Enhancement of signal quality in esophageal recordings of diaphragm EMG

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Sinderby, Christer A., Jennifer C. Beck, Lars H. Lindström, and Alejandro E. Grassino. Enhancement of signal quality in esophageal recordings of diaphragm EMG. J. Appl. Physiol. 82(4): 1370–1377, 1997.—The crural diaphragm electromyogram (EMGdi) is recorded from a sheet of muscle, the fiber direction of which is mostly perpendicular to an esophageal bipolar electrode. The region from which the action potentials are elicited, the electrically active region of the diaphragm (EARdi) and the center of this region (EARdir) may vary during voluntary contractions in terms of their position with respect to an esophageal electrode. Depending on the bipolar electrode's position with respect to the EARdir, the EMGdi is filtered to different degrees. The objectives of the present study were to reduce these filtering effects on the EMGdi by developing an analysis algorithm referred to as the “double-subtraction technique.” The results showed that changes in the position of the EARdir by ±5 mm with respect to the electrode pairs located 10 mm caudal and 10 mm cephalad provided a systematic variation in the EMG power spectrum center-frequency values by ±10%. The double-subtraction technique reduced the influence of movement of the EARdir relative to the electrode array on EMG power spectrum center frequency and root mean square values, increased the signal-to-noise ratio by 2 dB, and increased the number of EMG samples that were accepted by the signal quality indexes by 50%.

The electromyogram (EMG) of the human diaphragm is preferably recorded by bipolar electrodes mounted on an esophageal catheter that is positioned at the level of the gastroesophageal junction (10). Since the introduction of esophageal electrodes in the measurement of the human diaphragm EMG over 30 years ago (1, 9), a number of investigators have used the method in the experimental setting to evaluate diaphragm function and fatigue in healthy subjects (e.g., Refs. 6, 8) and in patients with respiratory-related deficiencies (e.g., Refs. 7, 11).

Esophageal recordings of the diaphragm EMG have been criticized because of the difficulties in obtaining signals that are of significant strength and sufficiently free of artifacts. Typical disturbances in esophageal recordings of the diaphragm EMG include noise, electromotion artifacts, esophageal peristalsis, the electrocardiogram (ECG), and other bioelectric sources. These disturbances can be controlled for today by computer algorithms (12). As well, changes in the distance between the diaphragm and the esophageal electrode strongly filter the EMG signal (5), and the bipolar electrode itself imposes a filter on the signal (4). These filtering effects can be minimized if the bipolar electrode position with respect to the diaphragm is controlled for. By implementing a cross-correlation technique, we were able to demonstrate that it is possible to locate the diaphragm's position along a multiple-electrode array for each selected EMG segment (4).

It has been demonstrated that the crural diaphragm EMG is recorded from a sheet of muscle, the fiber direction of which is mostly perpendicular to the bipolar electrodes (4). The diaphragm EMG recorded within this region represents the temporal and spatial summations of signals from asynchronously firing crural diaphragm motor units, and, therefore, during voluntary activity, the crural diaphragm can be considered as an “electrically active region” of the diaphragm (EARdi). The area from which action potentials are elicited may vary within a contraction in terms of position with respect to the esophageal electrode. It can be assumed that within the EARdi, the distribution of the active motor units has an effective center (EARdir), from which the majority of the diaphragm EMG signals originate. Depending on the bipolar electrode's position with respect to the EARdir, the diaphragm EMG is filtered to different degrees (4). The influence of bipolar electrodes oriented perpendicularly to the muscle fiber direction on the diaphragm EMG power spectrum was described to progressively increase the frequency and attenuate the power of the diaphragm EMG signal as the center of an electrode pair moved from 10 mm away from the EARdir toward it (4). More than 10 mm away from the EARdir, both the frequency and power decreased progressively because of muscle-to-electrode distance-filtering effects (5). It was concluded that EMG signals recorded by electrode pairs centered either 10 mm caudal or 10 mm cephalad to the EARdir.
with an array of electrodes with an interelectrode distance of 10 mm, were the least influenced by bipolar electrode filtering and muscle-to-electrode distance-filtering effects (4). The bipolar electrode-filtering effects and the muscle-to-electrode distance-filtering effects can therefore be reduced by using an array of electrode pairs (10 mm interelectrode distance) and by selecting signals 10 mm away from the EAR\(_{\text{distr}}\). Of particular importance for the present paper is that, for the electrode pair lying closest to the EAR\(_{\text{distr}}\), the actual position of the EAR\(_{\text{distr}}\) under that electrode pair can vary during a contraction, and, therefore, will influence the signals above and below relatively more or less. For example, in Fig. 1A, illustrating an array of electrodes with 10-mm interelectrode distance (center), the distance between the EAR\(_{\text{distr}}\) (located under electrode pair 4) and electrode pair 5 is less than the distance between EAR\(_{\text{distr}}\) and electrode pair 3. According to theory (4), signals from electrode pair 5 should show relatively more attenuation of power and higher center frequency (CF) values than electrode pair 3.

Assuming that the influence of the relative movement of the EAR\(_{\text{distr}}\) with respect to the electrode array has a reciprocal effect on the signals cephalad and caudal to the EAR\(_{\text{distr}}\), one possible way to reduce the influence would be to subtract the diaphragm EMG signals from the electrode pairs 10 mm cephalad and 10 mm caudal to the EAR\(_{\text{distr}}\). These two signals are negatively correlated at 0-ms time delay (4) and, hence, subtraction of the polarity-reversed signals will yield an effective summation. We hypothesized that subtraction of the polarity-reversed diaphragm EMG signals from the electrode pairs located 10 mm cephalad and 10 mm caudal to the EAR\(_{\text{distr}}\) would provide a signal that is less influenced by bipolar electrode filtering, and we refer to this method as the "double-subtraction technique." The purpose of the present work, therefore, was to evaluate whether the double-subtraction technique can reduce the effect of movement of the EAR\(_{\text{distr}}\) relative to the electrode array on the diaphragm EMG power spectrum.

**MATERIALS AND METHODS**

**Subjects**

Five healthy subjects volunteered to participate in the study. All were familiar with the respiratory maneuvers performed during the test.

**Signal Acquisition**

Diaphragm EMG signals were obtained via a multiple-array esophageal electrode consisting of eight stainless steel rings (width 2 mm and diameter 2 mm) placed 10 mm apart, creating an array of seven sequential differential electrode pairs. The center electrode was located closest to the diaphragm and was followed by sequential differential electrodes located 10 mm cephalad and caudal to the center electrode. The signals were amplified, filtered, and recorded using a computer-based system. Cross-correlation analysis was performed to determine the location of the center of electrical activity (EAR\(_{\text{distr}}\)). A schematic description of the method used to determine the location of the center of electrical activity is shown in Fig. 1A. The raw signals from each electrode pair (electrode is illustrated in center) were cross-correlated, and the correlation coefficient (r) was calculated. The r values were used to determine the position of the EAR\(_{\text{distr}}\). In this example, electrode pair 3 was located 10 mm cephalad to the EAR\(_{\text{distr}}\), and electrode pair 5 was located 10 mm caudal to the EAR\(_{\text{distr}}\). As revealed by cross-correlation analysis, signals from electrode pairs located cephalad and caudal to the EAR\(_{\text{distr}}\) were inversely correlated at 0 time delay. The signal obtained after subtraction of signal from electrode pair 5 from that of electrode pair 3 yielded a signal that was less influenced by bipolar electrode filtering, and we refer to this method as the "double-subtraction technique." The purpose of the present work, therefore, was to evaluate whether the double-subtraction technique can reduce the effect of movement of the EAR\(_{\text{distr}}\) relative to the electrode array on the diaphragm EMG power spectrum.

**Fig. 1.** A: schematic description of method used to determine location of center of electrically active region of diaphragm (EAR\(_{\text{distr}}\)). Left, raw signals from each electrode pair (electrode is illustrated in center). Right, r values from cross-correlation of signals from electrode pairs 1 vs. 3, 2 vs. 4, 3 vs. 5, 4 vs. 6, and 5 vs. 7. Dashed line through three most negative r values, square law-based function used to interpolate position of EAR\(_{\text{distr}}\). B: diaphragm EMG signals obtained from electrode pairs located 10 mm cephalad and 10 mm caudal to the EAR\(_{\text{distr}}\), electrode pairs 3 and 5, respectively, in this example, to the EAR\(_{\text{distr}}\), electrode pair 4 in this example (left). As revealed by cross-correlation analysis, signals from electrode pairs located cephalad and caudal to the EAR\(_{\text{distr}}\) were inversely correlated at 0 time delay. Right, signal obtained after subtraction of signal from electrode pair 5 from that of electrode pair 3. Double subtraction of inversely correlated signals resulted in a clearly visible increase in signal amplitude, whereas addition of signals (not shown) reduced amplitude.
pairs, and mounted on silicone tubing (diameter 2 mm). A schematic representation of the electrode is presented in Fig. 1A (center). The most-caudal electrode pair was defined as "electrode pair 1," whereas the most-cephalad pair was "electrode pair 7." A Teflon tube (internal diameter 0.75 mm) was placed inside the silicone catheter, and a 5-cm-long, 1.5-cm-diameter latex balloon was mounted 5 cm distal to the most-distal ring to allow the measurement of gastric pressure (Pga). The esophageal electrode was passed through the nose and swallowed to the level of the gastroesophageal junction. Esophageal pressure (Pes) was measured by a separate Pes catheter (internal diameter 1 mm) placed in the lower one-third of the esophagus. Transdiaphragmatic pressure (Pdi), a measure of diaphragm force, was calculated as the pressure difference across the diaphragm (Pga – Pes). A two-lead differential electrode pair was obtained from electrodes placed on the sternum, vertically and 10 cm apart (Graphic Controls, FC24).

Diaphragm EMG electrode positioning was achieved by on-line display of the raw signals, and the correlation coefficients were obtained by successively cross-correlating the diaphragm EMG signals from every second pair of electrodes along the array (see below).

Diaphragm EMG and ECG signals were amplified (INA102, Burr-Brown) and high-pass filtered at 10 Hz (single-pole filter) with an antialiasing filter at 1 kHz (D70L8L-1.00 kHz, 8-pole Bessel filter, Frequency Devices). The diaphragm EMG and ECG signals were acquired (DT 2821, Data Translation) at 2 kHz (12-bit resolution). Pes and Pga were acquired separately (DT 2801A, Data Translation) at a sampling frequency of 100 Hz (12-bit resolution).

On-Line Display and Analysis of Diaphragm EMG Signals

Diaphragm EMG signals were acquired, displayed, and analyzed by computer software that, based on predetermined criteria, makes an evaluation of signal contamination by such factors as the ECG, noise, motion artifacts, and esophageal peristalsis (12). The raw diaphragm EMG signals were automatically selected between the ECG QRS complexes (~50–75% of the R-R interval) from all seven electrode pairs. From the seven raw diaphragm EMG signals, the direct current levels and trends were removed by linear regression analysis: the tails of the raw signals were zero padded from the first and last zero crossings of the EMG signal to fit the segments for a fast Fourier transform of 1,024 points. The time domain diaphragm EMG segments were then converted into the frequency domain by fast Fourier transform, and the power spectra were calculated. CF was calculated from the diaphragm EMG power spectrum as the spectral moment of order one (M1) divided by that of order zero (M0)

\[
CF = M_2 / M_0
\]

and the root mean square (RMS) was calculated as

\[
RMS = (M_p/p)^{1/2}
\]

where p is the number of points in the signal (zero padding excluded), and spectral moments (M) of order n are obtained by

\[
M_n = \sum_{i=0}^{i_{max}} \text{power density}_i \times \text{frequency}^n
\]

where i is the index over which the power density-frequency product is summed, i = 0 is the direct current component, and i_{max} is the index associated with the highest frequency in the spectrum. CF values are expressed in hertz; the RMS is expressed in decibels with arbitrary reference.

In each subject, signal contamination was evaluated for each electrode pair’s power spectrum by contamination-sensitive indexes. The four indexes used to evaluate signal contamination were the signal-to-noise (SN) ratio, the signal-to-motion artifact (SM) ratio, the drop in power density of the spectrum (DP) ratio, and a spectral deformation (Ω) index. Below is a brief description of the signal-contamination indexes. The reader is referred to the recent work by Sinderby et al. (12) for a more detailed account of the indexes.

SM ratio. To evaluate the influence of motion artifacts, two assumptions are made: 1) motion artifacts usually occur at frequencies <20 Hz and 2) the uncontaminated power spectrum is considered linear from 0 to 20 Hz. The low-frequency slope of the power spectrum can be predicted by a straight line from 0 Hz to the peak power density in the spectrum. The SM ratio is obtained by taking the power of the entire spectrum, divided by the area under the spectral curve that falls above the prediction line, for the first 20 Hz of the spectrum. The SM is expressed in decibels and is sensitive to low-frequency motion artifacts.

SN ratio. Noise is defined as disturbances that can be detected in the high-frequency range of the spectrum. Calculation of the SN ratio assumes that no diaphragm EMG-related power density occurs in the upper 20% of the power spectrum-frequency range (3). First, the power in the upper 20% of the spectrum is calculated. The total noise contribution is predicted by integrating the upper 20% area for all frequencies in the spectrum. The SN ratio is then obtained by dividing the area under the entire spectrum by the area of the total noise. The SN ratio is expressed in decibels and is sensitive to high-frequency noise.

DP ratio. This ratio is obtained by dividing the highest power density of the spectrum (observed between 35 and 600 Hz) by the lowest power density of the spectrum (within the same frequency range). The DP ratio is expressed in decibels and is sensitive to reductions in “peaking” of the power spectrum in the range 35–600 Hz, where most of the diaphragm EMG power is located.

Ω Index. This index is sensitive to changes in the symmetry and peaking of the power spectrum and is derived mathematically (3) by the following formula

\[
\Omega = (M_3/M_2)^{1/2}(M_5/M_4),
\]

where M_2, M_1, and M_0 represent the spectral moments of orders 2, 1, and 0, respectively, and where the spectral moments of order n are as described above.

It has been determined that the following combination of the above-described indexes allows for an error of CF values in the range of -5 to +10 Hz: SM = 12 dB, SN = 15 dB, DP = 30 dB, and Ω ≥ 1.4 (12), and they were the acceptance levels used in the present study.

Determination of Position of EAR_{dirr}

With a perpendicular electrode arrangement, signals that are obtained either on opposite sides of the EAR_{dirr}, or on the same side of the EAR_{dirr} correlate with extreme values (i.e., the value is expected to be close to -1 or +1) at a 0-ms time shift. Cross-correlation analysis was performed between signals obtained from electrode pairs 1 vs. 3, 2 vs. 4, 3 vs. 5, 4 vs. 6, and 5 vs. 7 (Fig. 1A, left, shows the raw signals from all electrode pairs). The correlation coefficients obtained for the respective cross-correlations at zero time delay are plotted in
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Fig. 1A, right. The most-negative correlation coefficient between any two pairs of electrodes indicates that the respective signals are the most reversed in polarity (e.g., electrode pairs 3 vs. 5 in this example); the electrode pair that is between these two most negatively correlated pairs is the electrode pair closest to the EAR<sub>dictr</sub> (electrode pair 4 in this example). Samples were included in the analysis only if the correlation coefficient (for the two most negatively correlated signals) was less than or equal to −0.50. After the three most-negative adjacent correlation coefficients were determined (marked by an asterisk in the example), a square-law-based curve fit was applied to interpolate a more accurate location of the EAR<sub>dictr</sub> with respect to the multiple-array electrode.

Double-Subtraction Technique

We hypothesized that subtraction of the signals from electrode pairs centered 10 mm above and below the EAR<sub>dictr</sub> would provide a signal that is less influenced by movement of the bipolar electrodes (the double-subtraction technique). Figure 1 describes how the double-subtraction technique is performed. First, the electrode pair closest to the EAR<sub>dictr</sub> is determined, and then the electrode pairs located 10 mm caudal and 10 mm cephalad to the EAR<sub>dictr</sub> center are also determined. As depicted in Fig. 1A, left, signals from the electrode pairs located 10 mm caudal and 10 mm cephalad of the EAR<sub>dictr</sub> were reversed in polarity (electrode pairs 3 and 5). Figure 1B, right, gives an example of how the new signal is obtained (the “double-subtracted signal”) by subtracting the signal from the electrode pair located 10 mm cephalad to the EAR<sub>dictr</sub> (electrode pair 5) from the signal 10 mm caudal to the EAR<sub>dictr</sub> (electrode pair 3). For every EMG segment selected between the ECG QRS complex, the double-subtraction technique was applied. The double-subtracted signal was Fourier transformed into the frequency domain, and the power spectrum was calculated; CF and RMS values were also calculated for every double-subtracted signal segment (as described above for the individual electrode pairs).

Protocol

The esophageal electrode was passed through the nose, swallowed into the stomach, and positioned at the level of the gastroesophageal junction with the aid of on-line feedback from the EMG signals (see above). Subjects were seated upright in an armchair facing a computer monitor that displayed the raw diaphragm EMG signals, the power spectrum CF values, and the RMS values for each electrode pair in real time. Maximal transdiaphragmatic pressure (P<sub>dimax</sub>) maneuvers were performed at functional residual capacity (FRC) and at total lung capacity (TLC) (combined Mueller/expulsive maneuver). The highest of three reproducible values was considered to be maximal.

Subjects performed a series of five static, near isometric, voluntary diaphragm contractions. Each contraction lasted ~10 s, and a 2-min rest period was allowed between contractions. Contractions were performed at FRC at a P<sub>d</sub> corresponding to 20–30% of the P<sub>dimax</sub> value obtained at FRC and at TLC at a P<sub>d</sub> corresponding to 70–80% of the P<sub>dimax</sub> value obtained at TLC. The contractions at TLC were introduced in the protocol to evaluate whether the behavior of the diaphragm EMG signals over the span of the electrode array changes with lung volume or diaphragm activity. Signals were also acquired during 5 min of tidal breathing against a very slight inspiratory flow resistance at a target mean P<sub>d</sub> level corresponding to 10% of the maximum P<sub>d</sub> at FRC. The diaphragm EMG and P<sub>d</sub> were recorded during all runs.

Statistics

CF and RMS values from electrode pairs 10 mm caudal and 10 mm cephalad to the EAR<sub>dictr</sub> were compared with the signal created by the double-subtracted technique by using a Student’s t-test for matched comparisons. The effect of electrode positioning with respect to the EAR<sub>dictr</sub> on CF values was evaluated by linear regression analysis. Pearson product-moment correlation was used to analyze relationships.

RESULTS

The double-subtraction technique visibly resulted in an increase in signal amplitude, as shown in Fig. 1B, right. The resultant increase in amplitude was associated with an approximately twofold increase in RMS values (Table 1). The RMS values obtained by the double-subtraction technique were closely linearly related to the original signals; the average correlation coefficient (r) for the five subjects was 0.96 ± 0.02.

As depicted for one subject in Fig. 2, the CF values (y-axes) obtained from the electrode pair located 10 mm caudal to the EAR<sub>dictr</sub> (A, left) and from the electrode pair located 10 mm cephalad to the EAR<sub>dictr</sub> (A, right) were systematically influenced by the position of the EAR<sub>dictr</sub> (x-axes). The position of the EAR<sub>dictr</sub> is expressed as the distance (in mm) from the center of the electrode pair covering the EAR<sub>dictr</sub>. With respect to the

Table 1. Comparison of CF, RMS, and signal quality-index values between double-subtracted signal and signals obtained 10 mm caudal or 10 mm cephalad to EAR<sub>dictr</sub>

<table>
<thead>
<tr>
<th></th>
<th>CF, Hz</th>
<th>RMS, dB</th>
<th>SN Ratio, dB</th>
<th>DP Ratio, dB</th>
<th>Ω Ratio, Rel units</th>
<th>SM Ratio, dB</th>
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</thead>
<tbody>
<tr>
<td><strong>Double-subtraction technique</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>10 mm caudal to EAR&lt;sub&gt;dictr&lt;/sub&gt;</td>
<td>87.6 ± 7.9</td>
<td>21.9 ± 4.6</td>
<td>23.7 ± 0.9</td>
<td>34.3 ± 1.3</td>
<td>1.27 ± 0.03</td>
<td>38.4 ± 4.1</td>
</tr>
<tr>
<td>Difference</td>
<td>−0.4 ± 0.6</td>
<td>4.6 ± 0.6</td>
<td>1.2 ± 0.6</td>
<td>0.5 ± 0.5</td>
<td>−0.02 ± 0.05</td>
<td>4.3 ± 0.3</td>
</tr>
<tr>
<td><strong>Double-subtraction technique</strong></td>
<td></td>
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</tr>
<tr>
<td>10 mm cephalad to EAR&lt;sub&gt;dictr&lt;/sub&gt;</td>
<td>86.6 ± 8.2</td>
<td>22.3 ± 6.0</td>
<td>24.0 ± 0.9</td>
<td>34.7 ± 1.2</td>
<td>1.26 ± 0.02</td>
<td>35.9 ± 8.1</td>
</tr>
<tr>
<td>Difference</td>
<td>−3.6 ± 0.9</td>
<td>6.5 ± 0.9</td>
<td>2.6 ± 0.6</td>
<td>1.4 ± 0.4</td>
<td>−0.03 ± 0.06</td>
<td>−3.1 ± 1.0</td>
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Values are means ± SD; n = 5 subjects. CF, center frequency; RMS, root mean square; EAR<sub>dictr</sub>, center of electrically active region of diaphragm; SN, signal-to-noise; DP, drop in power density of spectrum; Ω, spectral deformation index; SM, signal-to-motion artifact; Rel, relative. *P < 0.01; **P < 0.02; ***P < 0.03; ****P < 0.001; *****P < 0.005; *not significant.
electrode pair located 10 mm caudal to the EAR_{dcltr} (A) and electrode pairs located 10 mm cephalad to EAR_{dcltr} (B) were systematically influenced by position of EAR_{dcltr} (x-axes) on electrode pair covering EAR_{dcltr}. Position of EAR_{dcltr} is expressed as distance (in mm) off center of electrode pair covering EAR_{dcltr}. With respect to electrode pair 10 mm caudal to EAR_{dcltr}, CF values increased when EAR_{dcltr} moved in a caudal direction relative to electrode array, whereas CF values obtained from electrode pair 10 mm cephalad to EAR_{dcltr} decreased, and vice versa. This reciprocal influence of position of EAR_{dcltr} was reduced for double-subtracted signal (C).

Table 2. Individual and mean slopes describing influence of position of EAR_{dcltr} on CF values obtained with electrode pairs located 10 mm caudal or cephalad to EAR_{dcltr} and CF values obtained with double-subtraction technique

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Double-Subtracted Signal, Hz/mm</th>
<th>Electrode Pair</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 mm cephalad to EAR_{dcltr}</td>
<td>10 mm caudal to EAR_{dcltr}</td>
</tr>
<tr>
<td>1</td>
<td>–1.6‡</td>
<td>2.0‡</td>
</tr>
<tr>
<td>2</td>
<td>1.5‡</td>
<td>4.9‡</td>
</tr>
<tr>
<td>3</td>
<td>2.5‡</td>
<td>3.9‡</td>
</tr>
<tr>
<td>4</td>
<td>1.0‡</td>
<td>2.1‡</td>
</tr>
<tr>
<td>5</td>
<td>0.3†</td>
<td>0.9*</td>
</tr>
<tr>
<td>Mean</td>
<td>–0.7</td>
<td>2.7</td>
</tr>
<tr>
<td>95% Confidence interval</td>
<td>1.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Significantly different: *P < 0.05; †P < 0.005; ‡P < 0.0005.

Mean CF values for the signals obtained 10 mm caudal or 10 mm cephalad of the EAR_{dcltr} during the entire run were not different from the CF values obtained from the double-subtracted signals (Table 1). Because SN levels are not a problem at high-diaphragm-contraction levels, the effect of the double-subtraction technique on signal quality was only analyzed for signals recorded at mild contraction levels (isometric contractions at 20–30% of \( P_{d_{\text{max}}} \)). The SN ratios for the double-subtracted signals were, on average, 2 dB higher than the SN ratios for the electrode pairs located 10 mm caudal or 10 mm cephalad to the EAR_{dcltr} (Table 1). Also, the DP and \( \Omega \) ratios improved somewhat, whereas no consistent changes were found.
for the SM ratio when the double-subtraction technique was applied (Table 1).

To quantify whether the double-subtraction technique increased the number of samples that were accepted by the signal-quality indexes, the number of accepted double-subtracted signals were compared with the number of accepted samples obtained from electrode pairs located 10 mm caudal and/or 10 mm cephalad to the EAR_dictr. Signals used in the analysis were obtained during tidal breathing with a slight inspiratory resistance (10% of Pdimax). Relative to the electrode pairs located 10 mm caudal and/or 10 mm cephalad to the EAR_dictr, 50% more signal segments were accepted by the inclusion criteria for the double-subtracted signals (Fig. 3).

The behavior of the CF and RMS values obtained along the span of the electrode array were different among subjects, but within a given subject the behavior of the CF and RMS values along the span of the electrode array was similar at FRC and TLC and did not change with increasing contraction levels. Figure 4 shows CF (squares) and RMS (circles) values for each electrode pair along the array in one subject contracting the diaphragm at 30% of Pdimax obtained at FRC (dashed line) and at 70% of the Pdimax obtained at TLC (solid line). Note that the Pd values are normalized to the Pdimax values obtained at the same lung volume.

It was noticed that the summation of diaphragm EMG signals from all seven pairs of electrodes, which is equivalent to a bipolar signal obtained between the most-caudal and -cephalad electrode rings, provides a large ECG signal. Figure 5 depicts the signals recorded from each of the seven electrode pairs as well as the summed signal obtained (top).

DISCUSSION

The present study demonstrates that subtraction of the diaphragm EMG signal 10 mm cephalad to the EAR_dictr from the signal 10 mm caudal to the EAR_dictr, the double-subtraction technique, reduces the influence of bipolar electrode movement relative to the EAR_dictr, improves the SN ratio, and increases the number of diaphragm EMG segments that can be used in the analysis.

Implications of Double-Subtraction Technique

One of the technical problems associated with the use and interpretation of esophageal recordings of the
diaphragm EMG has been the low SN ratio. Low SN ratio is especially a problem when the diaphragm EMG is recorded with esophageal electrodes at low levels of diaphragm contraction, e.g., breathing at rest (2). The double-subtraction technique shows itself to be a promising technique to overcome the difficulties associated with obtaining diaphragm EMG recordings of acceptable quality at low levels of diaphragm contraction. In contrast to the diaphragm EMG signals, signals from distant bioelectric sources will have the same polarity for all electrode pairs along the electrode array. The double-subtraction technique, therefore, results in enhancement of the diaphragm EMG signals (that effectively are added) and cancellation of any distant bioelectric sources common to both pairs of electrodes used in the subtraction and, hence, improves the SN ratio. A slight improvement was also seen in the DP and Q ratios, both being sensitive to high-frequency noise (3, 12). As a direct consequence of the improved signal quality, the double-subtraction technique allowed 50% more EMG signals to be accepted as uncontaminated, according to the signal-quality indexes. As expected, the SN ratio, being sensitive to electrode motion artifacts, was not affected by the double-subtraction technique.

In healthy subjects, diaphragm EMG CF values decrease by ~20–30% when subjects breathe against inspiratory loads until task failure (unpublished observations). Hence, early indications of diaphragmatic fatigue could be uncertain because of the 20% fluctuations in CF for ±5 mm changes in the position of the center of the EARdi, as demonstrated in the present study. The double-subtraction technique will allow for more accurate detection of developing fatigue and may increase the applicability of diaphragm EMG to detect fatigue in clinical settings.

Limitations of Double-Subtraction Technique

In an implementation of the double-subtraction technique, it is important to know the behavior of the diaphragm EMG signals over the span of the electrode array, i.e., the influence of the transfer function for signals measured with bipolar electrodes oriented perpendicularly to the diaphragm. We have previously shown that the diaphragm EMG recorded with an esophageal electrode in healthy subjects was the “least filtered” at a distance of ~10 mm away from the EARdi, with an interelectrode distance of 10 mm (4).

In the present study, we demonstrated that the symmetrical behavior of the CF and RMS over the bipolar electrode array remains stable with changes in lung volume and diaphragm-contraction levels (see Fig. 4). However, it should be noted the selection of signals 10 mm away from the EARdi used in the double-subtraction technique has so far only been applied to signals obtained in healthy subjects. In the case of anatomic or neuromuscular abnormalities, or changes in electrode configuration, the distance between electrode pairs used in the double subtraction and the EARdi may alter.

The behavior of the diaphragm EMG signals over the span of the electrode array, i.e., the influence of the transfer function for signals measured with bipolar electrodes oriented perpendicularly to the diaphragm, is dependent on the radial and axial distances between the esophageal electrode pair and the diaphragm, the thickness of the diaphragm, i.e., size of the EARdi, the interelectrode distance, and the dispersion in arrival times of the single-fiber contributions to the motor unit signal (4). The transfer function for human diaphragm EMG signals measured with bipolar electrodes oriented perpendicularly to the diaphragm has been discussed in detail elsewhere (4). The EARdi can move (due to diaphragm excursions) relative to the electrode array within a single breath and within a single EMG signal segment; as well, any change in motor unit recruitment may result in a repositioning of the EARdi relative to the electrode array. Hence, a power spectrum obtained from one single EMG segment will represent the mean position of the EARdi with respect to the electrode array, i.e., the mean filtering of the signal. Because of the reciprocal behavior of the bipolar electrode-filtering effect for electrode pairs 10 mm caudal and 10 mm cephalad to the EARdi, the signals used by the double-subtraction technique should represent the mean (reciprocal) filtering for the two electrode pairs. Hence, their sum should reduce the influence of relative changes in the position of the EARdi with respect to the electrode array that may occur within a given EMG segment.

We chose a square law-based function of the cross-correlation coefficients obtained between electrode pairs to predict a more accurate position of the EARdi relative to the electrode array. This square law-based function may not have indicated the exact position of the EARdi, however, assuming that the recorded EMG signals shift polarity at or close to the EARdi when obtained with an electrode array of the same configuration as that used in the present study, the square law-based function should adequately indicate the relative changes in position of the EARdi.

Extracting ECG From Esophageal Electrode Array

The setup in the present study included a separate ECG recording (with electrodes on the chest wall), as well as the seven pairs of EMG signals from the esophageal catheter, for a total of eight channels. The ECG is used in the analysis of the diaphragm EMG signals to guide the selection of EMG segments free of ECG (12). The large ECG signal obtained by summation of signals from all seven electrode pairs is useful because it allows the separate ECG recording to be replaced by an additional electrode pair for diaphragm EMG. The additional electrode pair for the diaphragm EMG is advantageous because it extends the span of the electrode array and hence reduces the possibility of the diaphragm moving off the electrode array.

Conclusion

The double-subtraction technique reduces the influence of the relative position of the EARdi with respect
to the bipolar electrode array on the frequency content of diaphragm EMG segments and improves the SN ratio. The latter increases the number of diaphragm EMG segments accepted by the signal quality indexes as uncontaminated by 50%.

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