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Diaphragmatic electromyography in preterm infants: The influence of electrode positioning

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Abstract

Objective: To determine the effect of changing electrode positions on vital signs and respiratory effort parameters measured with transcutaneous electromyography of the diaphragm (dEMG) in preterm infants.

Methods: In this observational study, simultaneous dEMG measurements were performed at the standard position and at one alternative electrode position (randomly assigned to lateral, superior, medial, inferior to the standard placement, or dorsal). The activity of the diaphragm was measured for 1 hour at both positions. Main outcome measures were the agreement in heart rate (HR), respiratory rate (RR), and percentage difference in dEMG parameters of respiratory effort (peak and tonic activity, amplitude, area under the curve, and frequency content) between the standard and alternative electrode positions.

Results: Thirty clinically stable preterm infants (gestational age 30.1 ± 3.0 weeks) with either no or noninvasive respiratory support were included. Agreement in HR was excellent at all positions (ICC > 0.95) while RR agreement showed more diversity (ICC range 0.40-0.86). Mixed modeling of dEMG parameters revealed that medial and inferior placement measured the weakest signals (median 75.5% and 64.5% lower dEMG amplitude). Lateral electrode placement showed the highest similarity to standard positioning (median 23.5% lower amplitude).

Conclusion: Measuring HR showed high similarity at all positions. However, registration of RR and respiratory effort is clearly influenced by the electrode position. Electrodes in the same transversal plane as the diaphragm, and at sufficient distance from each other, provide the best agreement with the standard positioning.

KEYWORDS

cardiorespiratory monitoring, neonatal intensive care unit, respiratory effort

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1 | INTRODUCTION

Chest impedance (CI) is the current standard for cardiorespiratory monitoring in preterm infants. Although it provides monitoring of heart rate (HR), respiratory rate (RR), and the breathing pattern, it does not provide information on the respiratory effort delivered by the infant.

Recently, transcutaneous electromyography of the diaphragm (dEMG) has been suggested as an alternative for CI.[1] dEMG measures the electrical activity of the frontal diaphragm with three surface electrodes. Previous research has shown that dEMG accurately measures HR and RR,[1] compared with CI, and does provide information on respiratory effort in preterm infants.[2,3]

In clinical practice, the electrodes used during CI monitoring are periodically repositioned to avoid damage to the vulnerable skin of preterm infants. This also applies to transcutaneous dEMG when used for daily clinical monitoring. However, the variability in signal acquisition and analysis procedures for dEMG is substantial[4-6] and, to our knowledge, the effect of using alternative electrode positions on the dEMG signal and its output parameters is unknown. This information is essential before this technique can be implemented as a reliable cardiorespiratory monitor in preterm infants in the neonatal intensive care unit (NICU). If alternative electrode positions to measure dEMG would show similar reliability in vital signs, this could introduce numerous clinical applications, including apnea detection and classification,[7] and more objective weaning of respiratory support based on electrical activity of respiratory muscles.[2] The aim of this observational study was to describe the effect of changing the electrode positions on the registration of vital signs and respiratory effort parameters measured by dEMG in preterm infants. We hypothesized that changing the electrode positions would influence signal strength and therefore the information on the respiratory effort, but that vital signs would be robust enough to be monitored accurately.

2 | MATERIALS AND METHODS

2.1 | Study population

This prospective observational study was conducted in the NICU of the Emma Children's Hospital, Amsterdam University Medical Centres, The Netherlands. We included clinically stable preterm infants (gestational age >26 weeks), defined as receiving no or noninvasive respiratory support with an oxygen need below 30% and having less than or equal to two apnea per hour. Infants with major congenital malformations were excluded.

2.2 | Study protocol

The electrical activity of the diaphragm was continuously measured in supine position for 1 hour using dEMG. Three skin electrodes (disposable Kendall H59P Electrodes; Covidien, Mansfield, MA) were placed at the standard position in all included infants: two electrodes placed bilaterally at the costo-abdominal margin in the midclavicular line, and one reference electrode placed on the sternum.[8] Subsequently, two electrodes were placed on an alternative position. The infants were randomly assigned using sealed opaque envelopes to a synchronized measurement in one of five alternative positions: lateral, superior, medial, or inferior to the standard placement or dorsal at the same level as the standard electrodes (Figure 1). The extra pair of electrodes used the same reference electrode as the standard position. This method resulted in five subgroups of patients in which in total five electrodes were used in each patient to measure the electrical activity of the diaphragm simultaneously and directly compare the standard and the alternative position. During the measurement nursing procedures, except feeding, were postponed to optimize measurement conditions. CI monitoring continued during the dEMG measurement according to the unit's standard of care. The study protocol was approved by the Institutional Ethics Review Board (METC AMC, ABR registration, NL62332.018.17) and both parents provided written informed consent.

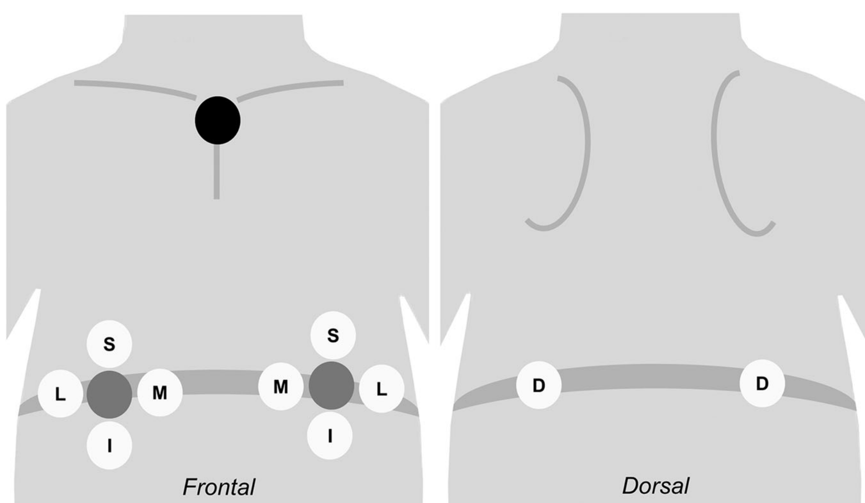

FIGURE 1 Schematic representation of the standard (gray circles) and alternative (white circles) electrode positions covering the diaphragm: D, dorsal; I, inferior; L, lateral; M, medial; S, superior. Reference electrode in black

2.3 | Signal acquisition

The electrodes were connected to a portable 16-channel physiological signal amplifier (Dipha-16; Macawi Medical Systems, Enschede, The Netherlands). The raw unipolar signals were digitally transformed into two bipolar dEMG signals by subtracting the unipolar electrode signals. Each bipolar derivation was filtered (using a digital first-order high-pass filter with a cut-off frequency of 20 Hz) to remove baseline noise. After removing the electrical activity of the heart with the gating technique, described by O'Brien et al[9] the gated dEMG signals were averaged with a moving time window and the root mean square was calculated to construct a breathing waveform. This analysis was done in real time within Polybench (Applied Biosignals, Weener, Germany). The resulting two breathing waveforms were used for further analysis. A camera was placed above the bed to be able to interpret signal artefacts afterward, by, for example, patient movements.

2.4 | Data collection and analysis

To analyze the electrical activity of the diaphragm at the standard and alternative electrode positions, for each infant six data segments of 30 seconds were selected, one segment in each 10-minute window. These epochs were estimated to be long enough to provide insight in the breathing pattern during each period. This multiple measures approach was used to provide an equal distribution of data points over time in both positions and look into the consistency of the dEMG signal parameters over time. As a result, these outcome parameters represent the entire measurement at this specific position. All selected segments were free of movement and/or technical artefacts in both bipolar derivations, to compare the exact time-linked data from both positions.

In each segment, vital signs and dEMG signal parameters were determined. The raw dEMG signal was used to determine HR and the processed dEMG signal, that is, the respiratory waveform, was used to calculate RR. With respect to the dEMG signal parameters the raw signal was used to determine the median power frequency (MPF), a measure for the frequency distribution of the raw dEMG signal. Respiratory effort was assessed by calculating the area under the curve (AUC), as a measure for signal power and by the following breath-by-breath parameters using the averaged dEMG signal: maximal electrical activity (peak activity, $dEMG_{Peak}$), lowest electrical activity (tonic activity, $dEMG_{Tonic}$), and the amplitude (the difference between the peak and tonic activity, $dEMG_{Amp}$). The dEMG parameters at the alternative positions were compared with the standard position, that is, the gold standard, and expressed as a percentage difference (%diff). For $dEMG_{Peak}$, $dEMG_{Tonic}$, and $dEMG_{Amp}$ the mean of each segment was calculated and stored together with AUC and MPF. This analysis resulted in six values per parameter, for each position (standard and alternative), per infant.

2.5 | Statistical analysis

Due to the exploratory nature of this study and the lack of available data on the outcome measures, we did not perform a formal sample size calculation. Instead a convenience sample of 30 infants was included.

All descriptive and continuous variables were expressed as mean and standard deviation (SD) or median and interquartile range (IQR), depending on their distribution. The intraclass correlation coefficient (ICC; two-way mixed, absolute agreement) and the mean difference were used to express the level of agreement in HR and RR registration. To correct for the repeated, multilevel, measurements design, we used a linear mixed effects model[10,11] to evaluate the differences in dEMG parameters between the standard and alternative positions. Skewed parameters were log-transformed. The alternative position with the smallest percentage difference to the standard position was used to estimate the intercept of the mixed model. Based on the expected individual differences a random intercept was added to the model for each patient.

SPSS (version 25; IBM, Armonk, NY) and Rstudio (version 3.5.1; R Foundation for Statistical Computing, Vienna, Austria) were used for statistical analysis. In all tests and models $P < .05$ was defined as statistically significant.

3 | RESULTS

Between September 2017 and May 2018, 33 preterm infants were included of whom 19 (63.3%) were male. Two infants could not be measured due to a transfer to a local hospital and the hardware malfunctioned in one infant. Inclusion continued until the sample size was reached, equally distributed over five groups (Table 1).

3.1 | Vital signs monitoring at alternative electrode positions

Table 2 shows that the agreement in calculated HR was excellent with an ICC above 0.95 and a median difference of 0 bpm. The agreement in RR calculation showed more diversity (ICC range 0.40-0.86). The lowest ICC values were found in the superior (ICC, 0.40) and medial position (ICC, 0.57). Furthermore, the median difference in RR shows that both an underestimation and overestimation was found for the RR at alternative positions, compared with the standard position.

3.2 | Assessment of respiratory effort

The boxplots in Figure 2 show the distribution of the five dEMG parameters at the alternative positions in relation to the standard position (which is set to be equal to 0, Supporting Information Data). Overall the median values of the dEMG parameters measured at alternative positions were lower compared with the standard position. The lateral position measured the signal with the highest similarity to the standard position (median $dEMG_{Tonic}$ and $dEMG_{Amp}$

TABLE 1 Patient characteristics in the different electrode position groups

	All (n = 30)	Lateral (n = 6)	Inferior (n = 6)	Superior (n = 6)	Medial (n = 6)	Dorsal (n = 6)
GA, wk	30.1 (3.0)	29.6 (3.4)	30.0 (2.9)	30.7 (2.7)	29.4 (3.7)	30.7 (2.9)
Age at inclusion, wk	32.1 (2.4)	33.3 (1.4)	31.6 (2.0)	32.0 (2.5)	32.2 (2.9)	31.6 (2.6)
Birth weight, g	1460 (645)	1330 (512)	1479 (560)	1478 (680)	1282 (820)	1730 (744)
Weight at inclusion, g	1584 (550)	1680 (342)	1492 (482)	1579 (572)	1503 (744)	1664 (698)
Respiratory support (n = 29[a])						
LFNC, n	3	1	1	0	0	1
HFNC, n	12	3	2	3	1	3
nCPAP, n	12	2	3	1	4	2
nIPPV, n	2	0	0	1	1	0
FiO_2, %	0.21 (0.2-0.24)	0.21 (0.21-0.23)	0.21 (0.21-0.24)	0.21 (0.21-0.21)	0.22 (0.21-0.23)	0.21 (0.21-0.23)

Note: Characteristics are expressed as mean (SD), median (interquartile range) or count. No significant differences were found between the individual groups ($P > .05$).

Abbreviations: FiO_2, fraction of inspired oxygen; GA, gestational age; HFNC, high-flow nasal cannula; LFNC, low-flow nasal cannula; n, number of infants; nCPAP, nasal continuous positive airway pressure; nIPPV, nasal intermittent positive pressure ventilation.

[a]One infant received no respiratory support.

difference, 1.3% and 23.4%, respectively) and was therefore used as the mixed model's intercept.

Overall, the weakest dEMG signals were measured at the medial, inferior, and dorsal positions. This is for example seen in a drop of signal amplitude with a median decrease in $dEMG_{Amp}$ of 75.5%, 64.5%, and 52.1%, respectively, compared with the standard position. Furthermore, spectral analysis showed that the medial position was more susceptible to noise with an MPF significantly higher than the intercept (median MPF 11.8% higher).

4 | DISCUSSION

This study shows that using different electrode positions for measuring dEMG in stable preterm infants does not impact HR monitoring compared with the standard electrode position. However, alternative electrode positioning does change monitoring RR and dEMG parameters of respiratory effort. Overall, lateral placement of the electrodes resulted in the smallest change in these parameters compared with standard positioning. All alternative positions showed a lower median measured electrical activity than the standard electrode position.

The similarity in dEMG monitoring between the lateral and standard position, is probably best explained by the fact that both positions are within the same transversal plane, covering the diaphragmatic muscle. Although this is also the case with the electrodes in medial position, medial signal strength was much lower. This difference may be caused by the small interelectrode distance (IED[12,13]), which is especially relevant in small preterm infants. When the electrodes are close to each other the measured differential is small and therefore the signal is more prone to noise (eg, electrical interference). This is also reflected by the high MPF in this position, indicating that a large number of high-frequency components remain after processing of the signal. Due to the lower signal-to-noise ratio breath detection as well as the detection of differences in respiratory effort is less accurate.

Placing the electrodes superior or inferior to the standard position, had an impact on the dEMG signal as monitoring was performed in a different transversal plane and the distance to the diaphragm increases. Furthermore, the level of cardiac interference changes and potential movement artefacts from lower or upper extremities can be picked up, which can deteriorate the respiratory signal's quality.

TABLE 2 Agreement in vital signs measured in pairs of standard and alternative electrode position

Standard position		Alternative positions			
HR standard (bpm)	RR standard (breaths/min)	Position[a]	ICC HR (95% CI)	ICC RR (95% CI)	Difference in RR[b] (breaths/min)
148 (142-158)	47 (39-56)	Lateral	1 (0.99, 1)	0.86 (0.74, 0.85)	1 (−1 to 6)
155 (137-168)	57 (49-68)	Superior	1 (0.99, 1)	0.40 (0.10, 0.64)	3 (−7.8 to 15.5)
153 (140-164)	48 (36-56)	Medial	1 (0.99, 1)	0.57 (0.30, 0.76)	1(−4.8 to 10)
150 (144-154)	58 (45-64)	Inferior	0.99 (0.99, 1)	0.86 (0.74, 0.93)	1 (−4 to 6)
148 (142-154)	53 (40-61)	Dorsal	0.98 (0.95, 0.99)	0.79 (0.62, 0.88)	−1 (−3 to 4.3)

Note: Data are presented as median (interquartile range), unless stated otherwise.

Abbreviations: bpm, beats per minute; CI, confidence interval; HR, heart rate; ICC, intraclass correlation coefficient; RR, respiratory rate.

[a]Each group consisted of six infants.

[b]Difference in HR is not shown because the median and interquartile range of this parameter was 0 and (0 to 0) for all positions.

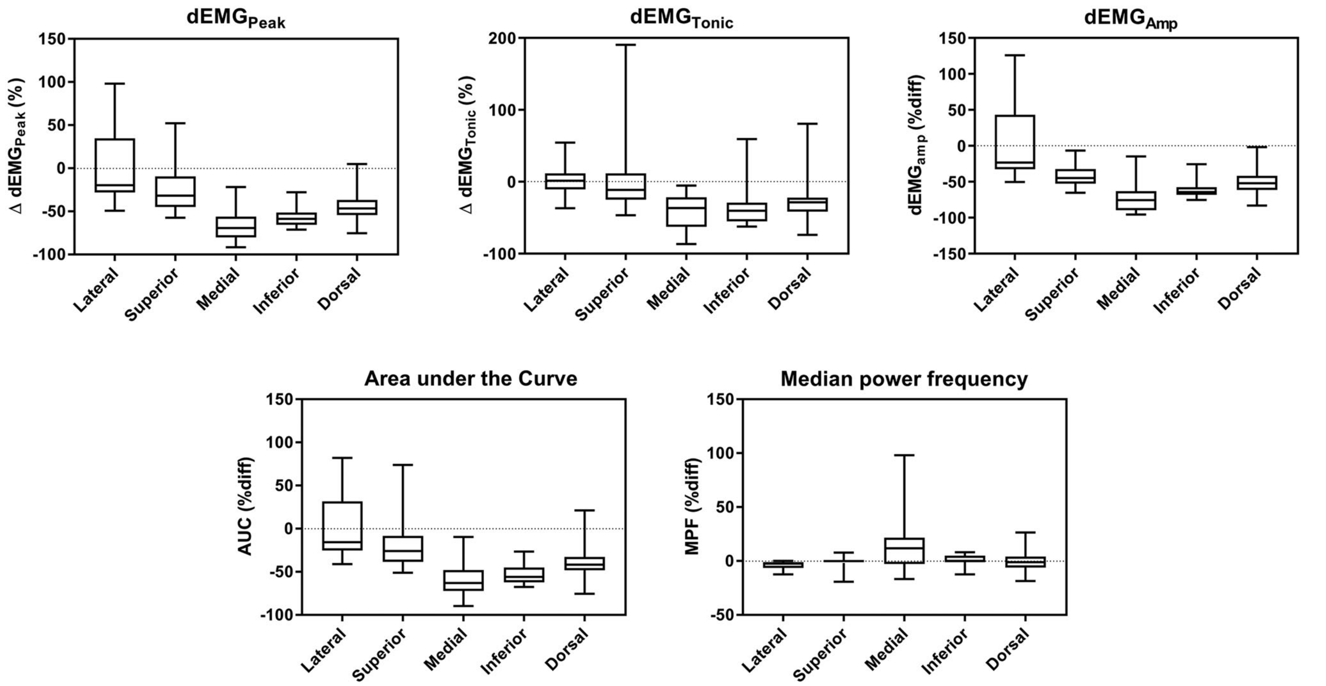

FIGURE 2 The differences in five dEMG signal parameters recorded at the alternative electrode positions as percentage change compared with the standard position (the dotted line, set to 0). AUC, area under the curve; dEMG, electromyography of the diaphragm; $dEMG_{Amp}$, breathing amplitude of dEMG; $dEMG_{Peak}$, peak electrical activity of dEMG; $dEMG_{Tonic}$, tonic electrical activity of dEMG; MPF, median power frequency; %diff, percentage difference of alternative to standard position

Finally, we tested the dorsal positioning of the electrodes. As monitoring is done in the same transversal plane as the standard position, we expected good agreement in dEMG monitoring parameters. This was true for RR monitoring, but not for respiratory effort. The anatomical difference in the diaphragm's orientation (measuring the frontal vs the dorsal diaphragm where the crural insertion is more caudal) can be a plausible explanation.

An aspect that might also partly explain the differences in dEMG parameters is the electrode-skin interface. Huigen et al[14] already described that the amount of signal noise is strongly related to the electrode-skin contact. In our study we used disposable Ag/AgCl electrodes, known to be suitable for this kind of recording.[15] However, electrode-skin contact may differ between alternative electrode positions due to differences in body geometry and the fact that in some positions the infant is lying on the electrode. This contact difference may affect the dEMG signal strength.

To our knowledge, this is the first study that investigated different electrode positions for dEMG measurements in preterm infants. Published data on electrode positioning for diaphragm monitoring in other age groups is also scarce. Lansing et al (1989) studied dEMG in adults and reported the phase and distribution of the electrical signal generated by the diaphragm in supine and upright position during different breathing patterns (normal and large tidal breaths). Electrodes were placed along the midaxillary, midclavicular, and sternal lines. They found a position-signal dependency and described that the inspiratory peak voltage shifted one electrode downward when subjects were breathing at 60% to 80% of their vital capacity, reflecting the movement of the diaphragm during respiration.[16] Although direct comparison with our study is difficult due to the clear difference in IED between preterm infants and adults, these results do support our finding that (change in) electrode position does impact the dEMG signal and should be taken into account when interpreting dEMG outcome parameters.

This study has several limitations. First, we did not record all positions simultaneously in each infant. Although this would have been the ideal setup, we considered it not feasible in preterm infants. The small size of the chest and abdomen limits the number of electrodes that can be applied. Furthermore, placing multiple skin electrodes would increase the risk of skin lesions and patient discomfort.

Second, as a result of this study design the sample size for each electrode position was relatively small. However, to get insight into the consistency of the signal at several time points, the repeated measures design enabled the incorporation of more individual patient data in a mixed-effects model. The model showed the differences between the various positions. However, with the use of a difference parameter (%diff to standard) the margin of error of the model's intercept should be kept in mind because the intercept is not the standard position but the difference between lateral and standard position. Finally, we included clinically stable infants only. We cannot determine whether the results will be similar in critically ill infants. For example, pulmonary distension in infants on mechanical ventilation or abdominal distension during necrotizing enterocolitis could change the position of the diaphragm with respect to the electrode position in these infants. It would be interesting to investigate if the current findings can be confirmed in these infants.

Despite these limitations, the current study provides important information for dEMG monitoring in clinical practice. It suggests that lateral placement is the best alternative position for standard midclavicular positioning to record HR, RR, and respiratory effort with dEMG. The small differences in RR are probably not clinically relevant. The dEMG breathing parameters show more variability when comparing standard to lateral positioning and this should be taken into account in future analysis software. A future solution could be the use of nonadhesive electrodes, incorporated in a belt, making changes in electrode position for skin integrity no longer necessary.

5 | CONCLUSION

This study suggests that in clinically stable preterm infants, measuring HR with dEMG is possible at different electrode positions. However, using different electrode positions does impact RR monitoring and respiratory effort parameters. In general, placing electrodes in the same transversal plane and at sufficient distance from each other provides the best agreement with the standard midclavicular positioning.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

AUTHOR CONTRIBUTIONS

RWvL wrote the first manuscript. RWvL, REB, CGdW, FHdJ, AHvK, and GJH revised the manuscript. All authors agreed to the submission of the manuscript. RWvL submitted the paper.

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REFERENCES

1. Kraaijenga JV, Hutten GJ, de Jongh FH, van Kaam AH. Transcutaneous electromyography of the diaphragm: a cardio-respiratory monitor for preterm infants. *Pediatr Pulmonol*. 2015;50(9):889-895. https://doi.org/10.1002/ppul.23116
2. de Waal CG, Hutten GJ, Kraaijenga JV, de Jongh FH, van Kaam AH. Electrical activity of the diaphragm during nCPAP and high flow nasal cannula. *Arch Dis Child Fetal Neonatal Ed*. 2017;102:F434-F438. https://doi.org/10.1136/archdischild-2016-312300
3. Kraaijenga JV, Hutten GJ, de Jongh FH, van Kaam AH. The effect of caffeine on diaphragmatic activity and tidal volume in preterm infants. *J Pediatr*. 2015;167(1):70-75. https://doi.org/10.1016/j.jpeds.2015.04.040
4. Hutten GJ, van Thuijl HF, van Bellegem AC, van Eykern LA, van Aalderen WM. A literature review of the methodology of EMG recordings of the diaphragm. *J Electromyography Kinesiol*. 2010;20(2):185-190. https://doi.org/10.1016/j.jelekin.2009.02.008
5. Dos Reis IMM, Ohara DG, Januário LB, Basso-Vanelli RP, Oliveira AB, Jamami M. Surface electromyography in inspiratory muscles in adults and elderly individuals: a systematic review. *J Electromyography Kinesiol*. 2019;44:139-155. https://doi.org/10.1016/j.jelekin.2019.01.002
6. van Leuteren RW, Hutten GJ, de Waal CG, Dixon P, van Kaam AH, de Jongh FH. Processing transcutaneous electromyography measurements of respiratory muscles, a review of analysis techniques. *J Electromyography Kinesiol*. 2019;48:176-186. https://doi.org/10.1016/j.jelekin.2019.07.014
7. Kraaijenga JV, Hutten GJ, de Waal CG, de Jongh FH, Onland WH, Kaam AH. Classifying apnea of prematurity by transcutaneous electromyography of the diaphragm. *Neonatology*. 2017;113:140-145. https://doi.org/10.1159/000484081
8. Prechtl HF, Van Eykern LA, O'Brien MJ. Respiratory muscle EMG in newborns: a non-intrusive method. *Early Hum Dev*. 1977;1(3):265-283. https://doi.org/10.1016/0378-3782(77)90040-8
9. O'Brien MJ, Van Eykern LA, Oetomo SB, Van Vught HA. Transcutaneous respiratory electromyographic monitoring. *Crit Care Med*. 1987;15(4):294-299. https://doi.org/10.1097/00132586-198804000-00008
10. Muth C, Bales KL, Hinde K, Maninger N, Mendoza SP, Ferrer E. Alternative models for small samples in psychological research: applying linear mixed effects models and generalized estimating equations to repeated measures data. *Educ Psychol Meas*. 2016;76(1):64-87. https://doi.org/10.1177/0013164415580432
11. De Livera AM, Zaloumis S, Simpson JA. Models for the analysis of repeated continuous outcome measures in clinical trials. *Respirology*. 2014;19(2):155-161. https://doi.org/10.1111/resp.12217
12. Beck J, Sinderby C, Weinberg J, Grassino A. Effects of muscle-to-electrode distance on the human diaphragm electromyogram. *J Appl Physiol*. 1995;79:975-985. https://doi.org/10.1152/jappl.1995.79.3.975
13. Farina D, Cescon C, Merletti R. Influence of anatomical, physical, and detection-system parameters on surface EMG. *Biol Cybern*. 2002;86(6):445-456. https://doi.org/10.1007/s00422-002-0309-2
14. Huigen E, Peper A, Grimbergen CA. Investigation into the origin of the noise of surface electrodes. *Med Biol Eng Comput*. 2002;40(3):332-338. https://doi.org/10.1007/BF02344216
15. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyography Kinesiol*. 2000;10(5):361-374. https://doi.org/10.1016/S1050-6411(00)00027-4
16. Lansing R, Savelle J. Chest surface recording of diaphragm potentials in man. *Electroencephalogr Clin Neurophysiol*. 1989;72(1):59-68. https://doi.org/10.1016/0013-4694(89)90031-X

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