Chest wall muscle cross talk in canine costal diaphragm electromyogram

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Sinderby, C., S. Friberg, N. Comtois, and A. Grassino. Chest wall muscle cross talk in the canine costal diaphragm electromyogram. J. Appl. Physiol. 81(5): 2312–2327, 1996.—The present paper describes the influence of cross talk from the abdominal and intercostal muscles on the canine dia-
phragm electromyogram (EMG). The diaphragm EMG was recorded with bipolar surface electrodes placed on the costal portion of the diaphragm (abdominal side), aligned in the fiber direction, and positioned in a region with a relatively low density of motor end plates. The results indicated that cross talk may occur in the diaphragm EMG, especially during conditions of loaded breathing and light general anesthesia. The cross-talk signals showed characteristics that were entirely different from the diaphragm EMG. Although the diaphragm EMG was typical for signals recorded with electrodes aligned in the fiber direction, the cross-talk signals were characteristic of those obtained with electrode pairs not aligned in the direction of the muscle fibers. Alterations in electrode positioning, interelectrode distance, and/or electrode surface area cannot guarantee the elimination of cross-talk signals, whereas spinal anesthesia at a high thoracic level will paralyze the sources of the cross talk and hence eliminate the cross-talk signals. By taking advantage of the differences in EMG signal characteristics for the diaphragm EMG and cross-talk signals, an index that has the capability to detect cross talk was developed.

electromyogram electrodes; spinal anesthesia; muscle fiber conduction velocity; power spectrum center frequency

SURFACE ELECTROMYOGRAM (EMG) recordings reflect the physiological properties of the muscle fiber (e.g., action potential conduction velocity) (16) and the motor unit (e.g., temporal/spatial summation of signals generated by fibers within a motor unit or summation of motor unit signals during increased activation) (14). However, analysis and interpretation of the surface EMG can easily be confounded if the recorded EMG signal of interest is contaminated by nonphysiological signals (24) or by signals originating from muscles located adjacent to the muscle under investigation, so-called cross-talk signals (18). The strength of the cross-talk signal is theoretically described to be related to the distance between the muscle where the cross talk originates and the recording site on the muscle under investigation (15) and to the electrode size and interelectrode spacing (8, 17).

In humans, there is evidence that EMG signals of the voluntarily activated diaphragm can be recorded with surface electrodes placed on the lower rib cage, as seen in subjects with spinal cord injury, i.e., absence of voluntary abdominal and intercostal muscle activity (9). Furthermore, diaphragm compound muscle action potentials evoked by phrenic nerve stimulation are routinely measured with electrodes on the lower rib cage in humans. However, to our knowledge, no studies investigating the influence of cross talk from intercos-
tal and abdominal muscles on the costal diaphragm EMG are available in the literature. The present paper describes the influence and characteristics of cross-talk signals originating from abdominal and intercostal muscles when measured with bipolar electrodes placed directly on the abdominal side (internally) of the costal diaphragm in dogs. The canine model is suitable for this type of investigation because it allows for strategic isolation of signals from abdominal and intercostal muscles from that of the diaphragm by denervation of the diaphragm and nerve blockade of the intercostal and abdominal muscles. The specific aims of the present paper are fourfold. The first is to investigate whether cross talk from the intercostal and abdominal muscles is present in surface recordings of the canine costal diaphragm EMG, and, if so, the second aim is to describe the characteristics of the cross-talk signal. The third aim, assuming that cross talk is present, is to evaluate whether the magnitude of the cross talk can be reduced or eliminated by alterations in electrode positioning, interelectrode distance (IED), and/or electrode surface area. The fourth aim is to find methods to quantify the influence of cross-talk signals on the canine costal diaphragm EMG.

METHODS
Definitions

For clarity, the diaphragm EMG that is free from cross talk is referred to as EMGdi. Cross-talk signals (free of EMGdi) are referred to as EMGxtlk. The term EMG is used to describe recorded signals that may or may not be influenced by cross talk.
CROSS TALK IN CANINE COSTAL DIAPHRAGM EMG

Standard Methods

All experiments were performed on mongrel dogs under general anesthesia with pentobarbital sodium. The initial dose was 25 mg/kg and the animals were kept at a deep level of anesthesia (absence of corneal reflex) during surgery. The levels of anesthesia maintained while the actual protocols were performed are described separately for each protocol. The EMG was recorded with an array of electrode pairs mounted on a polyethylene catheter that was placed directly on the diaphragm (internally from the abdominal side). The size of the surface area of the electrodes and the IED are described separately for each protocol. The EMG electrode catheter was always in the direction of the muscle fibers, in a region with a low density of motor end plates. To ensure that the EMG electrodes remained in position, the EMG electrode catheter was inserted in a tunnel created between the diaphragm and its fascia with a blunt instrument (1.5 mm in diameter). To allow for diaphragm shortening, the length of the myofascial tunnel was made 10 mm longer than the distance between the tip of the catheter and the most proximal electrode. Determination of the regions with a low density of motor end plates was accomplished 1) with low-voltage stimulation (0.5 V) at 5 Hz with a stimulus duration of 0.25 ms and 2) by the expected signal characteristics for a bipolar electrode aligned in the fiber direction and in a region with a low density of motor end plates (see below).

All EMG signals were amplified and band-pass filtered between 16 and 1,600 Hz (model TE4, TECA). Signals were converted from analog to digital (12-bit accuracy; DT 2821, Data Translation) and acquired at 4 kHz into an IBM-compatible personal computer for analysis and storage. The EMG was recorded with an array of electrode pairs mounted on a polyethylene catheter that was placed directly on the diaphragm (internally from the abdominal side). The size of the surface area of the electrodes and the IED are described separately for each protocol. The EMG electrode catheter was always in the direction of the muscle fibers, in a region with a low density of motor end plates. To ensure that the EMG electrodes remained in position, the EMG electrode catheter was inserted in a tunnel created between the diaphragm and its fascia with a blunt instrument (1.5 mm in diameter). To allow for diaphragm shortening, the length of the myofascial tunnel was made 10 mm longer than the distance between the tip of the catheter and the most proximal electrode. Determination of the regions with a low density of motor end plates was accomplished 1) with low-voltage stimulation (0.5 V) at 5 Hz with a stimulus duration of 0.25 ms and 2) by the expected signal characteristics for a bipolar electrode aligned in the fiber direction and in a region with a low density of motor end plates (see below).

All EMG signals were amplified and band-pass filtered between 16 and 1,600 Hz (model TE4, TECA). Signals were converted from analog to digital (12-bit accuracy; DT 2821, Data Translation) and acquired at 4 kHz into an IBM-compatible personal computer for analysis and storage. The EMG analysis was performed with automated computer algorithms, as previously described (24). In brief, EMG samples were automatically selected between 25 and 75% of the root mean square (RMS) as

\[ M_n = \sum_{i=0}^{n_{max}} \text{power density}_i \cdot \text{frequency}_i \]

where \( i \) is the index over which the power frequency product is summed, \( i = 0 \) is the direct current component, and \( n_{max} \) is the index associated with the highest frequency in the spectrum.

The power spectrum center frequency (CF) was calculated as

\[ M_1/M_0 \]

and the root mean square (RMS) as

\[ (M_0/p)^{1/2} \]

where \( p \) is the number of data points in the signal, not including zero padding.

Evaluation of EMG signal contamination was performed by four previously described indexes (1, 24) quantifying 1) the signal-to-noise ratio (SNR = \( \sigma / \rho \)), 2) the signal-to-electrode motion artifact ratio (SMR = \( \sigma / \rho \)), 3) the power spectrum drop in power density ratio (PD = \( \sigma / \rho \)), and 4) the spectral deformation ratio (SD = \( \sigma / \rho \)). Only signal samples that passed the inclusion criteria were used in the analysis.

Spinal anesthesia. Spinal anesthesia was used in the present study as a means to isolate diaphragmatic EMG by eliminating the activity of the abdominal and intercostal muscles. With the dog lying in lateral decubitus in a flexed position with its head and neck elevated, a 20-gauge spinal anesthetic needle was introduced into the lumbar region. When a clear flow of cerebrospinal fluid was obtained from the needle, a hyperbaric tetracaine solution was injected. The injection of tetracaine was halted when the intercostal EMG activity was abolished below intercostal spaces 3–4 (as determined by a needle electrode recording from the parasternals). With the head and neck elevated, the animal was then turned over to the supine position.

Unilateral phrenicotomy. Unilateral phrenicotomy was used in the present study as a means to isolate intercostal and abdominal muscle EMG (EMGxtk) by eliminating EMGdi. Unilateral phrenicotomy was performed via a small incision at the top of the sternum, and through this opening, the right or left side phrenic nerve was exposed and cut. To ensure that the phrenicotomy was successful, all experiments that involved phrenicotomy were followed by a spinal anesthesia. The phrenicotomy was regarded as successful if, after spinal anesthesia, diaphragm EMG activity was present on the side with intact phrenic innervation and absent on the phrenicotomy side. After the phrenicotomy, the pneumothorax was reversed by suction via two tubes left inside the thorax.

Signal Characteristics of EMG Obtained With Bipolar Surface Electrodes

This section (theoretical) and Fig. 1 (illustration) describe the relevant EMG signal characteristics for bipolar surface electrodes positioned in the direction of the muscle fibers in a region with a low density of motor end plates. A schematic representation of an electrode array consisting of one electrode pair with 10-mm IED and two electrode pairs of 5-mm IED is shown in Fig. 1. For this illustration, each electrode ring (stainless steel) was 1.2 mm in width and 1.5 mm in diameter.

First signal characteristic. A bipolar electrode with the electrode plates lined up in the direction of the muscle fibers and positioned in a region with a low density of motor end plates has a spectral transfer function that is proportional to

\[ \sin(\omega d/v) \]

where \( \omega \) is the angular frequency, \( (\omega = 2\pi f) \) is frequency in Hz, \( d \) is one-half the distance between the electrode plates, and \( v \) is the conduction velocity. A detailed derivation of the expression for the bipolar electrode transfer function can be found in Ref. 15. The \( \sin(\omega d/v) \) function indicates a high-pass filtering of the signal and the occurrence of “dips” in the power spectrum, i.e., regions of low spectral density where the \( \sin(\omega d/v) \) function attains low or zero values. Mathematically, we have the condition

\[ \sin(\omega d/v) \approx 0 \]

that is fulfilled when the argument is

\[ \omega d/v = k\pi, \hspace{1em} k = 0, 1, 2, \ldots \]

where \( k \) is an integer representing the number of the dip.

For the dip of order \( k = 1 \), we find the dip frequency

\[ f_{dp} = \omega d/2\pi \]

or, rearranged

\[ v = f_{dp}d \]

which was used to determine the mean action potential conduction velocity (APCVdp).
APCV is calculated as the product of the frequency of the first dip (in Hz) times the IED (in m). The position of the dips was determined by fitting the theoretical bipolar electrode transfer function to the averaged power spectrums (23). This fit was manually adjusted by visual inspection of power spectrums with a frequency range of 10–1,000 Hz displayed on a computer monitor.

Second signal characteristic. Surface EMG signals obtained with bipolar electrodes positioned in the fiber direction placed in a region with a low density of end plates should provide cross-correlograms with maximum (peak) correlations (r value) at a time delay clearly different from 0 ms, as indicated in the center of Fig. 1. The cross-correlogram presented in the center of Fig. 1 was obtained by cross-correlating the signals from the two 5-mm IED pairs. The time delay at which the cross-correlogram peaks can be used to evaluate APCV, which is the distance between the center of electrode pairs/time delay at which the peak occurs.

In the present study, cross-correlograms were obtained by repetitive cross-correlation of two interference pattern signals (obtained at 2 different positions on the muscle) while successively shifting the time delay between the signals. APCV values obtained from the cross-correlation and the dip methods were expected to be similar.

If the electrode pairs are aligned perpendicular to the fiber direction, the signals will occur at all electrode pairs at the same time and the highest of cross-correlation coefficients will be detected close to zero time delay.

Third signal characteristic. Single motor unit action potentials (MUAPs), obtained from two consecutive electrode pairs positioned in the fiber direction and in a region with a low density of end plates, should show a time delay between the signals, as indicated in the blow up of the MUAPs in Fig. 1. The time delay between the two MUAPs can be used to evaluate MUAP conduction velocity, which is the distance between the center of electrode pairs/time delay.
RESULTS

Evidence of Cross Talk: Phrenicotomy Model

To determine whether cross-talk signals from the intercostal and abdominal muscles are present in surface recordings of the diaphragm EMG, we studied two animals before and after unilateral phrenicotomy, with EMG catheter electrodes implanted in the left and right sides of the zone of apposition of the costal diaphragm. The phrenicotomy was performed on different sides in the two dogs. In both animals, the EMG was recorded during quiet breathing directly before and after the phrenicotomy under conditions of light anesthesia (presence of corneal reflex), with two electrode pairs (5 mm center-to-center distance between electrode pairs) on the same array, each of 2-mm IED as depicted on the left side of Fig. 2. Each electrode ring (stainless steel) was 1.2 mm in width and 1.5 mm in diameter. CF values were obtained with a 10-mm IED.

In the two animals, EMG activity was present during both inspiration and expiration, both before and after the phrenicotomy. Spinal anesthesia at the end of the protocol abolished all EMG activity. Figure 2 illustrates a 150-ms example of the raw signal before and after phrenicotomy. The EMG samples in this illustration were normalized by dividing the signal amplitude by the sum of the rectified signal calculated for each of the 150-ms segments depicted. As demonstrated in Fig. 2, before phrenicotomy, cross-correlograms demonstrated clear time delays (different from 0) during inspiration only. The cross-correlograms in Fig. 2 represent the 99% confidence interval around the mean for 120 s of quiet breathing. The cross-correlograms obtained during expiration before the phrenicotomy, as well as during inspiration and expiration after the phrenicotomy, did not demonstrate any conduction velocity-related time delays. CF values, as obtained with the 10-mm IED (mean ± 95% confidence interval for 120 s of quiet breathing), were >30 Hz higher during inspiration before phrenicotomy than during the other periods.

Evidence of Cross Talk: Spinal Anesthesia Model

In the previous phrenicotomy model, activity of the intercostal muscles was forced to increase, even during quiet breathing, and could be detected with the EMG electrodes on the surface of the diaphragm. In the present spinal anesthesia model, where intercostal and abdominal muscle activity are eliminated, we wanted to see whether the presence or absence of cross talk was related to the level of central anesthesia. We therefore compared the EMG obtained before and after spinal anesthesia. In one dog, the EMG was recorded under conditions of light anesthesia (presence of corneal...
The other dog was anesthetized deeply (absence of corneal reflex). The electrodes were implanted in the left side of the zone of apposition of the costal diaphragm. The EMG was recorded during quiet breathing, from two electrode pairs, each of 5-mm IED, on the same array as illustrated in Fig. 3. Each electrode ring (stainless steel) was 1.2 mm in width and 1.5 mm in diameter.

The dog observed under conditions of light anesthesia showed EMG activity during both inspiration and expiration before, but not after, the spinal anesthesia, as demonstrated by the raw signals in Fig. 3, top. Similar to what was found during the phrenicotomy protocol (Fig. 2), the cross-correlograms obtained during expiration before spinal anesthesia (Fig. 3) did not indicate the expected time delay between signals from the two electrode pairs. In addition, CF values obtained during expiration were lower than during inspiration, as indicated in Fig. 3. During inspiration, CF values obtained before the spinal anesthesia (Fig. 3) were >100 Hz lower than those obtained after the spinal anesthesia. The cross-correlogram obtained for the signals during inspiration before spinal anesthesia indicated an \( A_{PCV} \) value higher than those obtained after the spinal anesthesia. Note that the cross-correlograms obtained after spinal anesthesia have become double-peaked (probably due to recruitment of additional motor units), indicating the bidirectional propagation of MUAPs under the electrode pairs (23). The indications of a difference in \( A_{PCV} \) from before to after the spinal anesthesia could not be confirmed by the power spectrum dip method. Figure 4 shows the averaged power spectrums obtained from the 120-s period of quiet breathing during inspiration and expiration before spinal anesthesia and during inspiration after spinal anesthesia. The superimposed power spectrums in Fig. 4 show that the position of the first dip for the spectrums obtained during inspiration is similar before and after spinal anesthesia, whereas dips were not observed in the spectrum obtained during expiration. From the power spectrums shown in Fig. 4, it is evident that the lower CF values found during inspiration before spinal anesthesia are due to the addition of power density in the low-frequency region that corresponds to the distribution of power density in the spectrum obtained during expiration before spinal anesthesia.

In contrast to the dog studied under light anesthesia, the deeply anesthetized dog (data not presented) did not show any expiratory EMG activity. In the deeply anesthetized dog, we found no differences between averaged power spectrum or cross-correlograms ob-

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**Fig. 3.** Costal diaphragm EMG recorded from zone of apposition during quiet breathing in 1 dog under light anesthesia (presence of corneal reflex), with electrode configuration shown in top left. Electrode rings were aligned in same direction as diaphragm fibers and positioned in region with relatively low density of motor end plates. Two and a half-second examples of raw signals obtained before and after spinal anesthesia are shown together with cross-correlograms obtained between electrocardiograms (ECGs) from time domain signals shown directly below each cross-correlogram. CF values obtained between ECGs before (circles) and after (squares) spinal anesthesia are shown in bottom.
tained during periods (120 s) of quiet breathing before and after spinal anesthesia, suggesting that cross-talk signals were not influencing the diaphragm EMG signals in the deeply anesthetized animal.

Influence of Changing Electrode Configuration: Effects of Size and Spacing

Based on the above results, it appears that cross talk can be present in the EMG recorded from the zone of apposition. The following protocol was designed to test whether cross-talk signals could be avoided by decreasing the IED, i.e., the distance between rings (center to center) forming one electrode pair and electrode surface area, i.e., the size of each ring forming an electrode pair.

The effect of decreasing the IED from 10 to 6 to 2 mm on the EMG obtained with electrodes in the zone of apposition of the costal diaphragm was studied before and after unilateral phrenicotomy in two dogs. The phrenicotomy was performed on different sides in the two dogs. The electrode array configuration is depicted in the lower left corner on Fig. 5. Each electrode ring (stainless steel) was 1.2 mm in width and 1.5 mm in diameter.

In addition, electrode pairs with 2-mm IED, but with different surface areas, were implanted in the zone of apposition of the costal diaphragm. The electrode pairs with different surface areas consisted of single-filament copper wires (200 µm in diameter) wrapped around a polyethylene catheter (1.3 mm in diameter). The surface area was increased by increasing the number of turns of wire from 1 to 3 to 6. Each electrode pair was offset by 2 mm.

All signals were recorded during quiet breathing (120 s) with the dogs deeply anesthetized (absence of corneal reflex). Before the phrenicotomy, power spectrum dips occurred at mean action potential conduction velocity-related frequencies (see First signal characteristic in METHODS), and no expiratory activity could be detected. Cross-correlograms obtained between the signals for the electrode pair with one turn of wire and the electrode pair with six turns of wire (yielding 8-mm distance between the center of the 2 pairs) clearly indicated a mean action potential conduction velocity time-related delay of ~3.7 m/s.

Figure 5 shows the effect of decreasing the IED on the magnitude of EMGx/t, as obtained in one dog. Similar results were obtained in the other dog. Figure 5 also shows that the amplitude of the raw EMG during inspiration (500 ms) decreased progressively with reductions in IED, both before and after the phrenicotomy. Note that signals for all IEDs were normalized to the sum of the 500-ms-long rectified signal, obtained with the 10-mm IED, before and after phrenicotomy, respec-
tively. As illustrated in Fig. 5, the reduction in RMS with smaller IEDs (mean ± 95% confidence interval) was less before the phrenicotomy than after, implying that reducing the IED results in a filtering out of power relatively more for the EMGxtlk signals than the EMGdi signals. Different filtering effects before and after phrenicotomy were also observed in terms of the CF values (mean ± 95% confidence interval), where, before phrenicotomy, CF values progressively increased with reductions in IED (as predicted by the bipolar electrode transfer function described in METHODS). After phrenicotomy, CF values were similar for all IEDs, indicating that EMGxtlk signals did not obey the bipolar electrode transfer function (Fig. 5). The different filtering effects for EMGxtlk and EMGdi are also illustrated in Fig. 5 in terms of the difference in power between two averaged power spectrums (10- and 6-mm IED) obtained before and after phrenicotomy. Right: change in CF values and reduction in RMS with smaller IEDs (mean ± 95% confidence interval).

With respect to changes in electrode surface area, we were not able to detect any systematic differences for either CF or RMS values in the two dogs.

Spinal anesthesia at the end of the experiment abolished all EMG signals on the side where the phrenic nerve had been cut.

Influence of Increasing Distance Between Electrode Pairs and Intercostal and Abdominal Muscles

Two deeply anesthetized dogs (absence of corneal reflex) were studied before spinal anesthesia during 1) quiet breathing, 2) breathing with expiratory and/or inspiratory loads, 3) recovery after removal of the loads and 4) after spinal anesthesia during quiet breathing. The loads (resistance of −200 cmH2O·l−1·s) were progressively imposed in the order presented below. Two pairs of electrodes with 2-mm IED were mounted 5...
mm apart (center to center) on the catheter (Fig. 6). Each electrode ring (stainless steel) was 1.2 mm in width and 1.5 mm in diameter. The array electrode was implanted close to the central tendon, which should represent the maximum distance between the intercostal/abdominal muscles and the electrode array. The electrode array was implanted on the left side in one animal and on the right side in the other.

Figure 6 shows a raw EMG signal (4 s) in response to quiet breathing and breathing against an expiratory load, against both an inspiratory and an expiratory load, during recovery after removal of the load, and after the spinal anesthesia. Cross-correlograms are presented for signals between each QRS complex to indicate the time delay between signals. Similar results were observed in the two dogs.

During quiet breathing (Fig. 6, top), EMG signals measured from the surface of the diaphragm did not indicate the presence of expiratory muscle activity. The peak of the cross-correlograms obtained during inspiration were much different from zero, indicating the lack of cross talk during quiet breathing in this animal. With application of the expiratory load, expiratory muscle activity increased, as indicated by the raw EMG signals. The cross-correlograms peaked at zero time delay, indicating that EMG signals were still being picked up by the electrodes that were close to the central tendon. During inspiration, the shape and time delays of the cross-correlograms of the second electrode were similar to those obtained during the period of quiet breathing, implying that there was no influence of cross talk. After the removal of the inspiratory and expiratory loads, a period of hyperpnea followed, and a continuous alteration in the shape and time delays of the cross-correlograms could be observed during inspiration and expiration. After the spinal anesthesia, a prolongation in the inspiratory time was observed, and the cross-correlograms peaked at higher values, although their general shape remained the same as that observed during the preceding conditions.

**Fig. 6.** Time domain EMG signals and cross-correlograms (obtained between ECGs) obtained from 2 electrode pairs (top left) positioned close to central tendon in 1 deeply anesthetized dog. Electrode rings were aligned in direction of diaphragm fibers and positioned in a region with relatively low density of motor end plates. This electrode position represents maximum distance between intercostal/abdominal muscles and electrode array. Top: signals recorded before spinal anesthesia during quiet breathing, breathing with expiratory and/or inspiratory loads, and recovery after removal of loads. Bottom: quiet breathing after spinal anesthesia.
These results imply that although the largest distance (~2 cm) to the intercostal and abdominal muscles was achieved and the small IED of 2 mm was used, EMGxtlk signals (during expiration) were still present during higher levels of ventilation, as judged by the presence of expiratory activity with no time delay between signals from two adjacent electrode pairs.

Quantification of Cross Talk: Signal Influence in Canine Costal Diaphragm EMG

As described above, adjacent muscle cross talk appears to be difficult to avoid during light anesthesia (presence of corneal reflex) as well as during diaphragm loading. There is strong evidence to suggest that the characteristics of EMGxtlk signals are different from EMGdi signals obtained from the diaphragm with electrodes positioned in the fiber direction and hence, the muscle fibers producing the EMGxtlk cannot be parallel to the bipolar electrodes. The evidence includes 1) cross-correlograms that peak at zero time delay (Figs. 2, 3, 6), 2) the absence of dips in the power spectrum (Fig. 4), 3) there is no effect of decreasing the IED on CF (Fig. 5), and 4) there is a similar reduction in power at all frequencies with reductions in IED (Fig. 5). We therefore decided to take advantage of the differences in signal characteristics (for EMGdi obtained along the fiber direction and EMGxtlk not obtained along the fiber direction) to address the following question: can the magnitude of cross talk be quantified?

The electrode array used in this protocol consisted of three electrode pairs (5-mm IED) (Fig. 7) and was implanted in the zone of apposition of the costal diaphragm. Each electrode ring (stainless steel) was 1.2 mm in width and 1.5 mm in diameter. Five dogs were studied both before and after spinal anesthesia. Based on the above findings, the EMG recorded during expiration and before spinal anesthesia was considered to represent EMGxtlk signals, whereas the EMG recorded during inspiration and after spinal anesthesia was considered to represent EMGdi signals.

On the basis of the assumption that EMGxtlk signals occur as “common mode” signals for all electrode pairs on the same array (positioned along the diaphragm fibers), it should be possible to differentiate between signals with common mode characteristics and those that have a time delay related to propagation of action potentials along the muscle fibers. For instance, if two common mode MUAPs with zero time delay are subtracted, the residual signal amplitude should be reduced/abolished [channel (Ch.) A - Ch. B, Fig. 7, right]. This is not the case if the two recorded signals are delayed in time (Ch. A - Ch. B, Fig. 7, left; time delay = 1.6 ms). Addition of two common mode MUAPs that are propagating along the fiber direction with a time delay of 1.6 ms (Ch. A + Ch. B, Fig. 7, right) will produce a signal with a higher amplitude (Ch. A + Ch. B, Fig. 7, right) than addition of two MUAPs that are propagating along the fiber direction with no time delay (Ch. A + Ch. B, Fig. 7, left). We therefore expect, for two signals obtained from the diaphragm with electrodes aligned in the fiber direction, that the resulting signal after subtraction (e.g., Ch. A - Ch. B) will contain minimal amounts of cross talk compared with the original signals. This is compared with the addition of two signals, where the resulting signal should contain relatively more amounts of cross talk with respect to the original signals.

When using an electrode array consisting of three pairs of electrodes (Fig. 7), we can obtain two subtracted signals, i.e., A - B and B - C. Cross-correlation of these two subtracted signals will yield a cross-
A correlogram that peaks at a time delay mostly representative of the propagation of diaphragm action potentials (since the initial subtraction resulted in a reduction of the cross-talk influence). Conversely, cross-correlation of the two added signals, i.e., $A + B$ and $B + C$, will yield a cross-correlogram that is relatively more influenced by cross talk, i.e., peaks at or close to zero time delay.

To test this hypothesis, we mixed EMGdi signals (obtained after spinal anesthesia with EMGxtlk signals (obtained during expiration before spinal anesthesia) while progressively increasing the amount of EMGxtlk power (by multiplying the signal by 0 to $\infty$), thereby allowing the quantification of EMGdi/EMGxtlk for each level of increase in EMGxtlk power. As well, cross-correlograms were computed for correlation of signals from electrode pairs: $A$ vs. $B$, $B$ vs. $C$, $A + B$ vs. $B + C$, and $A - B$ vs. $B - C$ at each level of increasing EMGxtlk.

In Fig. 8, the original EMGdi signals, free from cross talk, from electrode pairs Ch. A, B, and C are illustrated (see electrode configuration in Fig. 7). Note that the EMGdi for all three electrode pairs consisted of a single biphasic MUAP. Figure 8, top, is a presentation of EMG signals with a progressive increase in the EMGdi/EMGxtlk ratio: 30, 0, and $-20$ dB. Figure 8, middle and bottom, show the same information when adding ($A + B$, $B + C$) or subtracting ($A - B$, $B - C$) the MUAPs. Note in Fig. 8 that the signal amplitude can only be compared for the same EMGdi/EMGxtlk value, since panels of different EMGdi/EMGxtlk had to be rescaled to fit into the graph. To the right of the MUAPs (Fig. 8) are the cross-correlograms obtained for correlation of signals from electrode pairs $A$ vs. $B$ and $B$ vs. $C$ (top), $A + B$ vs. $B + C$ (middle), and $A - B$ vs. $B - C$ (bottom) for the three different EMGdi/EMGxtlk values (30, 0, and $-20$ dB).

For the signals that are relatively free from EMGxtlk (30 dB), the raw signals in Fig. 8, middle, show that the added MUAPs ($A + B$, $B + C$) maintain their biphasic waveform, with a modest increase in amplitude and duration, a phenomenon that can be attributed the effective increase in IED. The effect of adding the MUAPs can also be observed as a relative broadening of the cross-correlogram obtained between the added signals ($A + B$ vs. $B + C$) compared with the cross-correlogram obtained between the original signals. The subtracted MUAPs ($A - B$, $B - C$) become triphasic in shape and show a significant increase in amplitude, demonstrating a more complex effect due to the double differentiation of the MUAPs. The cross-correlogram obtained for the subtracted signals ($A - B$ vs. $B - C$) remains as peaked as the cross-correlograms obtained.

Fig. 8. Effect of adding EMGxtlk to MUAP of diaphragm EMG on raw signals and cross-correlograms (x-axes = time delay; y-axes = correlation coefficient) obtained with different electrode pair combinations i.e., $A$ vs. $B$, $B$ vs. $C$, $A + B$ vs. $B + C$, or $A - B$ vs. $B - C$. EMG signals and cross-correlograms are representative for EMGdi/EMGxtlk values of 30, 0, and $-20$ dB. Note that while cross-correlograms obtained for $A$ vs. $B$, $B$ vs. $C$, $A + B$ vs. $B + C$ (middle and top) move their peaks toward 0 time delay, cross-correlograms obtained for $A - B$ vs. $B - C$ remain relatively unaltered (bottom).
for the original signals; however, the negative deflections are more enhanced.

The raw EMG tracings in Fig. 8, center (EMGdi/EMGxtlk of 0 dB) and right (EMGdi/EMGxtlk of −20 dB) confirm our expectation of an amplification of the EMGxtlk signals relatively more for the added signals (middle) with respect to the original signals (top). The subtracted signals did not demonstrate the presence of EMGxtlk. Regarding the influence of EMGxtlk on the cross-correlograms, the correlograms of the original and added signals progressively moved their peaks toward the zero time offset as the amount of EMGxtlk increased. In contrast, the cross-correlograms for the subtracted signals do not change for the same increase in EMGxtlk. Although not illustrated, the same findings were obtained for triphasic MUAPs; however, it was noted that the waveforms of the subtracted MUAPs tended to attain a biphasic waveform.

In a three-dimensional perspective (Fig. 9), the dynamics of a progressive decrease in EMGdi/EMGxtlk on the cross-correlogram for single biphasic and triphasic MUAPs are presented. The x-axes indicate the time delay between cross-correlated signals (−5 to 5 ms), the y-axes represent EMGdi/EMGxtlk, with progressively decreasing values from 30 to −20 dB, and the z-axes show the correlation coefficients (scale = −1 to 1) for each time delay between signals at each EMGdi/EMGxtlk. With respect to the cross-correlation obtained for the original (A vs. B and B vs. C) and the added (A + B vs. B + C) signals, it was evident that decreasing EMGdi/EMGxtlk induced a progressive shift of the cross-correlogram symmetry, where the peak r value moved toward the zero time delay. The rate of change of the time delay (of the peak r value) was highest between EMGdi/EMGxtlk of 10 and −10 dB. Regarding the cross-correlograms obtained for the subtracted signals, decreasing the EMGdi/EMGxtlk did not alter their symmetry.

As described in Fig. 3, the interference pattern EMGdi does not necessarily provide a cross-correlogram with one distinct peak, as is the case for single MUAPs. Due to the distribution of motor end plates in the canine diaphragm, one frequently obtains cross-correlograms that contain two peaks, one at a negative and one at a positive time delay. The cause of this is most likely because the electrode array covers diaphragmatic fibers in which the end plates are located beyond either end of the array and, hence, MUAPs will propagate in opposite directions under the electrode (23).

We therefore evaluated how bidirectional propagation of MUAPs would affect the symmetry of the cross-correlogram for interference pattern EMG when EMGdi/EMGxtlk values were progressively decreased (i.e., relative increases in cross talk). Figure 10 describes the results on the EMG interference pattern obtained in five dogs. The x-axes indicate the time delay between signals (−5 to 5 ms), the y-axes represent progressively decreasing EMGdi/EMGxtlk values from 30 to −20 dB, and the z-axes show the correlation coefficients (scale = −1 to 1) for each time delay between signals at each EMGdi/EMGxtlk.

As depicted in Fig. 10, the cross-correlograms of the interference pattern EMG signals (A vs. B and B vs. C) sometimes had different shape at high EMGdi/EMGxtlk values (up front) than the cross-correlograms found for the single MUAPs in Fig. 9. For example, the cross-correlograms obtained in animals 2 and 4 indicate two peaks for the cross-correlograms for the original signals (A vs. B and B vs. C) but barely indicate peaks for the added signals (A + B vs. B + C). This increased variation in symmetry was likely due to the interference of bidirectionally propagating MUAPs and/or the influence of certain MUAPs originating from motor end plates located under the electrode.

The influence of decreasing the EMGdi/EMGxtlk value for the interference pattern EMG showed that the peak r values for the original and added signals became progressively more centered toward the zero time delay, although relative to what was found for the MUAPs, it did not appear as a shift but rather as a buildup in the center region (0 time delay) of the
cross-correlogram. The effect of decreasing the EMGdi/EMGxtlk on the subtracted signals (A – B vs. B – C) did not result in any changes of the cross-correlogram symmetry.

Based on these observations, we believe that changes in the r value at the zero time delay could provide the most reliable information about the influence of cross talk. We hypothesized that the difference in r values (at the 0 time delay) between cross-correlograms for the added signals (assumed to be sensitive to changes in EMGdi/EMGxtlk) and the subtracted signals (assumed to represent EMGdi only) should yield an approximation of the EMGxtlk influence.

The results of the testing of this hypothesis are illustrated in Fig. 11, where the actual EMGdi/EMGxtlk values (x-axis) are plotted vs. the difference between (0 time delay) r values of added signals (i.e., A + B vs. B + C) and subtracted signals (A – B vs. B – C) on the y-axis (mean values ± 99% confidence interval). It was evident that the difference between r values for added and subtracted signals [r of (A + B vs. B + C) – r of (A – B vs. B – C)], was influenced by decreasing EMGdi/EMGxtlk from 15 to –10 dB, and was quasilinear between 10 and 0 dB. The 99% confidence interval.
was lowest between 10 and 0 dB, implying that the prediction of the EMGdi/EMGxtlk value within this range is the least erroneous.

To verify anatomically that the fiber direction of the intercostal and abdominal muscles was different from that of the costal diaphragmatic fibers, we performed a dissection of the different muscle layers of the rib cage in two dogs. The dissection preparation from one dog is demonstrated in Fig. 12, which shows the fiber direction of the thoracic and abdominal muscles in relation to the costal diaphragm. Similar fiber directions were found in the second dog. According to Fig. 12, only the direction of the oblique abdominal muscle fibers was similar to that of the costal diaphragm.

DISCUSSION

Presence of Cross Talk

The presence of cross talk from muscles other than the muscle under study has previously been demonstrated in limb muscles in both humans (5, 10–12, 20, 26, 27) and animals (7, 18, 25). According to the results obtained with surface electrodes on calf muscles in humans, DeLuca and Merletti (5) argued that “particular caution should be exercised in interpreting surface recordings of the myoelectric signal when nearby muscles may be active.” Similarly, from the study on hindlimb muscles in adult cats and salamanders, Mangun et al. (18) concluded that “while cross talk may not be present in every recording situation, it is a more significant problem for various electrode types than has generally been considered.”

The evidence of cross talk in limb muscle recordings has been observed for considerable electrode-to-muscle distances, i.e., detection of the quadriceps femoris activity with electrodes placed on the hamstrings muscles (11) or recordings of signals originating in triceps surae with electrodes placed over the tibialis anterior (5, 12). These distances are relatively large compared with those used in the present study, i.e., distance between the EMG electrode array, placed internally in the zone of apposition on the abdominal side of the diaphragm and the abdominal/intercostal muscles. The thickness of the canine costal diaphragm is described to be ~2–3 mm (19), and the size of the intrapleural space is negligible in the zone of apposition region. Hence, all intercostal and abdominal muscles should be located within a 5- to 10-mm distance away from the electrode array when positioned in the zone of apposition region. One should note that the distance of 5–10 mm is equal to the skinfold thickness involved in the surface electrode recordings of limb muscles (4).

Boriek et al. (2) measured costal diaphragm displacement in dogs between functional residual capacity and total lung capacity. Their data indicate that changes in the distance between the chest wall and the costal diaphragm zone of apposition from functional residual capacity to total lung capacity are <2 cm and that the changes in distance between the chest wall and the central tendon can reach up to 3–4 cm during similar changes in lung volume. Considering 3–4 cm as the maximal distance between the chest wall and the EMG electrode array positioned close to the central tendon, it is still a moderate distance compared with the dis-
tances involved in the cross-talk studies performed in human leg muscles. It is therefore not too surprising that cross-talk signals were observed in EMG recordings obtained with electrodes placed close to the central tendon during loaded breathing.

We can conclude that, similar to the conclusions about limb muscle EMG recordings, diaphragm EMG signals should not be assumed to be free from cross talk originating from adjacent muscles. During quiet breathing and deep anesthesia (absence of corneal reflex), cross talk from the intercostal and abdominal muscles appears to be negligible. This is in accordance with the findings of DeTroyer (6), who showed that the intercostal muscles of the caudal rib cage are not recruited when expiratory resistance was applied (Fig. 6) that is likely to have activated the oblique abdominal muscles.

Characteristics of Cross Talk

In the present study, cross-talk signals from the intercostal and/or abdominal muscles were characterized by 1) the peaking of the cross-correlograms at 0 ms time delay (Figs. 2, 3, 6), 2) the absence of dips in the power spectra (Fig. 4), and 3) the lack of a frequency-dependent reduction in power of the spectrum with reductions in IED (Fig. 5). The EMGxtlk characteristics described above provide evidence that the cross-talk signals did not follow the behavior predicted by the bipolar electrode transfer function for electrodes that are aligned in the fiber direction.

Another characteristic feature of the EMGxtlk signals was that they usually had lower CF values than the EMGdi signals (Fig. 2, 3, 5). This is because increasing the muscle-to-electrode distance results in a reduction of signal power in the high-frequency region of the spectrum (15), resulting in low-frequency addition to the signal recorded on the diaphragm.

Hence, the present electrophysiological findings suggest that the characteristics of EMGxtlk signals are different from EMGdi when EMG signals are obtained with bipolar electrodes aligned in the diaphragm fiber direction. The difference between EMGxtlk and EMGdi signals are likely due to the differences in orientation of the diaphragm fibers with respect to the intercostal muscle fibers, as suggested by anatomic evidence.

Control of Cross Talk

The most efficient way to avoid the influence of cross talk from the intercostal and abdominal muscles in the diaphragm EMGdi is to use the spinal anesthesia model. Although spinal anesthesia guaranteed the absence of cross talk from the intercostal and abdominal muscles, not all experimental preparations allow for the spinal anesthesia-induced paralysis of the chest and abdomen and associated loss in sympathetic responses.

The selectivity of a surface electrode, i.e., the area from which the electrode will pick up signals, has been related to the electrode surface area and the IED (8, 17, 28). However, the influence of the electrode size and the IED on the selectivity of the EMG recordings remains to be discussed. Lynn et al. (17), using a two-dimensional conducting paper analog and a three-dimensional field theory model, described that the detection depth was approximately equivalent to the IED and suggested a small influence of electrode size. Recording the biceps muscle EMG with bipolar electrodes of 15, 35, and 150-mm IED, Zipp (28) demonstrated that the intensity of cross talk recorded from the surface of a nonactive muscle is diminished by >50% of its initial value as the IED is reduced. Using a mathematical model for the IEDs of 11–25 mm and an electrode surface area of 4–49 mm², Fuglevand et al. (8) reported that the “variation in electrode surface area has little effect on the detection depth of motor unit action potentials,” and that an "increased interelectrode spacing moderately increases detection depth." Koh and Grabiner (12) reported that decreasing the IED from 20 to 12 mm, for electrodes placed over the tibialis anterior, did not provide a significant reduction of cross-talk signals originating from the triceps surae.

In the present study, the effect of reducing the electrode size did not result in any systematic changes in signal amplitude, either before or after the phrenicotomy, which is in line with the above-listed arguments that a reduction in electrode size has a small influence on the detection depth. With respect to reductions in IED, decreasing the IED from 10 to 2 mm resulted in large decreases in RMS both before and after the phrenicotomy (see Fig. 5). Before the phrenicotomy, the reduction in RMS was due to bipolar electrode filtering (i.e., the signals behaved according to the bipolar electrode transfer function) because the electrode array was oriented in the direction of the fibers. This was supported by the additional finding of an increase in CF values with reductions in IED. After the phrenicotomy, reductions in RMS were somewhat larger, but the filtering effect did alter the frequency content of the signal (as was evident by similar CF values for all IEDs), suggesting the bipolar electrode transfer function no longer held true. Hence, it appears that the influence of reducing IED on the amount of cross talk in the signal is not as straightforward as previously believed, since two different filter functions
are involved: 1) the bipolar electrode transfer function that affects the signals conducting along the fibers and 2) a frequency-independent damping of volume-conducted signals.

Broman et al. (3) were the first to use a second differentiation of differentially recorded (bipolar) signals obtained from two consecutive electrode pairs (the double-differentiation technique) to avoid the influence of cross talk. Broman et al. used an analog technique to obtain the double-differentiated signals, which can be exemplified with our data shown in Fig. 7, bottom, the purpose of which was to remove the volume-conducted signals from the signals that were used in the cross-correlation calculations of the mean muscle fiber action potential conduction velocity. Note that the double-differentiation technique described by Broman et al. requires that signals be recorded with electrodes oriented in the fiber direction and in a region with a low density of motor end plates.

To separate signals conducting along the fibers and volume-conducted signals, Deluca and Merletti (5) used the same technique, in combination with single-differentiated signals and maximal nerve stimulation. They stated that “such a technique allows the cancellation, from the double-differential outputs, of signals simultaneously present on every electrode couple and due to relatively far sources.” Koh and Grabiner (11, 12) demonstrated that the double-differentiation and branched electrode (a scaled version of double differentiation) techniques significantly reduce cross talk between human limb muscles. Koh and Grabiner (11) related the reduction in cross talk to a relatively higher selectivity for the double-differentiated signal compared with the single-differentiated signal. Their statement was based on the works by Reucher and co-workers (21, 22), which demonstrate that the double-differentiation technique provides a high-pass transfer function and hence selects signals of relatively shorter wavelengths than the signals obtained with the single-differentiation technique. A high-pass filtering effect is also obtained with reductions in IED, if the electrode is placed parallel to the fiber direction. Therefore, it was surprising that Koh and Grabiner (12) reported that the method of double differentiation produced the highest elimination of cross talk when the IED was large.

An efficient reduction in cross-talk signal can be obtained by using the double-differentiation technique, and the method is relevant for most applications of signal analysis. Broman et al. (3) used the double-differentiation technique for cross-correlation determination of the signal time lag to determine the mean action potential conduction velocity. Koh and Grabiner (11, 12) calculated the average amplitude values (rectified or peak to peak) and the power spectrum median frequency (MF) for their EMG signals and reported that interday and intraday coefficients of variation were acceptable for both signal amplitude (range 5.9–14.6%) and MF, with IEDs of 20 mm (range 3.9–6.1%). The power spectrum for a double-differentiated signal obtained with electrodes oriented in the direction of the muscle fibers which is also in a region with a low density of motor end plates will have a high-pass filtering of 12 dB/octave and have dips in similar positions as the single-differentiated signal. CF and MF values will be sensitive to changes in conduction velocity as seen with fatigue. The RMS and peak-to-peak amplitude values will also be sensitive to conduction velocity changes.

One of the aims of the present study was to develop a method with 1) the ability to detect cross talk in the EMG signal and 2) the ability to reject signals that are considered to be contaminated. Our EMGdi/EMGxtlk value was based on the concept that the correlation of added signals (A + B vs. B + C) will provide r values at zero time delay that are sensitive to common mode signals, whereas the correlation of subtracted signals (A – B vs. B – C) represents a signal with no common mode influence to be used as a reference. By using the r value for the subtracted signals at zero time delay, the index for evaluating cross talk becomes quite insensitive to variations in the mean action potential conduction velocity, since changes in conduction velocity will induce similar shifts in the cross-correlograms obtained for both the added and subtracted signals. The EMGdi/EMGxtlk ratio made it possible to detect cross talk when the signals of the muscle under study were ~5–10 times larger than the cross-talk signals. The EMGdi/EMGxtlk value was possible to calculate for each selected sample without the use of any reference signals obtained by nerve stimulation. It is our opinion that this method to detect cross talk, in combination with methods to reduce the influence of cross talk by positioning electrodes far away from the cross-talk muscles (i.e., central tendon region) and using relatively small IEDs, will be successful in situations where it is important to keep all muscles intact.

Conclusions

The present study shows that cross-talk signals from the intercostal and abdominal muscles may be present in surface recordings of the diaphragm EMG obtained from the zone of apposition of the costal diaphragm. The characteristics of the cross-talk signals are different from those of the diaphragm EMG and do not follow the behavior predicted by the bipolar electrode transfer function for electrodes that are aligned in the fiber direction. By taking advantage of the difference in characteristics between the cross-talk signals and the diaphragm EMG signals, the magnitude of the cross-talk influence on the diaphragm EMG can be estimated.

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