Respiratory muscle effort during expiration in successful and failed weaning from mechanical ventilation

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Supplemental Digital Content 1

SUPPLEMENTAL MATERIALS AND METHODS

Diaphragm electrical activity processing

EAdi signal processing from the multiple electrodes on the nasogastric catheter was performed based on the method of Sinderby and colleagues and implemented in Matlab (R2014b, The Mathworks, Natick, MA).[1-3]

Step1: Raw EAdi recordings from all electrodes were bandpass filtered between 16 Hz and 800 Hz to remove low-frequency and high-frequency noise (Figure 1).

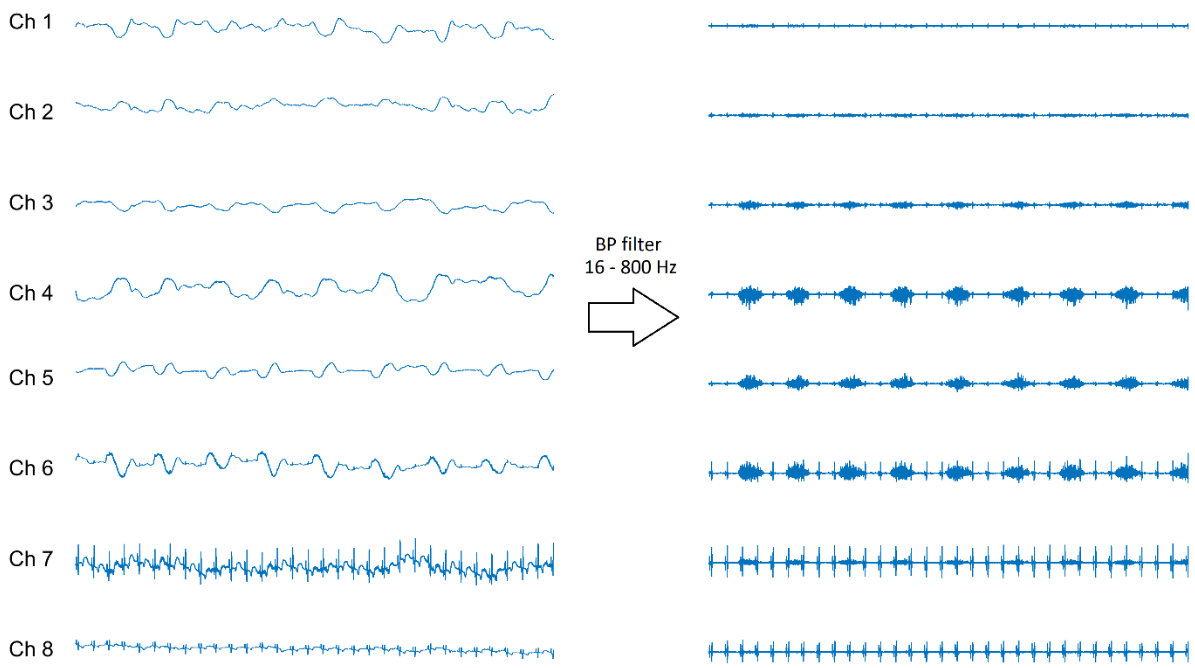

Figure 1. Bandpass filtering of the EAdi signal from all 8 channels of the esophageal electrode.

Step 2: The cross-correlation and double-subtraction technique, developed by Sinderby and colleagues, was applied to determine the center of the electrical active region of the diaphragm (EAR_{di} center).[2] The diaphragm is a thin flat muscle which moves downwards during inspiration, as a result the EAR_{di} center moves downwards during inspiration. The location of the center of the EAR_{di} can be identified by cross-correlation analysis of EAdi signals obtained with a multiple-array electrode. With a perpendicular electrode arrangement cross correlation values are expected to be close to -1 when the signals, obtained on opposite sides of the EAR_{di}, are correlated at a lag of 0 ms. Cross-correlation analysis can be performed between signals from, e.g., electrode channels 1 vs. 3, 2 vs. 4, and 3 vs. 5, etc for each signal segment between 50% and 75% of the QRS complexes. The most negative correlation coefficient between any two channels indicates that the respective signals are the most reversed in polarity. After the EAR_{di} center position is determined, the signal segment obtained from the two electrode channels that are located next to the EAR_{di} center are subtracted from each other. This algorithm yields a new signal, which is less influenced by electrode filtering and enhanced in signal-to-noise (SN). In Figure 2 an example of the double-subtracted signal is shown.

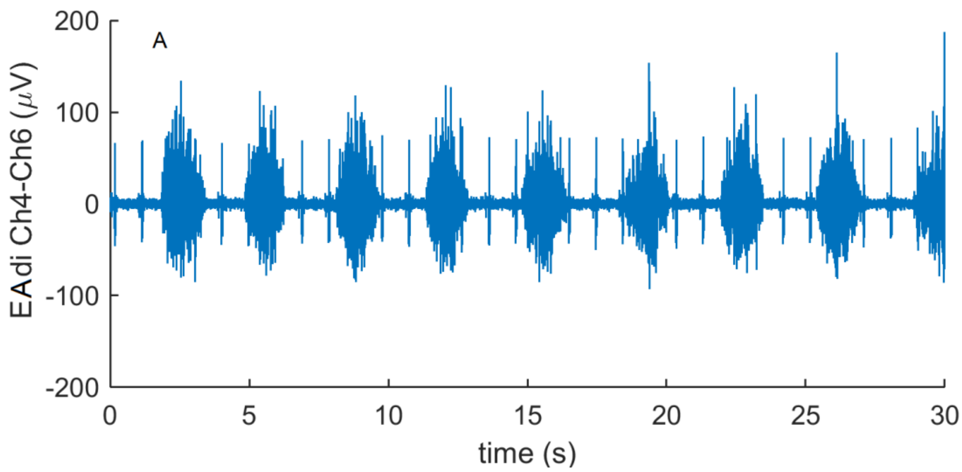

Figure 2. The EAdi signal from Figure 1 after the double-subtraction technique. Channel 4 and 8 have a cross-correlation value around -0.8. QRS complexes from the ECG are visible.

Step 3: The EAdi signal is often contaminated with the QRS complexes from the ECG signal. We used a wavelet-based adaptive filter for removing ECG interference in EAdi signals.[4] This filter has negligible effects on the power spectrum of the EAdi. See Figure 3.

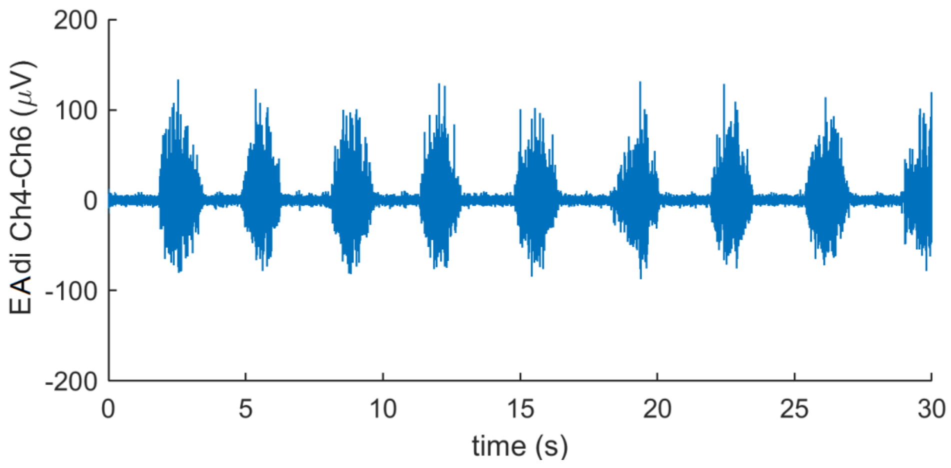

Figure 3. The EAdi signal from Figure 2 after removal of ECG interference.

Step 4: To be able to reliably place markers for peak EAdi and onset of neural inspiration we performed rectification of the EAdi signal followed by a low-pass filter of 3Hz. This results in an envelope EAdi, which many clinicians may will recognize as a typical Neurally Adjusted Ventilatory Assist (NAVA) signal from the Servo-I ventilator (Maquet Critical Care, Sölna, Sweden). See Figure 4.

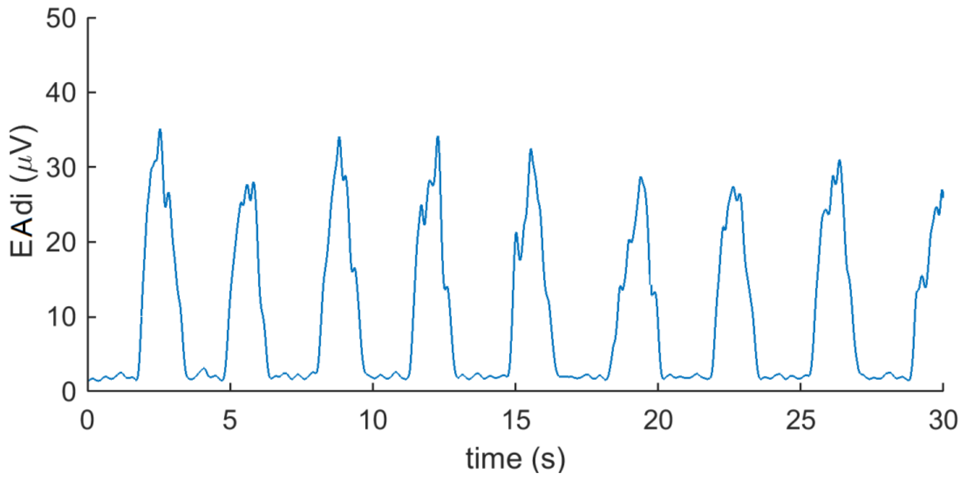

Figure 4. The EAdi envelope signal from Figure 3 after rectification and low-pass filtering.

For each filtering step we applied zero-phase digital filters. These filters can be used in offline signal processing to create filtered signals that have no phase-shifting of the signal.

Noise level calculation EAdi

The “true” noise level in the study be Emeriaud and colleageus was estimated by the level of the signal during short periods of apnea.[5] In the current study, however, no short periods of apnea were present. Therefore, we estimated the noise level of the EAdi by evaluating the noise level on an electrode channel where no diaphragm activity was measured during the same period. Signals were visually inspected to control for the absence of diaphragm activity on the electrode channel. Noise level was calculated between QRS complexes. In Figure 5 an examples is shown.

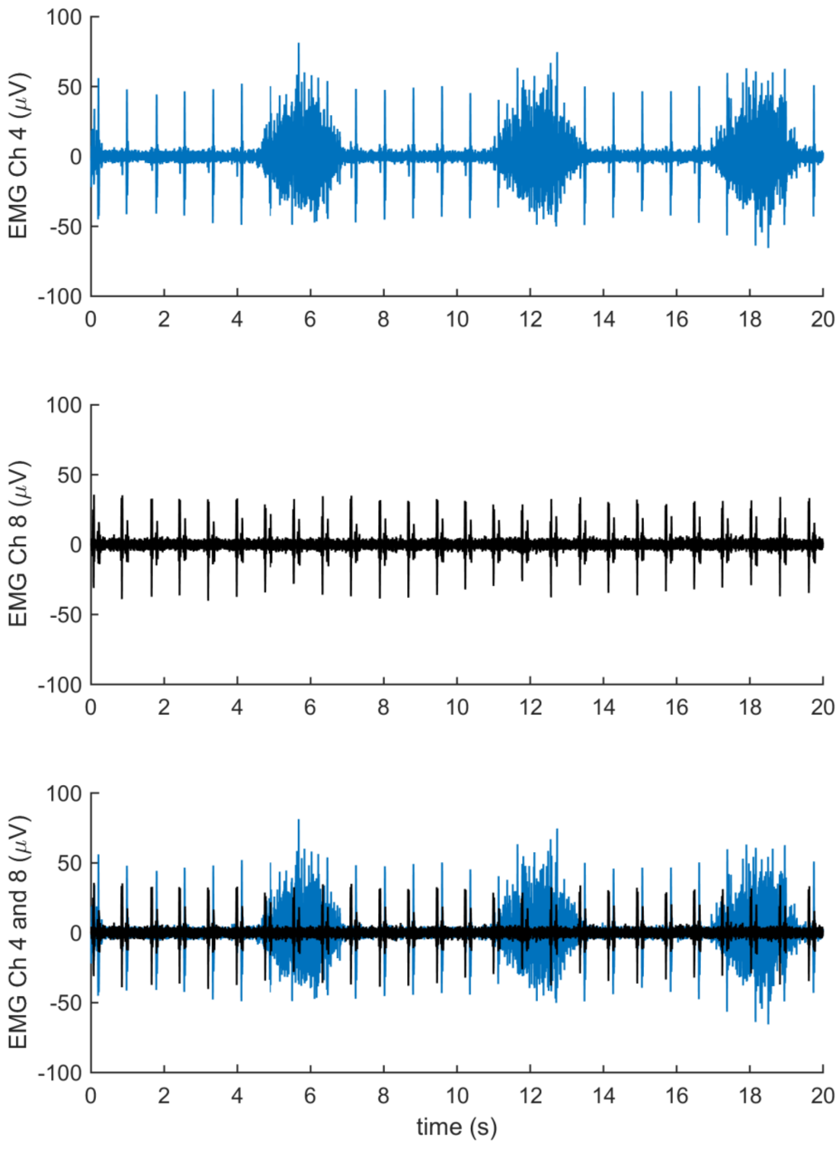

Figure 5. Electrical activity of the diaphragm measured on channels 4 and 8 from the esophageal electrode during the exact same period. There is no diaphragm activity present in channel 8, whereas the noise level is equal to channel 4. In the bottom panel the two signals are superimposed.

SUPPLEMENTAL REFERENCES

1. Sinderby CA, Lindstrom L, Grassino AE: Automatic assessment of electromyogram quality. J Appl Physiol 1995; 79: 1803-1815

2. Sinderby CA, Beck JC, Lindstrom LH, Grassino AE: Enhancement of signal quality in esophageal recordings of diaphragm EMG. J Appl Physiol 1997; 82: 1370-1377

3. Sinderby CA, Beck J, Spahija J, Weinberg J, Grassino A: Voluntary activation of the human diaphragm in health and disease. J Appl Physiol 1998; 85: 2146-2158

4. Zhan C, Yeung LF, Yang Z: A wavelet-based adaptive filter for removing ECG interference in EMGdi signals. J Electromyogr Kinesiol 2010; 20: 542-9

5. Emeriaud G, Beck J, Tucci M, Lacroix J, Sinderby C: Diaphragm electrical activity during expiration in mechanically ventilated infants. Pediatr Res 2006; 59: 705-710