the ribs and an increase in lung volume when they contract (31). Therefore, one might have expected that in-phase vibration would lead to an increase in tidal volume. The reason that this did not occur in our animals is uncertain, but three explanations come to mind. First, in-phase vibration might elicit concomitant contraction of the rib cage expiratory muscles, in particular the internal interosseous intercostals, which would reduce or suppress the effect of the increased external intercostal activity on tidal volume. Second, vibrating the intercostal muscles in the second to fourth segments might cause inhibition of diaphragmatic activity through one of the so-called intercostal-to-phrenic reflexes (32, 33). Finally, and perhaps more importantly, the external intercostal muscles in supine anesthetized dogs contribute only 10–15% of the inspiratory cranial displacement of the ribs during resting breathing (34). Since rib cage expansion in such animals contributes about 40% of the tidal volume (35), this implies that the external intercostal contribution to tidal volume is about 4–6%. Consequently, even if one assumes that in-phase vibration did not produce any rib cage expiratory muscle activation and any diaphragmatic inhibition, the predicted increase in tidal volume in our animals would be only 14 to 22 ml. The measured change in tidal volume was a 12-ml reduction. The predicted and measured effect cannot be said to agree, but they are both small.

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