Respiratory muscle activity measured with a noninvasive EMG technique: technical aspects and reproducibility

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Respiratory muscle activity measured with a noninvasive EMG technique: technical aspects and reproducibility. J Appl Physiol 88: 1955–1961, 2000.—A new method is being developed to investigate airway obstruction in young children by means of noninvasive electromyography (EMG) of diaphragmatic and intercostal muscles. The purpose of this study was to evaluate the reproducibility of the EMG measurements. Eleven adults, 39 school children (20 healthy, 19 asthmatic), and 16 preschool children were studied during tidal breathing on separate occasions: two for adults with a time interval of 3 wk and three for children with time intervals of 1 and 24 h. Single electrodes were placed on the second intercostal space left and right of the sternum and at the height of the frontal and the dorsal diaphragm. Bipolar electrode pairs were placed on the rectus abdominis muscle. A newly designed digital physiological amplifier without any analog filtering was used to measure the EMG signals. Except for the average dorsal diaphragm EMG derivation in healthy school children on the second occasion, a significant correlation between the mean peak-to-peak inspiratory activity of different age groups on the different measurement occasions was found (P < 0.05). To assess the repeatability, we described the agreement between the repeated measurements within the same subjects. No significant differences were found between the measurements on the separate occasions. Our observations indicate that the EMG signals derived from the diaphragm and intercostal muscles are, in different age groups with and without asthma, reproducible during tidal breathing.

MATERIALS AND METHODS

Subjects and Procedures

We studied the reproducibility of the measurements in subjects of three age groups: 1) 11 young adults (age = 20–30 yr), 2) 20 healthy school children (age = 6–13 yr) and 19 school children with asthma (age = 7–14 yr), and 3) 16 healthy preschool children (age = 7 mo to 5 yr). Subject characteristics are summarized in Table 1. Over the past decades, surface electromyography (EMG) of the respiratory muscles has been used in several research and clinical studies, in animals as well as in humans. EMG is the most direct way to obtain information on respiratory muscle function.

In a previous study, we investigated the relationship between transcutaneous diaphragmatic and intercostal EMG activity and the fall in forced expiratory volume in 1 s (FEV1) after a histamine challenge. The EMG activity at the provocation concentration level of 20% for histamine was compared with the EMG activity at baseline by calculating the ratio of the mean peak-to-peak average EMG excursion at the highest histamine dose to that at baseline. In that study, we found increased electrical activity of the diaphragm and intercostal muscles that correlated with a fall in FEV1.

In the present study, we present a noninvasive, easy-to-perform method that could be used on young children. A measurement device has been constructed to process transcutaneous EMG of the diaphragmatic and intercostal muscles as an indirect measure to estimate airflow limitation. The following question was addressed: Is the diaphragmatic and intercostal EMG signal, obtained with this new device, reproducible in adults, school children, and preschool children during tidal breathing?

IN PEDIATRIC PRACTICE, THE MAJORITY OF YOUNG CHILDREN WITH AIRWAY OBSTRUCTION ARE NOT ABLE TO PERFORM ADEQUATE AND RELIABLE FORCED BREATHING MANEUVERS. ALTERNATIVE METHODS HAVE BEEN DEVELOPED TO INVESTIGATE AIRWAY OBSTRUCTION. MOST OF THESE METHODS ARE NOT USED ROUTINELY BECAUSE THEY ARE OFTEN EXPENSIVE, UNPLEASANT FOR THE PATIENT (I.E., REQUIRING SEDATION), OR DIFFICULT TO PERFORM.

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preschool children were measured on three occasions with
time intervals of 1 and 24 h. Sixteen of the asthmatic school
children used inhaled corticosteroids, with a dosage ranging
from 200 to 400 µg twice a day. All of them used bronchodila-
tor therapy on demand. Bronchodilator therapy was withheld
for at least 8 h (short acting) or 24 h (long acting) before EMG
measurements were performed. All children were in a stable
phase of the disease and had not suffered from respiratory
infections for at least 1 mo before the measurements.

The EMG measurements were simultaneously recorded
with magnetometer respiration (MR) bands (see MR moni-
tor). The adults and school children were asked to sit in an
upright posture, with hands resting on their legs. The sub-
jects were asked to relax for 15 min before the test; mean-
while, the procedure was carefully described by the operator.
After this resting period, recording of EMG measurements
started. This was followed by spirometry, which was per-
formed on the adults and the school children. EMG measure-
ments of the preschool children were performed while the
children sat in an upright position on a parent's lap. Subjects
were unable to watch their respiration on the monitor and
were asked not to move or talk during the measurements.

The study was approved by the Medical Ethics Committee
of the Academic Hospital of Groningen. Informed consent was
obtained from both subjects and parents.

Technical Aspects of Measurements and
Measurement Devices

A compact measurement apparatus (Porti-X, Twente Medi-
cal Systems International, Enschede, The Netherlands), which
allows for the acquisition of electrophysiological signals (elec-
tro-x-gram, EXG) and physical signals [auxiliary (AUX), a
general purpose differential input with unity gain] at the
same time, was designed. We used a Porti-16 front-end
configuration, comprised of eight bipolar EXG channels and
eight differential AUX channels. It measured, conditioned,
and digitized the analog signals and preprocessed the digital
signals. For patient safety, all signals were sent to a computer
via fiber optics. The front-end was isolated from the main
supply by a highly isolated power supply. The bipolar EXG
channels had a high input impedance (>2 GΩ) and actively
driven, shielded electrode cables (guarding). The common
mode signal range was 6 V, the differential signal range was
300 mV, and the common mode rejection ratio (CMRR) was
>100 dB at 50–60 Hz. Analog high-pass or low-pass filters
were absent so that the analog signals could not be degraded
before sampling. The analog signals were digitized by means of
sigma-delta analog-to-digital converters (ADC) with inher-
ent digital antialiasing filters. The converters put out samples
with a resolution of 22 bits, resulting in a least significant bit
of 71.5 nV for the differential signal. The total amplifier and
ADC noise was <2 µVpp. The AUX channels had an instrumen-
tation amplifier with common-mode and differential sig-
nal ranges of 6 V, a high input impedance of >1 GΩ, and a
CMRR of >100 dB. We utilized the same ADC as that used for
the EXG channels but with a resolution of 1.43 µV least
significant bit. Each AUX input connector was provided with
a symmetrical 10-V, 10-mA power supply for powering analog
signal conditioning circuits. Although the maximum sample
frequency of the front end was 2 kHz, we found that, during
tidal breathing, the sensitivity for the detection of respira-
tory muscle activity was optimal at a sample frequency of ~400
Hz. At higher sample frequencies, to allow for an increased
bandwidth for EMG signals, it appeared that the power of the
EMG did not significantly exceed the power of the amplifier
and ADC noise in the higher frequency bands. The EXG
signal was transformed into an EMG signal by means of a
digital first-order, high-pass filter (time constant = 0.01 s), as
an EXG is characterized by the position of the electrodes in
relation to the electrically active tissue and its signal proper-
ities. Gross changes in depth of breathing were measured by
means of MR bands connected to and powered by the AUX
input. After analog-to-digital conversion, scaling and filtering
of the data were performed digitally, transforming the AUX
input signal into a MR monitor signal.

All data processing, recording, postanalysis, and reporting
were conducted by the POLY data-acquisition and processing
package (Inspektor Research Systems, Amsterdam, The Neth-
erlands).

EMG recordings. The electrical muscle activities of the
diaphragm and intercostal muscles were derived transcutane-
ously from electrodes (Neotrode, ConMed, New York, NY)
placed as follows: two bilaterally at the costal margin in the
nipple line, two bilaterally on the back at the same height,
and one each in the left and right second intercostal spaces,
~3 cm parasternal. The EMG signals of the rectus abdominis
muscle were derived from bipolar electrode pairs, one pair
each on the right and left sides, 4 cm apart, at the height of
the umbilicus. The common or ground electrode was placed at
the height of the sternum. See Fig. 1 for placement of electrodes.

Substantial heart activity (electrocardiogram) interferes
with the diaphragm EMG signals measured at the trunk.

Table 1. Demographic and baseline pulmonary function data for all test subjects

<table>
<thead>
<tr>
<th></th>
<th>Adults</th>
<th>Healthy School Children</th>
<th>Asthmatic School Children</th>
<th>Preschool Children</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>11</td>
<td>20</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>Age, yr</td>
<td>27.2 ± 3.1</td>
<td>9.0 ± 1.6</td>
<td>10.5 ± 1.9</td>
<td>2.4 ± 1.1</td>
</tr>
<tr>
<td>Height, cm</td>
<td>177.5 ± 9.7</td>
<td>137.6 ± 10.5</td>
<td>147.4 ± 13.2</td>
<td>94.3 ± 12.6</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>69.6 ± 10.4</td>
<td>34.0 ± 9.8</td>
<td>40.7 ± 14.3</td>
<td>13.8 ± 3.0</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Female</td>
<td>5</td>
<td>13</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>VC₅₋₁₀</td>
<td>5.4 ± 1.2</td>
<td>5.2 ± 1.1</td>
<td>2.3 ± 0.6</td>
<td>2.3 ± 0.6</td>
</tr>
<tr>
<td>%Pred</td>
<td>106 ± 8.4</td>
<td>104 ± 8.4</td>
<td>96 ± 8.1</td>
<td>100 ± 13.5</td>
</tr>
<tr>
<td>FEV₁/VC₅₋₁₀,max, %</td>
<td>80 ± 6.2</td>
<td>80 ± 6.9</td>
<td>89 ± 5.1</td>
<td>80 ± 10.8</td>
</tr>
</tbody>
</table>

Values are means ± SD. VC₅₋₁₀, vital capacity in ambient temperature and pressure; saturated; FEV₁, forced expiratory volume in 1 s; VC₅₋₁₀, maximum vital capacity; %Pred, percentage of predicted value.
This heart activity was removed from the respiratory muscle activity by the process described by O'Brien et al. (14). In brief, the electrical ventricle activity of the heart (QRS) complexes of the ECG were easily detected and stretched to a standard pulse width of 100 ms. During this pulse, a cut was made in the slightly delayed (40 ms) EMG signal to completely filter out the QRS complex (gated EMG). Next, the gated EMG was rectified and averaged out with a moving time window of 200 ms. Finally, the missing signal in the gate was filled with the running average, resulting in a fairly good interpolation during the gate and an almost ECG-free average EMG signal (see Fig. 2A). The excursions in the average diaphragm EMG are of an inspiratory nature, and the amplitude changes suggest a form of airflow control.

MR monitor. An MR monitor (Respiband, SensorMedics, Bilthoven, The Netherlands), consisting of two respiration bands (one placed around the thorax and one around the abdomen; Fig. 1), was used for measuring a reference respiratory signal. This reference respiratory signal has been particularly useful when used in conjunction with an EMG to display approximate tidal volume. Mead et al. (11) used the magnetometer technique on adults and found a good correlation between the magnetometer signal and spirometrically measured tidal volumes.

Data analysis and statistics. The average EMG and MR band signals were sampled in buffers. Sampling started at a trigger event that marked the beginning of a breath and stopped at the beginning of the next. Trigger events may be time marked and labeled in two ways: 1) a peak/bottom detection algorithm on average EMG or MR band, with automatic comment annotation, or 2) visual peak/bottom detection on either raw or average EMG and MR band, with manual comment annotation. The data in the sample buffers were resampled to a normalized interval time by use of linear interpolation. The sample buffers were then added to averaging buffers. The means ± SD of the two MR bands and the average EMGs of diaphragm, intercostal, and abdominal muscles are shown in Fig. 2B as an example of the data analysis. The trigger point of an averaging sweep is derived from the chest band at the start of an inspiration. We used 6–10 tidal breathing maneuvers for analysis. From the average data, the highest and lowest peaks were detected. The number of sweeps, the mean peak-to-peak values ± SD, the mean and SD of the breath-interval times, the minimum and maximum interval time, and the correlation coefficient of the trend in the interval times was reported and exported in a spreadsheet format.

To compare the mean peak-to-peak values, we used a Pearson's correlation coefficient (r) for all three respiratory EMG leads. For assessing agreement between repeated measurements from the same subjects, the analysis method described by Bland and Altman was used (3). Statistical analysis and graphics were performed with Microsoft Excel and SPSS (SPSS, Chicago, IL).

RESULTS

EMG recordings of the diaphragm and intercostal muscles were successful among all volunteers. Healthy volunteers had no complaints and/or symptoms of pulmonary origin during and 1 mo before the study. Two school children with asthma felt mildly obstructive during measurements, but the recordings could be continued. The demographic data and baseline pulmonary function data of the healthy volunteers, healthy
Fig. 2. A: MR bands and EMG recordings during tidal breathing in 1 subject. Top 2 lines show excursions of chest (Ches) and abdomen (Abdb), in arbitrary units, measured by MR bands. Remaining lines show preprocessed, average (Av) EMG signals from muscle derivations. Vertical lines mark onset of a single inspiration, as detected by chest signal. I, intercostal; DF, frontal diaphragm; DA, dorsal diaphragm; AR, right abdomen; AL, left abdomen. B: computer screen, during result phase of EMG analysis, showing compound signals of MR bands and EMG recordings during tidal breathing in 1 subject. Top and middle mean (bold line) ± SD (thin lines) of 9 inspiration intervals of signals from chest and abdomen bands and AvI, AvDF, AvDA, AvAR, and AvAL. All measurements were triggered at inspiration mark (first large vertical line), and interval time was normalized. Second and third vertical lines represent peak detection window; short lines mark detected peak and bottom. Bottom left: successive interval times. Bottom right: interval times statistics. N, number of intervals; Max, maximum interval time; Min, minimum interval time; R, time-trend indicator; Yn, intercept.
school children, school children with asthma, and the preschool children are shown in Table 1.

Young Adults

Figure 3 shows the correlation coefficients between the average EMG of the measurements during tidal breathing on test days 1 and 2 (time interval = 3 wk), and the plots of the mean differences between the measurements against the average of the two measurements in these groups are shown in Table 2 (comparison of measurements 2 and 3 to measurement 1; time intervals = 1 and 24 h). The three leads are presented: AvDF, AvDA, and AvI. The range of the average EMG amplitudes of the diaphragm in school children with and without asthma was 5–15 µV during quiet breathing. The average EMG amplitudes of intercostal muscles ranged between 2 and 5 µV.

Fig. 3. Left: Pearson's correlation coefficient (r) between the average EMG of the measurements during tidal breathing.
Right: plots of the mean differences (Diff) between the measurements vs. mean average (Avg) EMG of the two measurements for adults. Three leads are presented: AvDF, AvDA, and AvI. M-1, measurement 1; M-2, measurement 2; Time interval was 3 wk.

Healthy School Children, School Children with Asthma, and Preschool Children

The correlation coefficients between the average EMG of the measurements and the mean differences between the measurements against the average of the three measurements in these groups are shown in Table 2.
In the preschool children, the ranges of the average EMG amplitudes of the diaphragm and the intercostal muscles during quiet breathing were 3–10 µV and 2–5 µV, respectively.

DISCUSSION

In this study we developed an online, transcutaneous EMG measurement technique. We tested the reproducibility of this new method in measuring diaphragmatic and intercostal muscle activity during tidal breathing in adults and children. To our knowledge, no data have yet been published on the reproducibility of respiratory muscle activity in children during tidal breathing.

Veiersted (18) and Ferrario et al. (7) found good reproducibility of EMG measurements of the trapezius and jaw muscles, respectively. To evaluate the reproducibility of EMG measurements and, specifically, to test a calibration procedure, Veiersted (18) studied the trapezius muscles with submaximal test contractions. Ferrario et al. (7) reported reproducible EMG results in measuring jaw muscles under distinct conditions, from a state of resting to maximum voluntary clench. The actions of muscles in the limbs and the jaw were different from those of breathing muscles; therefore, these observations cannot be extrapolated to a study on respiration muscles (6, 10). Muscles of the limbs and the jaw usually work against an inertia, but respiratory muscles work against the elastic recoil of the lung and chest wall.

In contrast, Ng (12) reported poor reproducibility of surface respiratory muscle EMG measurements during 50% and 75% of maximum inspiratory pressure for between-day recordings in adult volunteers. We measured three different age groups (adults, school children with and without asthma, and preschool children) during tidal breathing and found a highly significant correlation between the measurements in all groups. In assessing agreement between the repeated measurements within the same subjects, we found no significant differences between measurements on separate occasions. Furthermore, the SD of the differences for all groups was ~1 µV or less.

We wanted to know the degree to which the second and third measurements are likely to agree with the first measurement. Criteria for reproducibility of EMG measurements of respiratory muscles have never been well defined. Moreover, with this new device, we had no prior knowledge of the magnitude and SD of the signal. Opinions will differ on the question of how much EMG values of repeated measurements may diverge while remaining reproducible. A correlation of 0.8, as an arbitrary limit of agreement in reliability, was reported to be acceptable in EMG measurements (8). The test of significance shows that the two measurements are related, but measuring agreement between the two measurements may give more insight in the assessment of repeatability. Ideally, the limits of agreement should be defined beforehand to help interpret comparison between measurements. Because ours is a new measure, reference values were not available. According to the ATS recommendations for establishing reproducibility, an acceptable variation in FEV₁ is 5% (1). This means that the largest and the second largest FEV₁ must not vary by more than 5%. Comparing the mean differences and the SD of the differences to the magnitude of the peak-to-peak amplitude, we found an acceptable amount of agreement in respiratory EMG measurements with 1- and 24-h intervals in the asthmatic and nonasthmatic school children and in the preschool children and with a 3-wk interval between the measurements in the adult group. Compared with the ATS standard, the agreement between two EMG measurements in our study seems reasonably good.

During the first measurements, we found that the method for measuring respiratory EMG activity was easy to perform and good EMG signals were easy to obtain, even in the preschool children. One of the problems mentioned in the literature is contamination by body posture and the activity of other muscles when diaphragmatic activity is measured by means of surface electrodes (4). To minimize posture contamination, all measurements were performed in an upright, seated position. Also, variation in electrode positioning is known to influence the amplitude of EMG signals; therefore, in this study, electrode position was controlled by marking the sites on the skin around the electrodes. Due to the method of signal measurement, we did not experience problems with interference pickup (i.e., shielded cables) or with loss of electrode signal due to cable capacity (i.e., guarding) (15).

The repeatability of measurements with a time interval of 1 h was relatively poor for the healthy school children. A possible cause for this poor correlation within the group could be a lack of experience with lung function testing. Because this group of children was not accustomed to visiting the hospital and undergoing lung function tests, nervousness could have played a role during the first day of testing. The fact that the children were moving or talking did not influence the analysis of the electrical signal because we analyzed only the parts of the measurements during which the subject was breathing quietly.

**Table 2. Pearson’s correlation coefficient, mean differences between measurements, and SD of the differences for all test subjects**

<table>
<thead>
<tr>
<th></th>
<th>Adults</th>
<th>Healthy School Children</th>
<th>Asthmatic School Children</th>
<th>Preschool Children</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 wk</td>
<td>1 h</td>
<td>24 h</td>
<td>1 h</td>
</tr>
<tr>
<td>AvDF</td>
<td>r</td>
<td>0.93</td>
<td>0.75</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>MD, µV</td>
<td>-0.22</td>
<td>-0.50</td>
<td>-0.37</td>
</tr>
<tr>
<td></td>
<td>1.96·SD</td>
<td>1.77</td>
<td>2.26</td>
<td>1.77</td>
</tr>
<tr>
<td>AvDA</td>
<td>r</td>
<td>0.98</td>
<td>0.59</td>
<td>0.41†</td>
</tr>
<tr>
<td></td>
<td>MD, µV</td>
<td>-0.03</td>
<td>-0.57</td>
<td>-0.10</td>
</tr>
<tr>
<td></td>
<td>1.96·SD</td>
<td>0.81</td>
<td>2.35</td>
<td>3.24</td>
</tr>
<tr>
<td>AvI</td>
<td>r</td>
<td>0.98</td>
<td>0.53*</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>MD, µV</td>
<td>-0.12</td>
<td>-0.05</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>1.96·SD</td>
<td>0.32</td>
<td>1.02</td>
<td>0.92</td>
</tr>
</tbody>
</table>

AvDF, average frontal diaphragm EMG; AvDA, average dorsal diaphragm EMG; AvI, average intercostal EMG. Pearson’s correlation coefficient (r) is significant at *P < 0.01, unless otherwise specified. †P < 0.05; ‡not significant.
A repeated point of criticism of the transcutaneous measurement of respiratory muscles is the effect of the electrical activity of abdominal muscles in the region of the frontal diaphragm. As Fig. 2A shows, some electrical activity is detectable in the leads of the abdominal signals. However, the activity is of an inspiratory nature. Because the abdominal muscles are expiratory, the source of this activity must reside elsewhere. The amplitude, being only 0.2 µV, suggests a distant source. As Fig. 1 indicated, the electrodes of the abdominal leads are placed vertically, so that the upper electrode could pick up some of the electrical activity from the frontal diaphragm. As Fig. 1 indicated, the upper electrode was 2 cm, and the distance from the abdominal electrodes to the frontal diaphragm was 8 cm. Considering the two-dimensional skin impedance, the upper electrode, at this distance, could measure 1/25 (1/5)^2 of the electrical activity of the diaphragm (~0.2 µV). Another piece of evidence may be found in the close timing of the peaks in both abdominal curves and that of the frontal diaphragm (within 75 ms).

In young children, measuring pulmonary function without sedation is difficult. In this age group, tools to confirm clinical diagnosis, to monitor response to therapy, and to follow the course of the disease are required. Validation of this new method is necessary to be able to make comparisons between individuals, as well as to make repeated EMG measurements in the same subject.

In conclusion, this new instrument and the protocols used for positioning the electrodes and for recording reproducible EMG signals are noninvasive and appear easy to perform. Although the results should be interpreted with caution, our observations indicate that the peak-to-peak values of the average EMG of the diaphragm and intercostal muscles are reproducible during tidal breathing in different age groups with and without asthma.

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