Responses of the anterolateral abdominal muscles during cough and expiratory threshold loading in the cat

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Bolser, Donald C., Paul J. Reier, and Paul W. Davenport. Responses of the anterolateral abdominal muscles during cough and expiratory threshold loading in the cat. J Appl Physiol 88: 1207–1214, 2000.—The present study was conducted to determine the pattern of activation of the anterolateral abdominal muscles during the cough reflex. Electromyograms (EMGs) of the rectus abdominis, external oblique, internal oblique, transversus abdominis, and para- sternal muscles were recorded along with gastric pressure in anesthetized cats. Cough was produced by mechanical stimulation of the lumen of the intrathoracic trachea or larynx. The pattern of EMG activation of these muscles during cough was compared with that during graded expiratory threshold loading (ETL; 1–30 cmH2O). ETL elicited differential recruitment of abdominal muscle EMG activity (transversus abdominis > internal oblique > rectus abdominis = external oblique). In contrast, both laryngeal and tracheobronchial cough resulted in simultaneous activation of all four anterolateral abdominal muscles with peak EMG amplitudes 3- to 10-fold greater than those observed during the largest ETL. Gastric pressures during laryngeal and tracheobronchial cough were at least eightfold greater than those produced by the largest ETL. These results suggest that, unlike their behavior during expiratory loading, the anterolateral abdominal muscles act as a unit during cough.

METHODS

Cats (n = 6; 2.5–5.0 kg) were anesthetized with pentobarbital sodium (35 mg/kg iv). End-tidal CO2 was monitored, and supplemental anesthetic was administered when this value dropped below 3.9%. Animals with end-tidal CO2 above 5.0% usually did not cough consistently and were excluded from analysis. Catheters were placed in a femoral artery and vein for monitoring blood pressure and administering drugs, respectively. Atropine sulfate (1.0 mg/kg iv) was administered to block reflex tracheal secretions. A tracheal cannula was inserted through an incision at the fourth tracheal segment, and the animals were allowed to breathe spontaneously. Body temperature was maintained at 37 ± 1°C with an electric heating pad. A balloon-tipped catheter was passed down the esophagus and into the stomach to record gastric pressure. The balloon was inflated with a syringe and was considered to be positive during normal breathing; and not the thorax, increased balloon pressure; 2) pressure was positive during normal breathing; and 3) cough elicited only positive pressure changes. The animals were placed in a supine position.

Bipolar Teflon-coated stainless steel wire electrodes were placed in the parasternal, rectus abdominis, external oblique, internal oblique, and transversus abdominis muscles according to the technique of Basmajian and Stecko (2). All electrodes were placed 2–3 mm apart on the left side of the animal. Electrodes were placed in the parasternal muscle at T3. For the rectus abdominis muscle, the electrodes were placed through a small incision in the skin ~7 cm caudal to the xiphoid process and 1 cm lateral to the midline. Electrodes were placed in the external oblique muscle approximately halfway between the midaxillary line and the linea alba, ~5 cm caudal to the costal margin. After electrode
placement, an incision was made in the external oblique ~2 cm from the electrode site, and a 2-cm × 2-cm sheet of plastic was placed between the electrode site and the underlying muscle. For electrode placement in the internal oblique muscle, a 1-cm² section of the overlying musculature was removed at a location ~4 cm caudal to the external oblique electrode site. After placement of the electrodes in the internal oblique muscle, a small section of plastic was introduced underneath the muscle from an incision ~2 cm away from the electrode site to electrically insulate it from the transversus abdominis. Electrodes were placed in the transversus abdominis approximately halfway between the internal oblique electrodes and the linea alba. All overlying muscle was removed for ~1 cm² before electrode placement.

EMGs from these muscles were amplified, band-pass filtered (0.1–5 kHz), monitored on an oscilloscope, and integrated with a resistance-capacitance circuit (100-ms time constant). These signals were displayed along with blood pressure and gastric pressure on a chart recorder.

Cough is characterized by coordinated bursts of activity in inspiratory and expiratory muscles (27). Cough was defined as an inspiratory-related burst of EMG activity in the parasternal muscle immediately followed by a burst of EMG activity in the abdominal muscles (4). This definition differentiates augmented breaths, the aspiration reflex, and the expiration reflex from cough (40–43). Expiration reflexes were defined as a large EMG burst in the abdominal muscles but no inspiratory-related increased activity in the parasternal muscle (28). Augmented breaths were defined as a large inspiratory-related EMG burst in the parasternal muscle with no subsequent activity in expiratory abdominal muscles (43).

Cough was elicited by mechanical stimulation of the intrathoracic trachea or larynx with a small length of flexible plastic tubing (3, 4). The intrathoracic trachea was accessed via the tracheal cannula, and the larynx was stimulated by inserting the plastic tubing 3–5 cm rostrally in the trachea. A nonrebreathing valve was attached to the tracheal cannula. Expiratory threshold loads of 1, 3, 5, 10, 15, and 30 cmH₂O were applied by attaching a hose to the expiratory port of this valve and immersing the end of this hose in a reservoir of water. Each load was 2 min in duration. Two minutes were allowed to elapse between successive loads. Loads were applied in increasing magnitude until the highest load was completed.

All values are expressed as means ± SE. Statistical differences between means were evaluated with Student’s t-test or one-way analysis of variance. The EMG amplitudes of the last five bursts during each expiratory load were averaged to obtain a single value for each load. These EMG burst amplitudes during expiratory loading, as well as those during cough, were expressed as a percentage of the largest amplitude burst of that particular EMG in each animal (6, 43). The largest EMG burst in each animal always occurred during cough or expiration reflexes. Relationships between normalized burst amplitudes of the EMGs and gastric pressure during coughs were evaluated by linear regression analysis. Differences were considered significant if P < 0.05.

RESULTS

A total of 246 coughs (211 tracheobronchial and 35 laryngeal) were elicited in 6 animals. The anterolateral abdominal muscle EMGs were normally silent during eupneic breathing but became active during cough or expiratory threshold loading (Figs. 1 and 2). The parasternal muscle EMG had inspiratory-phased activity during eupneic breathing and was more intensely activated during either cough or expiratory threshold loading (Figs. 1 and 2).

Both laryngeal and tracheobronchial cough elicited large increases (averaging 50–60% of the maximum EMG burst amplitudes) in the EMGs of all four anterolateral abdominal muscles (Figs. 1 and 2). There were no significant differences between the magnitudes of activation of the EMGs of any single anterolateral abdominal muscle during tracheobronchial or laryngeal cough. However, the normalized EMG amplitude for the parasternal muscle was significantly greater during laryngeal cough than during tracheobronchial cough (Fig. 2).

Graded expiratory threshold loads elicited graded increases in peak EMG activity of the parasternal, internal oblique, and transversus abdominis muscles (Fig. 2). The responses of the rectus abdominis and external oblique muscles to graded expiratory threshold loading were small and not easily identified as graded in all animals.

The magnitude of activation of the anterolateral abdominal muscles during cough was greater than that achieved during even the highest expiratory threshold loads (Figs. 1 and 2). The increase in rectus abdominis and external oblique muscle EMGs during cough was at least 10-fold greater than their maximum activation.
during expiratory threshold loading (Fig. 2). The internal oblique and transversus abdominis muscles were activated to a greater extent by expiratory loading, but the EMG response was still at least three- to fourfold greater during cough (Fig. 2). The amplitude of the parasternal muscle EMG during the highest expiratory threshold load was approximately one-half of the EMG response of this muscle during cough (Fig. 2).

Abdominal muscle EMG activity was observed during the inspiratory phase of cough in all animals (Fig. 3). This abdominal muscle activity will be termed preexpulsive because it occurred during the inspiratory phase and before the expulsive phase of cough. Preexpulsive abdominal activity was not always present in each EMG during every cough but was present in each EMG during most coughs. This preexpulsive EMG activity was observed in a given muscle during 70–85% of coughs (rectus abdominis: 85 ± 7%, external oblique: 69 ± 8%, internal oblique: 75 ± 7%, transversus abdominis: 85 ± 6%; P < 0.4). The duration of this preexpulsive EMG activity was 600–700 ms (rectus abdominis: 614 ± 88 ms, external oblique: 730 ± 127 ms, internal oblique: 686 ± 86 ms, transversus abdominis: 654 ± 121; P < 0.89). Similar activity was not observed in the expiratory muscles during expiratory threshold loading.

Cough elicited by mechanical stimulation of the trachea or larynx elicited an increase in gastric pressures of 49 ± 7 (laryngeal cough) and 53 ± 7 mmHg (tracheobronchial cough; Figs. 1 and 4). Peak gastric pressures during individual coughs often reached 100 mmHg. Graded expiratory threshold loads elicited graded increases in gastric pressures, ranging from 0.5 ± 0.5 mmHg at 1-cmH₂O loads to 6 ± 1 mmHg at 30-cmH₂O loads (Fig. 4). Gastric pressures during tracheobronchial or laryngeal cough were approximately ninefold higher than the highest gastric pressures observed during expiratory threshold loads of 30 cmH₂O (Fig. 4).

The normalized EMG amplitudes of the anterolateral abdominal muscles were correlated with the magnitude of gastric pressure during tracheobronchial cough.
Linear relationships with positive slopes significantly greater than zero existed between the EMG amplitudes of these muscles and gastric pressure during cough (Fig. 5). The average regression coefficient for the relationship between gastric pressure and the abdominal muscle EMG amplitudes during cough was $0.76 \pm 0.08$ for rectus abdominis, $0.62 \pm 0.15$ for external oblique, $0.78 \pm 0.08$ for internal oblique, and $0.80 \pm 0.08$ for transversus abdominis. The average slope for each relationship for cough was $0.81 \pm 0.15$ for rectus abdominis, $0.46 \pm 0.27$ for external oblique, $0.74 \pm 0.23$ for internal oblique, and $0.77 \pm 0.13$ for transversus abdominis. During expiratory threshold loading, EMG amplitudes were less well correlated with gastric pressure. The average regression coefficient for the relationship between gastric pressure and the abdominal muscle EMG amplitudes during expiratory threshold loading was $0.12 \pm 0.12$ for rectus abdominis, $0.46 \pm 0.27$ for external oblique, $0.86 \pm 0.09$ for internal oblique, and $0.79 \pm 0.1$ for transversus abdominis. The average slope for each relationship was $-0.12 \pm 0.3$ for rectus abdominis, $0.42 \pm 0.22$ for external oblique, $1.8 \pm 0.5$ for internal oblique, and $2.5 \pm 1.1$ for transversus abdominis.

Peaks in the EMGs of each muscle preceded peaks in gastric pressure during cough by $\sim 70$ ms (rectus abdominis $65 \pm 11$ ms, external oblique $76 \pm 34$ ms, internal oblique $63 \pm 4$ ms, transversus abdominis $76 \pm 11$ ms). There were no significant differences between the latencies from the peak EMG to the gastric pressure peak during cough for any of the muscles ($P < 0.96$). Similar information could not be obtained for the expiratory threshold loading responses because the EMGs and gastric pressures during this maneuver often had very rounded or flattened peaks, making precise temporal measurements difficult.

**DISCUSSION**

The major findings of this study were that EMG responses of the anterolateral abdominal muscles and gastric pressures during cough were much larger than these values during expiratory threshold loading in pentobarbital sodium-anesthetized cats. Furthermore, the activation patterns of the different anterolateral abdominal muscle EMGs during cough were very similar to one another, unlike the differential activation patterns of these four abdominal muscles during expiratory loading.

This is the first report to investigate the response patterns of all four anterolateral abdominal muscles during the cough reflex. Tomori and Widdicombe (40) systematically investigated the motor pattern of a single abdominal muscle during cough. They found that the rectus abdominis muscle was vigorously activated during this reflex and this activation was associated with large (>50-mmHg) intrathoracic pressures (40). Subsequently, other investigators (20, 41, 42) reported the EMG responses of single anterolateral abdominal muscles, including the rectus abdominis, external oblique, or transversus abdominis muscles, during cough in various preparations. Our findings confirm and extend these previous results by showing that all four anterolateral abdominal muscles are simultaneously and vigorously activated in a similar fashion during the cough reflex. However, our findings are not consistent with those of Floyd and Silver (21), who reported that the rectus abdominis muscle was relatively inactive during voluntary cough in the awake human. This apparent difference could be explained by species differences or the presence of anesthesia in our study. However, in two studies (9, 35) our laboratory found that the rectus abdominis was strongly activated during either voluntary or capsaicin-induced cough in awake humans. Indeed, coactivation of the rectus abdominis and other abdominal muscles during voluntary cough in humans has been reported by others (15, 25).

Tomori and Widdicombe (40) first documented the presence of motor discharge in the rectus abdominis muscle during the inspiratory phase of cough. We have termed this type of discharge preexpulsive, given that
it occurs before the onset of the expulsive phase of cough. Our results confirm and extend the findings of Tomori and Widdicombe in that we observed significant preexpulsive EMG activity in all four anterolateral abdominal muscles. This preexpulsive discharge in the anterolateral abdominal muscles is probably responsible, at least in part, for the positive gastric pressures observed during the inspiratory phase of cough (39). Positive gastric pressures during the inspiratory phase of cough have previously been attributed to descent of the diaphragm (27). The relative importance of preexpulsive activity in the anterolateral abdominal muscles and descent of the diaphragm in producing positive gastric pressures during the inspiratory phase of cough is unknown.

The parasternal EMG was larger during laryngeal cough than during tracheobronchial cough. This observation is consistent with our previous work on the cough responses of the pectoralis major (8). Taken together, these findings suggest that inspiratory muscles of the upper chest wall have larger EMG responses during laryngeal cough than during tracheobronchial cough. This conclusion is also consistent with the observations of Tomori and Widdicombe (40) that laryngeal cough elicited a more negative intrapleural pressure than did tracheobronchial cough in the cat. However, in the dog, there was no difference in the magnitude of esophageal pressure during the inspiratory phase between the two types of cough (38). On the other hand, tracheobronchial cough elicited larger changes in esophageal pressure during expulsion than did laryngeal cough (38). In the cat, we found no difference between the magnitudes of gastric pressures produced during the two types of cough.

We believe that cough represents a clear change in state of the brain stem respiratory muscle motor control system compared with its behavior during eupnea, respiratory loading, or increased chemical drive. There are several lines of evidence that support this idea. First, the level of activation of expiratory muscles during 20–25 cmH2O of positive end-expiratory pressure is usually considered to represent the maximum level of respiratory activation that these muscles can achieve (16). It is clear from our results that the EMGs of the four anterolateral abdominal muscles and gastric pressures during cough both are far greater than those observed during maximal expiratory loading in the cat. It follows that the level of descending motor drive to expiratory muscles during cough is far greater than during loading maneuvers, previously thought to represent maximum respiratory motor drive to these muscles (16, 19, 24, 36). However, it is important to note that Gilmartin et al. (24) recognized that positive end-expiratory loads of 25 cmH2O might not represent the true maximum respiratory activity of an abdominal muscle. Second, the effect of vagally mediated volume-related feedback on the motor pattern of respiratory muscles during cough is different from its well-known effects during eupnea. Romaniuk and co-workers (32) have shown that tracheal occlusion does not alter abdominal motor discharge during cough. Recent results from our laboratory (5) indicate that there is no
relationship between lung volume and inspiratory- or expiratory-phase timing during cough. It also has been known for some time that slowly adapting stretch receptor feedback has a permissive effect on the cough reflex (26, 34), which is very different from the manner in which the eupneic motor pattern is modulated by these sensory afferents (12, 23, 45). Third, we have recently found that a central gating mechanism may regulate afferent input to the brain stem respiratory pattern generator during cough (7). To our knowledge, this mechanism does not function during eupnea. Taken together, these findings suggest that the regulation of respiratory muscle activity during loading or eupnea is fundamentally different from the regulation of these muscles during cough.

These studies were conducted in pentobarbital sodium-anesthetized animals. This anesthetic can depress spontaneous expiratory abdominal and thoracic motor discharge (13, 18, 22). Warner et al. (44) have shown that the depressant effects of pentobarbital sodium on spontaneous expiratory muscle activity are transient. Furthermore, there is no evidence that pentobarbital sodium depresses expiratory motor discharge during cough. Cats anesthetized with pentobarbital sodium cough vigorously, with gastric or intrapleural pressures often well in excess of 100 cmH2O (27, 40). The level of excitatory motor drive to expiratory motor neurons during cough is far greater than that present during eupnea (6, 41) and probably overwhelms any depressant effect of the anesthetic.

The differential pattern of activation of the anterolateral abdominal muscles during graded expiratory threshold loading observed in the present study is consistent with that previously reported during expiratory maneuvers in anesthetized animals (13, 18, 24), awake animals (16), and humans (15). Indeed, the relatively weak level of activation of the rectus abdominis muscle during loading maneuvers and hypercapnia has led some investigators to suggest that this muscle has little respiratory function (24). On the other hand, the transversus abdominis is considered to be a primary respiratory muscle because it is active during eupnea as well as a variety of other conditions (15, 16, 18, 24, 36). Our results show clear differences in regulation of motor drive to abdominal muscles between expiratory loading and cough. The anterolateral abdominal muscles behave much more like a unit during cough than during expiratory loading. DeTroyer et al. (15) concluded that the anterolateral abdominal muscles in the human tend to contract in concert during cough and other maneuvers that were produced voluntarily, whereas involuntary maneuvers, such as hypercapnia and respiratory loading, were associated with a differential pattern of recruitment of these muscles. Our results, consistent with this report, were obtained when cough was elicited by mechanical stimulation of the intrathoracic airway. Therefore, we do not believe that the differences in abdominal muscle recruitment patterns between cough and expiratory loading are due to voluntary or involuntary activation but are more likely due to changes in neural pattern generation. The abdominal muscle activation patterns are appropriate for a given behavior. For example, the very large gastric pressures necessary to support cough airflows [that rise as high as 12 l/s in humans (29)] require vigorous and relatively synchronous activation of all the anterolateral abdominal muscles. In contrast, behaviors that do not require large gastric pressure changes, such as active expiration during eupnea or changes in posture, can be accomplished without synchronous recruitment of all of these muscles.

Our results suggest that each of the anterolateral abdominal muscles contributes to the increased gastric pressure during cough. The EMG amplitudes of each muscle were directly related to gastric pressure during cough. However, during expiratory threshold loading, only the internal oblique and transversus abdominis muscles had discharge patterns that were related to gastric pressure, in part because the rectus abdominis and external oblique muscles were not consistently activated during this maneuver. Previous studies have shown that stimulation of the rectus abdominis and external oblique muscles can increase abdominal pressure in animals and humans (17, 31). These two muscles can have complex actions on the lower rib cage depending on their level of activation (17, 31). The extent to which the function of the rectus abdominis and external oblique muscles during cough involves modulation of lower rib cage shape or stiffness in addition to increasing abdominal pressure is unknown.

In these studies, expiratory airflow was directed out of the tracheal cannula, so there was no mechanical compression phase during cough. The extent to which the abdominal muscle EMG and gastric pressure patterns during cough may have been different if the trachea had been intact in these experiments is unknown. However, humans with tracheostomies can still cough effectively (21). Indeed, Sant’Ambrogio and coworkers (33) have shown that the motor pattern for laryngeal muscles during tracheobronchial cough is not altered when the larynx is bypassed. The level of activation of the anterolateral abdominal muscles is known to be affected by posture, with greater activation of these muscles in the prone or head-up position (14, 19, 24). The present experiments were conducted in supine animals. It is, therefore, possible that greater levels of activation of these muscles could have been observed if the animals were suspended in the prone position. However, it should be noted that the magnitude of postural enhancement of abdominal muscle discharge in most cases is considerably less than the maximum produced during 20- to 25-cmH2O expiratory threshold loading (14, 19, 24). Given that our results show that the magnitude of EMG activity of the anterolateral abdominal muscles during cough is larger than that observed during large expiratory threshold loads, it is difficult to predict the postural effects during cough.

In summary, EMG burst amplitudes of the anterolateral abdominal muscles and gastric pressures were
much greater during tracheobronchial or laryngeal cough than during expiratory threshold loading. Differential activation of the anterolateral abdominal muscles was observed during expiratory threshold loading, whereas these muscles were activated simultaneously and to approximately the same extent during cough. In contrast to expiratory threshold loading, EMG amplitudes of all of these muscles were positively correlated with gastric pressures during cough. Our results suggest that the anterolateral muscles are activated as a unit during cough and that this pattern of activation is appropriate for generation of the large gastric pressures necessary to produce this defensive reflex.

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