Transesophageal Versus Surface Electromyography of the Diaphragm in Ventilated Subjects

Joost LC Lokin, Soray Dulger, Gerie J Glas, and Janneke Horn

BACKGROUND: Detection of diaphragmatic muscle activity during invasive ventilation may provide valuable information about patient-ventilator interactions. Transesophageal electromyography of the diaphragm (tEA_{di}) is used in neurally adjusted ventilatory assist. This technique is invasive and can only be applied with one specific ventilator. Surface electromyography of the diaphragm (sEA_{di}) is noninvasive and can potentially be applied with all types of ventilators. The primary objective of our study was to compare the ability of diaphragm activity detection between sEA_{di} and tEA_{di}. METHODS: In this single-center pilot study, sEA_{di} and tEA_{di} recordings were obtained simultaneously for 15 min in adult subjects in the ICU who were invasively ventilated. The number of breathing efforts detected by sEA_{di} and tEA_{di} were determined. The percentage of detected breathing efforts by sEA_{di} compared with tEA_{di} was calculated. Temporal and signal strength relations on optimum recordings of 10 breaths per subject were also compared. The Spearman correlation coefficient was used to determine the correlation between sEA_{di} and tEA_{di}. Agreement was calculated by using Bland-Altman statistics. RESULTS: Fifteen subjects were included. The tEA_{di} detected 3,675 breathing efforts, of which 3,162 (86.0%) were also detected by sEA_{di}. A statistically significant temporal correlation ($r = 0.95$, $P < .001$) was found between sEA_{di} and tEA_{di} in stable recordings. The mean difference in the time intervals between both techniques was 10.1 ms, with limits of agreement from –410 to 430 ms. CONCLUSIONS: Analysis of our results showed that sEA_{di} was not reliable for breathing effort detection in subjects who were invasively ventilated compared with tEA_{di}. In stable recordings, however, sEA_{di} and tEA_{di} had excellent temporal correlation and good agreement. With optimization of signal stability, sEA_{di} may become a useful monitoring tool. *Key words: mechanical ventilation; neurally adjusted ventilatory assist (NAVA); electromyography of the diaphragm (EAdi); surface electromyography.* [Respir Care 2020;65(9):1309–1314. © 2020 Daedalus Enterprises]

Introduction

Patient-ventilator asynchrony frequently occurs during invasive ventilation and is associated with patient discomfort, a prolonged duration of invasive ventilation, and increased hospital and ICU length of stay.[1-4] Although adjustments of the ventilator settings and reducing analgo-sedation can sometimes resolve patient-ventilator asynchrony, detection in clinical practice is difficult.[5-8] Patient-ventilator interactions are not assessed continuously, and waveform interpretation can be complex.[9]

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The study was performed at the Department of Intensive Care, Amsterdam UMC, Amsterdam University Medical Center, location AMC, Amsterdam, the Netherlands.

The authors have disclosed no conflicts of interest.

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Information about diaphragm muscle activity during invasive ventilation could improve monitoring of patient-ventilator interactions.[10] Currently, the electrical activity of the diaphragm (EA_{di}) can be recorded by transesophageal electromyography (tEA_{di}). This requires insertion of a specialized nasogastric tube (EA_{di} catheter) with electrodes at the level of the gastroesophageal junction. The tEA_{di} is used in neurally-adjusted ventilatory assist mode.[11] Because tEA_{di} is a reflection of spontaneous breath initiation, Neurally-adjusted ventilatory assist mode improves synchrony between the patient and the ventilator compared with conventional assisted modes.[12,13] Despite the great potential of tEA_{di}, its use in general ICU practice is limited because only one specific type of ventilator supports neurally-adjusted ventilatory assist mode ventilation.

Surface electromyography of the diaphragm (sEA_{di}) could overcome this disadvantage. It is easy to apply, noninvasive, and can theoretically be used in combination with all type of ventilators. Over the past decade, surface electromyography of the respiratory muscles has been investigated.[14-16] However, this technique has not been compared with tEA_{di} in adult patients who are invasively ventilated. The primary objective of our study was to investigate the ability of breathing effort detection with sEA_{di} compared with tEA_{di} during invasive ventilation. Because this was a pilot study, we were also interested in the best possible performance of sEA_{di}. As a proof of concept, we determined the temporal relation between sEA_{di} and tEA_{di} on optimal recordings.

QUICK LOOK

Current knowledge

Patient-ventilator asynchrony is a common problem in invasive ventilation. Information about transesophageal electrical activity of the diaphragm (tEA_{di}) during invasive ventilation can improve interaction between the patient and the ventilator. Surface electromyography of the diaphragm (sEA_{di}) is noninvasive and can potentially be applied with all ventilators. Yet, it has not directly been compared with tEA_{di} in the clinical ICU setting.

What this paper contributes to our knowledge

In stable recordings, sEA_{di} provided accurate information about patient-ventilator interaction. Due to signal disturbances, however, sEA_{di} is not yet sufficient to perform as a reliable monitoring tool in current ICU practice.

Methods

Study Design

This prospective observational cohort study was conducted in the ICU of the Amsterdam University Medical Center, location Academic Medical Center, Amsterdam, the Netherlands. The study protocol was approved by the medical ethics committee of the Amsterdam University Medical Center, location Academic Medical Center (NL5006.018.14). Subjects were included after written informed consent was signed by the legal representative. Adult patients who were invasively ventilated were eligible for inclusion if (1) ventilation was expected for at least 48 h, (2) they were ventilated with a Servo-i ventilator (Maquet, Wayne, New Jersey), (3) on a spontaneous mode of ventilation, and (4) an EAdi catheter was inserted. The exclusion criteria were (suspected) neuromuscular disease or cervical spinal cord injury, known phrenic nerve injury, and contraindication for surface electrode placement (eg, severe skin infections at the electrode site). Because of the pilot character of this study, a sample size calculation was not performed.

The ethical committee of the Amsterdam University Medical Center (MEC 10/107 # 10.17.0921) approved this study (registration number NTR4766, 01/09/2014). Detailed written and verbal information about this study was provided to patients' legal representatives. When subjects were mentally recovered after study inclusion, confirmatory consent was asked of the subjects to use the recordings for research purposes. The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Recordings of sEA_{di} and tEA_{di}

The sEA_{di} and tEA_{di} recordings were obtained simultaneously for a period of 15 min. Ventilator settings were not adjusted during the recordings. For sEA_{di} recordings, 4 disposable electrodes (Covidien, Dublin, Ireland) were placed bilaterally below the lower frontal and dorsal ribs. An additional electrode (ie, ground) was placed on the sternum (see the supplementary materials at http://www.rcjournal.com) All the electrodes were connected with shielded cables to a Dipha-16 physiological amplifier (Inbiolab BV, Groningen, Netherlands). The electromyography signals were combined to obtain the electrical activity of the diaphragm (sEA_{di}). Data were wirelessly transmitted to a laptop computer placed at the bedside of the patient. The tEA_{di} recordings, by using the tEA_{di} catheter (Maquet, Solna, Sweden), were registered trough wired connection between this laptop computer and the Servo-i ventilator.

Data Collection and Processing

The first 2 min of each measurement were exempted from analysis to limit signal disturbances. In each subject, the analysis was performed on the 10 min of recording

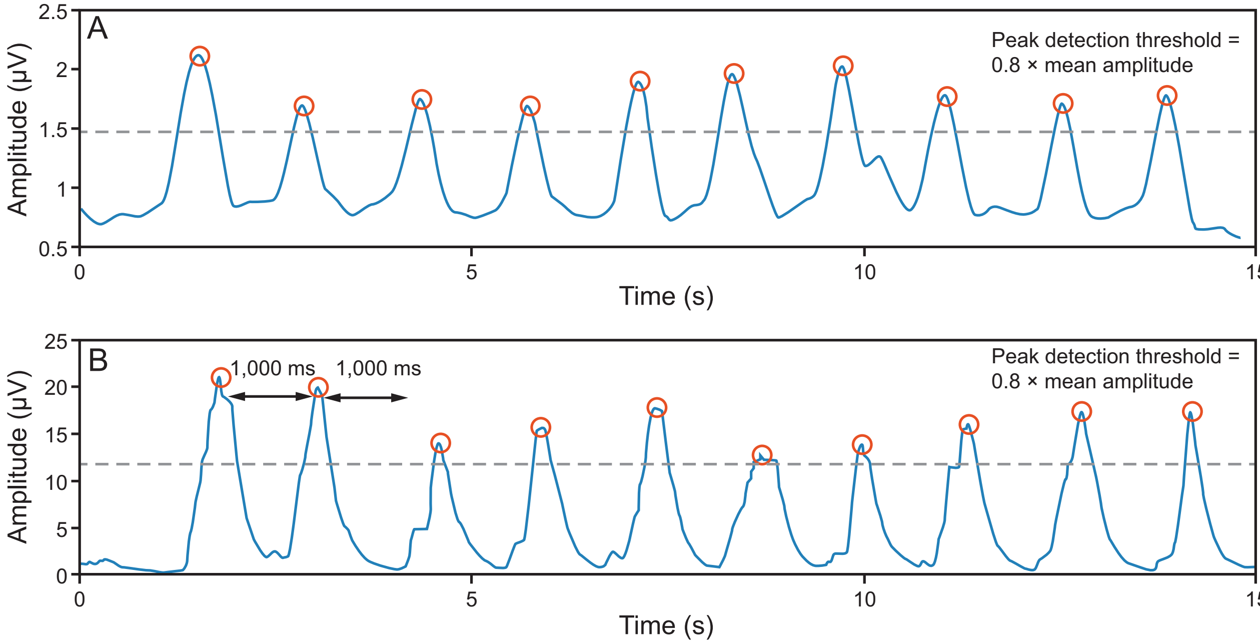

Fig. 1. Automatic peak detection for A: surface electrical activity of the diaphragm [sEA_{di}] and B: transesophageal electrical activity of the diaphragm [tEA_{di}].

directly after the exempted first 2 min. Peak diaphragm muscle activity of each breathing effort was detected automatically by using a minimum peak height threshold and a minimum peak distance threshold (Fig. 1). For both sEA_{di} and tEA_{di}, a respiratory peak was detected when the signal strength was at least 80% of the mean signal strength amplitude. Respiratory sEA_{di} peaks had to be within a range of 1,000 ms around the respiratory peak in the tEA_{di} signal to be detected as a matching breathing effort. When multiple sEA_{di} peaks were detected within this range from de tEA_{di} peak, the closest the sEAdi peak closest to the tEAdi peak was defined as the respiratory sEA_{di} respiratory peak. The sEA_{di} signal was processed with an electrocardiogram gating technique as described in previous studies and was further processed with a boxcar averager.[17,18] Processing of tEA_{di} was integrated into the Servo-i ventilator.[19]

Other documented data were age, sex, and body mass index of the patient; reason for ICU admission; Richmond Agitation Sedation Scale at the moment of assessment; number of days on invasive ventilation at the moment of assessment; Acute Physiology and Chronic Health Evaluation II score; and ventilator mode and parameters (including F_{IO_2}, breathing frequency, oxygen saturation, PEEP, peak inspiratory pressure, and tidal volume).

Data Analysis

The number of matching breathing efforts detected by sEA_{di} and tEA_{di} was divided by the total number of breathing efforts detected by tEA_{di}. The temporal relation was investigated on selected stable recordings of 10 successive breathing efforts per subject. The stable recordings were visually selected from the recording. First, we determined the duration of peak-to-peak time intervals between successive breathing efforts (the time between peak amplitudes) in both sEA_{di} and tEA_{di} (9 peak-to-peak intervals per patient). Thereafter, the temporal correlation and agreement between both methods were calculated.

Statistics

Non-parametric statistics were used with median (interquartile range [25th–75th percentile]) because of the small population size. The Spearman rank correlation coefficient (r) was calculated to determine the strength of the relation between sEA_{di} and tEA_{di}. Bland-Altman plots were used to determine the agreement between sEA_{di} and tEA_{di}.[20] Values with significance levels of ≤.05 were considered significant. Data analysis was performed with MATLAB R2016a (MathWorks, Natick, Massachusetts). The statistical analyses were performed by using SPSS version 24 (SPSS, Chicago, Illinois).

Results

Between December 2014 and April 2015, we screened all patients in the ICU who were ventilated with a Servo-i. Results of the screening and inclusion process are shown in Figure 2. Fifteen subjects were included (see Table 1 for baseline characteristics), all the

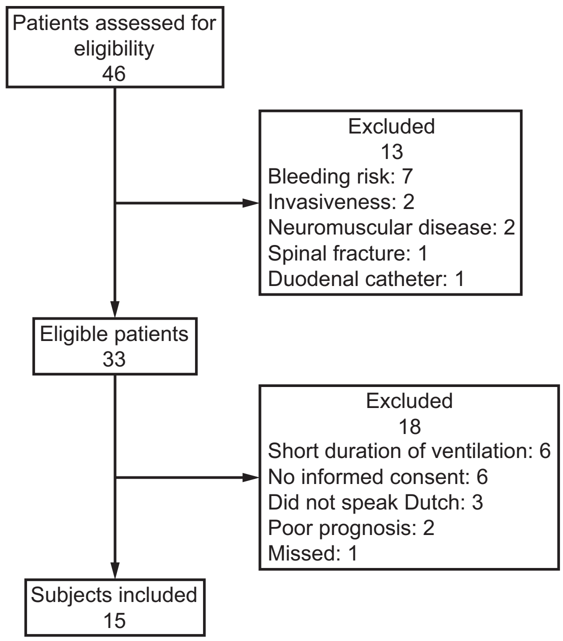

Fig. 2. Flow chart.

Table 1. Baseline Characteristics

Characteristic	Value
Subjects, *N*	15
Age, median (IQR) y	62 (45–72)
Males, *n* (%)	9 (60)
Body mass index, median (IQR) kg/m^2	26 (23.1–26.4)
Reason for ICU admission, *n* (%)	
Medical	9 (60)
Elective surgery	3 (20)
Emergency surgery	3 (20)
RASS score at assessment, median (IQR)	−2.0 (−4.0 to 1.0)
Duration of ventilation at assessment, median (IQR) d	4 (2–7)
APACHE II score, median (IQR)	22.5 (20–26.8)
ICU mortality, *n* (%)	5 (33)

IQR = interquartile range
RASS = Richmond Agitation Sedation Scale
APACHE II = Acute Physiology and Chronic Health Evaluation II

subjects tolerated the measurements well. Ventilator settings and respiratory parameters during the measurements are shown in Table 2.

Breathing Effort Detection

A total of 3,675 breathing efforts were accurately obtained by using tEA_{di}, of which 3,162 (86.0%) were matched by sEA_{di} detection. There was a great variety in the number of matching breathing efforts on a per-subject level, which ranged from 66.1 to 98.5% (see the supplementary materials at http://www.rcjournal.com for detailed per-subject results).

Table 2. Ventilator Settings and Respiratory Parameters

Settings and Parameters	Value
Ventilation mode, *n* (%)	
Pressure support	11 (73)
NAVA	4 (27)
F_{IO_2}, median (IQR)	25 (21–30)
Frequency, median (IQR) breaths/min	21 (18–26)
Oxygen saturation, median (IQR) %	97 (95–98)
P_{aO_2}/F_{IO_2}, median (IQR)	297 (210–344)
PEEP, median (IQR) cm H_2O	5 (5–7)
Peak inspiratory pressure, median (IQR) cm H_2O	14.5 (11.1–20.7)
Tidal volume, median (IQR) mL/kg	6.8 (5.3–7.9)

NAVA = neurally adjusted ventilatory assist
IQR = interquartile range (25th–75th percentile)

Temporal Relation Between sEA_{di} and tEA_{di}

The temporal relation could not be determined in 4 patients due to impaired signal quality of the sEA_{di}. Breathing effort time intervals for the selected stable recordings showed a statistically significant correlation ($r = 0.95$, $P < .001$) between sEA_{di} and tEA_{di}. The mean difference in the time intervals between sEA_{di} and tEA_{di} was 10.1 ms, with limits of agreement from –410 to 430 ms (Fig. 3).

Discussion

This pilot study compared sEA_{di} with tEA_{di} in subjects who were invasively ventilated. Only 86.0% of all tEA_{di} that detected breathing efforts were matched by sEA_{di} recordings. In stable parts of the recordings, however, sEA_{di} and tEA_{di} had excellent temporal correlation. Further visual analysis revealed that the inability to determine breathing efforts with sEA_{di} was mainly caused by impaired signal quality. Recently, surface and esophageal electromyography were compared in healthy subjects after phrenic stimulation. As with our study, esophageal signal amplitudes were higher than amplitudes of surface electromyography.[21]

High body mass indices and thus increased electrode-to-diaphragm distance could have influenced the sEA_{di} signal strengths. Although interindividual variability in signal strengths was high, the ratio of tEA_{di} to sEA_{di} remained relatively stable between the successive breathing efforts per subject. Differences in signal strengths between patients might indicate an effect of differences in anatomy

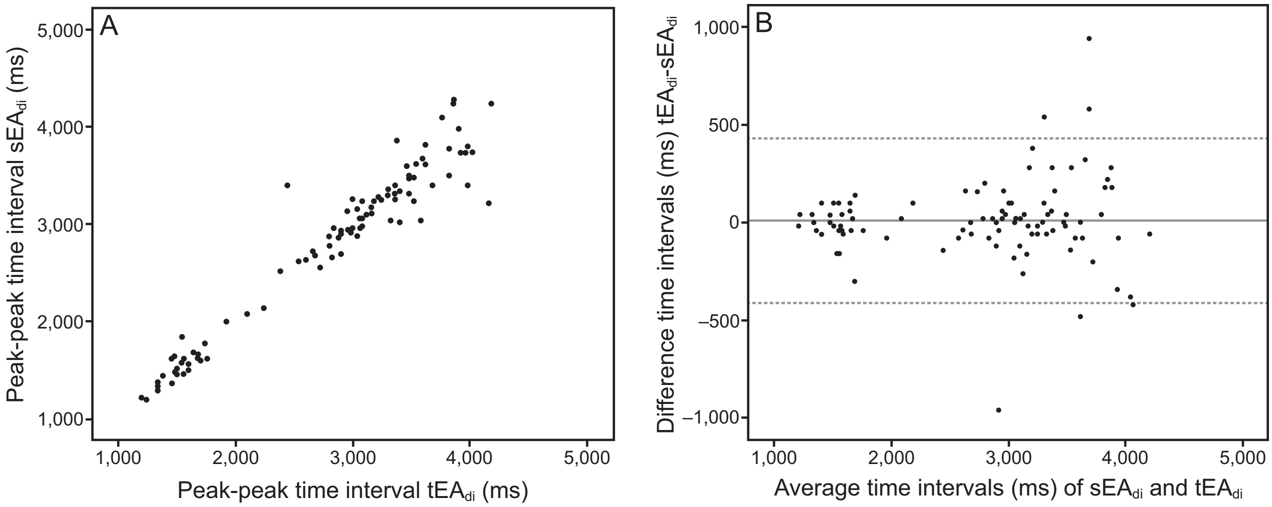

Fig. 3. A: A scatterplot of peak-to-peak time intervals, showing the correlation between surface electrical activity of the diaphragm (sEA_{di}) and transesophageal electrical activity of the diaphragm (tEA_{di}). B: Bland-Altman plot, showing the temporal agreement between sEA_{di} and tEA_{di}. The dashed lines indicate the limits of agreement.

and measurement conditions. Because electrodes were placed after palpation, we could not rule out the possibility of variety in the electrode-to-diaphragm distance among subjects. The sEA_{di} was thereby more susceptible for signal disturbances and noise than tEA_{di}. Activity of the abdominal muscles near the diaphragm could have interfered with the diaphragmatic activity. This phenomenon, also known as cross-talk, might be a disadvantage of surface electromyography.[22]

In our study, coughing or subject movements could have interfered with sEA_{di} measurements. However, visual analysis of stable recordings showed similar sEA_{di} and tEA_{di} tidal breathing curves (Fig. 1). This suggested that minimal interference of adjacent muscle activity was present in these parts of the recording. Unfortunately, our study was too small to determine possible external causes of impaired sEA_{di} signal quality. Although not interfering with the sEA_{di} recording, the sternocleidomastoid and parasternal muscles also contribute to inspiration. However, the diaphragm is the main inspiratory muscle and, therefore, is a reliable signal for triggering invasive ventilation. Thus we chose to compare only sEA_{di} with tEA_{di}.

The sEA_{di} and tEA_{di} signals were processed differently. The tEA_{di} signal was processed with the double-subtraction technique and was smoothed with an exponential filter, whereas the sEA_{di} signal was processed with a root mean square signal.[19,23] Therefore, peak amplitudes of sEA_{di} and tEA_{di} have a quadratic difference. Studies so far have used different thresholds for analysis of tEA_{di} breathing effort detection.[9,24] Because signal strengths were higher in tEA_{di}, we chose a uniform threshold based on the percentage of maximum peak signals to compare sEA_{di} with tEA_{di}.

So far, sEA_{di} has been studied in subjects with COPD without invasive ventilation, neonates on noninvasive respiratory support, and in healthy subjects without invasive ventilation in which sEA_{di} was compared with tEA_{di}.[16,18,21,25,26] As a proof of concept, we were interested in the best possible performance of sEA_{di} compared with tEA_{di} during invasive ventilation. Therefore, 10 successive breathing efforts per subject were visually selected on parts of the recordings without signal disturbances. In these parts, we found excellent temporal correlation and good agreement between the matching sEA_{di} and tEA_{di} breathing efforts.

Recently, Beloncle et al[27] showed, in a small study, that EA_{di}-based monitoring of subjects during supportive invasive ventilation can improve patient-ventilator interaction. Synchrony between patient and the ventilator during invasive ventilation is pivotal to minimize adverse events, sEA_{di} provides additional information about patients' efforts during invasive ventilation and thus might function as a noninvasive bedside monitoring tool in the future.[28,29] However, because of the many signal instabilities in our recordings, this method is not yet reliable and more research has to be conducted to address external causes of signal noise.

Limitations

This study had some limitations. Most importantly, the small number of subjects precluded us from designating factors that significantly impaired the performance of sEA_{di} We, therefore, were unable to perform a subgroup analysis. Furthermore, we recorded sEA_{di} and tEA_{di} over a short period of time and only once in each patient.

Therefore, the reproducibility of sEA_{di} compared with tEA_{di} was not assessed. More so, our algorithm for automatic breathing effort detection was not capable of discriminating the stable from the instable recordings.

Conclusions

We found that sEA_{di} was not reliable for breathing effort detection in adult subjects invasively ventilated because of signal instabilities. However, in stable situations, sEA_{di} and tEA_{di} had excellent temporal correlation and good agreement. Although optimization of sEA_{di} is necessary, these findings indicated that sEA_{di} has potential as a monitoring tool during invasive ventilation.

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