Transcutaneous electromyography of the diaphragm

Monitoring breathing and the effect of respiratory support in preterm infants

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Chapter 8

Breath detection by transcutaneous electromyography of the diaphragm and the Graseby capsule in preterm infants

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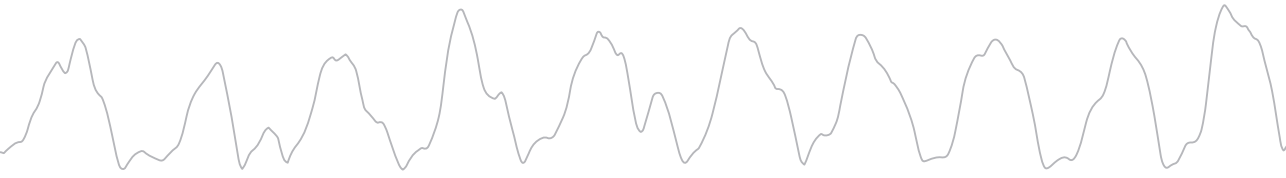
Pediatric Pulmonology 2017 Dec;52(12):1578-1582



Abstract

Objective

To compare triggering, breath detection and delay time of the Graseby capsule (GC) and transcutaneous electromyography of the diaphragm (dEMG) in spontaneous breathing preterm infants.

Methods

In this observational study, a 30-minute respiration measurement was conducted by respiratory inductance plethysmography (RIP), the GC and dEMG in stable preterm infants. Triggering was investigated with an in vitro set-up using the Infant Flow® SiPAP™ system. The possibility to optimize breath detection was tested by developing new algorithms with the abdominal RIP band (RIP_{AB}) as gold standard. In a subset of breaths, the delay time was calculated between the inspiratory onset in the RIP_{AB} signal and in the GC and dEMG signal.

Results

Fifteen preterm infants with a mean gestational age of 28 ± 2 weeks and a mean birth weight of 1,086 ± 317 g were included. In total, 14,773 breaths were analyzed. Based on the GC and dEMG signal, the Infant Flow® SiPAP™ system, respectively, triggered 67.8% and 62.6% of the breaths. Breath detection was improved to 99.9% for the GC and 113.4% for dEMG in new algorithms. In 1,492 stable breaths, the median delay time of inspiratory onset detection was +154 ms (IQR +118 to +164) in the GC and -50 ms (IQR -90 to -22) in the dEMG signal.

Conclusion

Breath detection using the GC can be improved by optimizing the algorithm. Transcutaneous dEMG provides similar breath detection but with the advantage of detecting the onset of inspiration earlier than the GC.

Introduction

Nasal intermittent positive pressure ventilation (nIPPV) is an advanced mode of non-invasive respiratory support that is often used to treat preterm infants at risk of respiratory failure. It provides positive inspiratory pressure inflations on top of a positive end-expiratory pressure.[1] nIPPV decreases the need for invasive mechanical ventilation when compared to nasal continuous positive airway pressure (nCPAP).[2,3]

Ideally, the pressure inflations during nIPPV should be synchronized with the spontaneous breathing efforts of the infant, with as little delay time as possible between the infant's onset of inspiration and the mechanical inflation by the ventilator.[4] However, synchronization of nIPPV in spontaneous breathing preterm infants remains a clinical challenge. The Graseby capsule (GC), a pneumatic capsule, is often used for nIPPV synchronization and a GC specific trigger algorithm is incorporated in a widely used device for delivering nCPAP (Infant Flow® SiPAP™ system, Vyaire, Lake Forest, IL). The GC is placed on the abdominal wall of the infant where it detects pressure differences due to expansion of the abdomen during respiration, which can be used to trigger mechanical nIPPV inflations. However, previous studies have shown that detection of spontaneous breaths with the GC varies between 56 to 88% and it is unclear if this suboptimal detection is caused by the GC itself or the trigger algorithm.[5–7] Furthermore, there is limited data on the delay time between the infant's onset of inspiration and its detection by the GC.

Recently, transcutaneous electromyography of the diaphragm (dEMG) was introduced in neonatal intensive care. It provides information on spontaneous breathing and neural respiratory drive.[8] dEMG is considered an ideal candidate for non-invasive breath detection and therefore triggering of nIPPV. In theory, dEMG should detect a breath earlier than the GC because diaphragm excitation and contraction occurs prior to abdominal expansion during spontaneous breathing.

The aim of this study was to test the triggering function of the Biphasic mode of the Infant Flow® SiPAP™ using the GC and the dEMG signal in spontaneous breathing preterm infants. When the analysis of the trigger function of the Infant Flow® SiPAP™ revealed suboptimal triggering and therefore breath detection, we assessed if this breath detection could be improved by using new algorithms. Finally, we compared the delay time in detecting the inspiratory onset of spontaneous breaths between the GC and dEMG. We hypothesized that breath detection would be superior using dEMG compared to the GC in both accuracy and delay time.

Methods

This observational study was conducted in the Neonatal Intensive Care Unit of the Academic Medical Center (AMC) Amsterdam, the Netherlands. Stable preterm infants on nCPAP were included after written informed consent was obtained from both parents. The study was approved by the institutional review board.

Study procedure

In each infant spontaneous breathing was simultaneously recorded by the GC, dEMG, and respiratory inductance plethysmography (RIP) for 30 minutes in supine position. The GC (Vyaire) was taped to the abdominal wall in the left midaxillary line below the lower rib margin and connected to a pressure port of a Bicore-II device (Vyaire). Data from the Bicore-II device were stored on a bedside personal computer.

Transcutaneous dEMG measured electrical activity of the diaphragm with three skin electrodes (disposable Kendall H59P Electrodes; Covidien, Mansfield, MA). Two electrodes were placed in the left and right nipple line on the edge of the lower ribs and one electrode (the ground electrode) was placed on the sternum. The electrodes were connected to a portable Dipha-16 device (Macawi Medical Systems, Eindhoven, The Netherlands), a 16-channel physiological amplifier. The raw signals were wirelessly sent to the same bedside personal computer as the Bicore-II data. The signals were filtered and the electrical activity of the heart was eliminated by the gating technique. The gated dEMG signal was filled with a running average.[9] The averaged dEMG signal was used for all analyses.

For RIP measurements two Teflon coated wires in elastic bands (Respiband, Vyaire) were used. One band was placed around the rib cage (RIP_{RC}) in the nipple line and one band around the abdomen (RIP_{AB}) just above the umbilicus. These two bands were also connected to the Bicore-II device which sends an oscillating signal through the wires. Frequency changes in the wires due to expansion of the rib cage and abdomen were demodulated into a voltage signal.

All data were simultaneously and in sync recorded and pre-processed using the software package Polybench (Applied Biosignals, Weener, Germany).

Data analysis

The software packages Polybench and Pulmochart (Advanced Life Diagnostics, Weener, Germany) were used for post-processing and data analysis.

The RIP_{AB} signal was used as reference signal for spontaneous breathing in this study. Blinded for the other signals, we first selected all stable RIP recorded breaths in the 30-minute measurement of each infant. These selected RIP recordings and the corresponding GC and dEMG recordings were used for further analysis.

First, the GC and dEMG recordings were used for in vitro testing of the Biphasic mode of the Infant Flow® SiPAP™ using the built-in GC-based trigger algorithm. The Infant Flow® SiPAP™ system was calibrated and set in the triggering function of the Biphasic mode, with a back-up frequency of one breath per minute and apnea time of 30 seconds. The digital GC signal was transformed to an analogue signal by a digital-analogue (DA) converter and sent to the Infant Flow® SiPAP™ system. The same procedure was then repeated using the dEMG signal. The resulting (real-time) triggering of the Biphasic mode of the Infant Flow® SiPAP™ system via the GC and dEMG signal was recorded by the Bicore-II and in sync added to the previously recorded RIP_{AB}, GC and dEMG signals (Figure 1). Based on these recordings, the percentage of GC and dEMG breaths that resulted in an Infant Flow® SiPAP™ trigger was calculated.

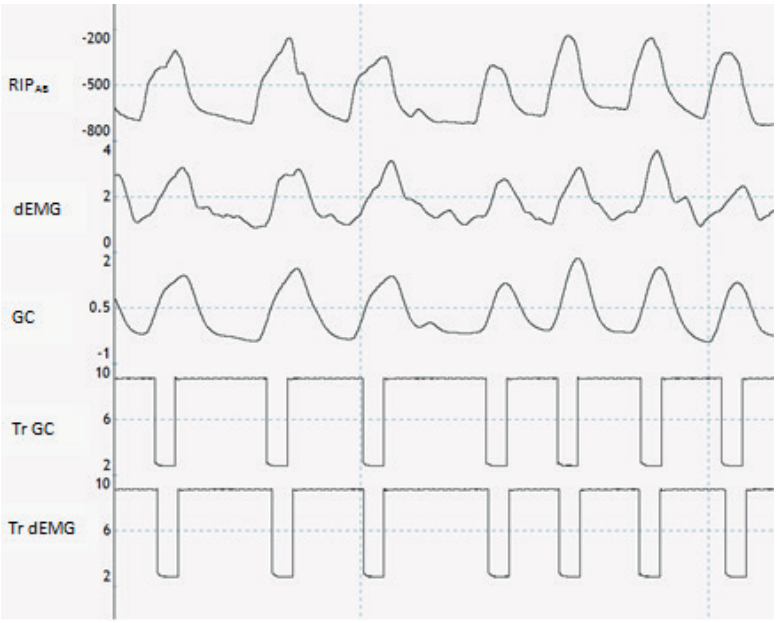


Figure 1. Example of a final recording file after triggering by the Infant Flow® SiPAP™ system. RIP_{AB}, respiratory inductance plethysmography abdominal belt; dEMG, transcutaneous electromyography of the diaphragm; GC, Graseby capsule; Tr GC, trigger of the Infant Flow® SiPAP™ system based on the GC signal; Tr dEMG, trigger of the Infant Flow® SiPAP™ system based on the dEMG signal.

To determine if the breath detection could in theory be optimized, we reanalyzed the GC and dEMG recordings using two new breath detection algorithms. The first algorithm was based on the RIP_{AB} signal (RIP-based) and therefore especially designed to detect breath-induced abdominal expansion as measured by the GC. The second algorithm was based on the dEMG signal and designed to detect breath-induced

changes in electrical activity of the diaphragm (dEMG-based). Both algorithms automatically determined the number of breaths in the recordings. First, the "true" number of breaths was determined by analyzing the RIP_{AB} recordings with the RIP-based algorithm. Next, the number of breaths in the GC recording was determined using the RIP-based algorithm. The number of breaths in the dEMG recording was determined using the dEMG-based algorithm. Based on these data the percentage of "true" breaths detected in the GC and dEMG signal was calculated.

To obtain additional information on the accuracy of breath detection in the new algorithms, we selected the first 1 minute of stable RIP_{AB} recording in each infant for breath-by-breath analysis. Similar to the analysis of all breaths, the RIP-based breath detection algorithm was used to identify the number of breaths in the 1 minute RIP_{AB} and GC recordings. The number of breaths in the dEMG signal was identified based on the dEMG-based algorithm.

Finally, the delay time between the onset of inspiration in the RIP_{AB} signal (reference signal) and the onset of inspiration in the GC and the dEMG signals was calculated with an automatic delay time algorithm in Polybench. All selected recordings containing only matched breaths were used for delay time calculation. A negative time of the GC or dEMG signal indicated that the onset of inspiration occurred before and a positive time indicated that the onset of inspiration occurred after the inspiratory onset in the RIP_{AB} signal.

Statistical analysis

SPSS version 23 (IBM SPSS software, Chicago, IL) was used for data analysis. Data were expressed as mean ± standard deviation (SD) or median (interquartile range (IQR)) depending on their distribution. Analyses were done first for each individual infant and then averaged for the whole group.

Results

Study population

We included 15 preterm infants with a mean gestational age (GA) of 28 ± 2 weeks and birth weight of 1,086 ± 317 g. At the day of measurement, the median postnatal age was 16 (IQR 5-29) days and the infants weighted 1,130 ± 263 gram. All infants were supported with nCPAP with a median pressure of 4 cmH_2O (IQR 3–5) and median fraction of inspired oxygen (FiO_2) of 0.22 (IQR 0.21–0.25). The mean respiratory rate was 79 ± 16 breaths per minute.

In vitro triggering of the Infant Flow® SiPAP™ system

After selection of stable RIP_{AB} recordings, in total 14,773 breaths were detected in the RIP_{AB} signals of all 15 infants. Sending the GC and dEMG signals back to the Infant Flow® SiPAP™ system resulted in a trigger in 10,009 (67.8%) and 9,255 (62.6%) breaths, respectively.

Breath detection using a RIP-based and dEMG-based algorithm

Of the 14,773 breaths detected in the RIP_{AB} signal, 14,761 (99.9%) breaths were detected in the GC using the RIP-based algorithm. The dEMG-based algorithm detected in the same stable recordings 16,756 (113.4%) breaths in the dEMG signal.

In the breath-by-breath analysis of 1-minute recordings of all included infants, a total number of 1,184 "true" breaths were detected in the RIP_{AB} signal with the RIP-based algorithm. Using this algorithm, 1,189 breaths were detected in the GC signal, of which 1,183 breaths were matched with breaths in the RIP_{AB} signal. One "true" breath was not detected by the GC. The dEMG-based algorithm, detected a total number of 1,461 breaths in the dEMG signal, of which 1,140 breaths corresponded with RIP_{AB} breaths. Forty-four "true" breaths were not detected by dEMG.

To explain the high number of "extra" breaths in the dEMG signal, we visually inspected all tracings. This showed that some of the dEMG breaths had a biphasic shape and were therefore detected as two separate breaths by the dEMG algorithm. This biphasic shape was not present in the RIP_{AB} and GC signal (Figure 2).

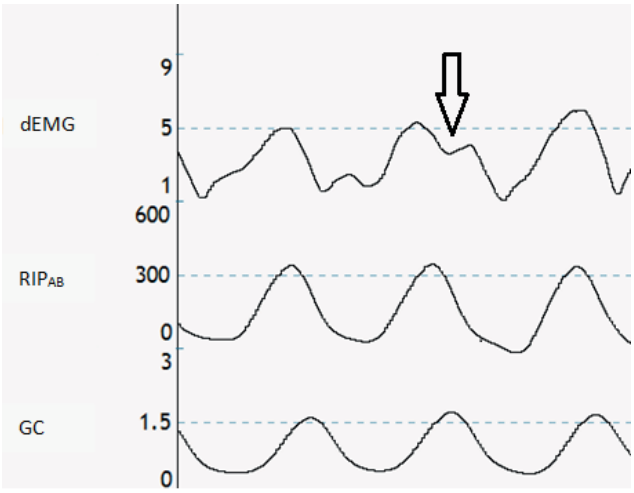


Figure 2. Example of a biphasic breath in the dEMG signal corresponding to one breath in the RIP_{AB} and GC signal. dEMG, transcutaneous electromyography of the diaphragm; RIP_{AB}, respiratory inductance plethysmography abdominal belt; GC, Graseby capsule

Delay time analysis

A total of 1,472 breaths was used for the delay time calculation. The median delay time of the inspiratory onset between the RIP_{AB} signal and the GC signal was +154 ms (IQR +118 to +164) and -50 ms (IQR -90 to -22) between the RIP_{AB} and the dEMG signal.

Discussion

This study shows that triggering of the Infant Flow® SiPAP™ system via the GC is suboptimal and that this is mainly caused by limitations of the built-in breath detection algorithm and not by the GC interface itself. Breath detection was improved using new algorithms. Furthermore, dEMG results in similar breath detection as the GC but has the distinct advantage of detecting the onset of inspiration earlier than the GC.

Because the breath detection algorithm used in the Infant Flow® SiPAP™ system was not available as standalone software, we assessed the trigger rate of the synchronized Biphasic mode by entering the GC signal obtained in spontaneous breathing preterm infants offline in an in vitro set-up. The relatively low trigger rate of 67.8% found in this study is consistent with previous published data.[6,7] However, up to now it remained unclear if this suboptimal triggering is a consequence of the technique used to detect spontaneous breathing, that is, a pneumatic capsule placed on the abdominal wall, or the algorithm used for breath detection that is incorporated in the system. To answer this question, we also entered the spontaneous breaths detected by dEMG in the Infant Flow® SiPAP™ and found a similar trigger rate as for the GC signal. This finding suggests that the suboptimal triggering is mainly due to limitations of the built-in algorithm.

To further substantiate this assumption and to assess the possibility to improve breath detection, we developed a new algorithm based on the RIP_{AB} signal. The RIP_{AB} signal reflects the expansion of the abdomen during inspiration which is similar to what is measured by the GC. This new algorithm improved breath detection in the GC signal to up to 99.9%. To assess if breath detection was accurate, we performed a breath-by-breath analysis in a subset of the measurements. Using the RIP_{AB} as the gold standard, we showed that all "true" breaths were also detected by the new algorithm in the GC signal. The number of breaths that did not match the RIP_{AB} signal was small. These results indicate that significant improvement can be made in breath detection via the GC by adapting the current trigger algorithm in the Infant Flow® SiPAP™ system.

The relative high respiratory rate in our population could be a potential contributor to the suboptimal breath detection by the Infant Flow® SiPAP™. However, other studies found trigger rates of 56-88% for this system in infants with mean respiratory rates ranging from 50 to 64 breaths per minute.[5,7] Furthermore, the respiratory rate did not limit the detection rate in the new developed algorithm where 99.9% of the breaths were detected. Therefore, the respiratory rate is not expected to be the explanation for

the low trigger rate of the Infant Flow® SiPAP™ system found in this study.

This study is the first to assess transcutaneous dEMG as a possible source for breath detection and future triggering of nIPPV modes. The fact that dEMG provided a similar triggering rate as the GC when entered in the Infant Flow® SiPAP™ system, is promising. Because the source of triggering during dEMG (electrical activity of the diaphragm) is different from the GC (abdominal expansion), we developed a preliminary breath detection algorithm based on the dEMG signal. This new dEMG algorithm improved breath detection but also resulted in an overestimation of the number of breaths. Breath-by-breath analysis showed that this was mainly due to a sometimes biphasic dEMG waveform during one single breath. The dEMG algorithm counted this biphasic waveform as two separate breathing efforts instead of one. This biphasic change in electrical activity of the diaphragm during one breath has been described before.[10] Future studies have to further explore this phenomenon. In addition, a next version of the dEMG algorithm software should identify this biphasic waveform and count it as one breath.

Synchronization of nIPPV with spontaneous breathing not only requires correct breath detection, but the breath detection should also be as early as possible in the breathing cycle.[11] Early detection will ensure that most of the inspiratory effort is supported by a positive pressure inflation, which is especially important in preterm infants with high respiratory rates and short inspiration times. As expected, dEMG detected the onset of inspiration before abdominal expansion occurred while breath detection with the GC occurred after abdominal expansion. Physiologically, this finding can be explained by the fact that inspiration starts with a brain stem-generated phrenic nerve output that is transmitted to the diaphragm and leads to excitation of the motor units in the muscle. The latter is measured by dEMG. The resulting diaphragmatic contraction leads to a negative pressure in the thorax followed by air influx and thoracic and abdominal expansion, which is detected by the GC. Theoretically, the dEMG technique will therefore reduce the patient delay of inspiratory onset detection as described by John et al[12] compared to the RIP_{AB} and the GC.

The timing of future real-time triggering based on the dEMG signal is influenced by several factors. First, the raw dEMG signal needs to be processed to reduce the cardiac artefacts to be able to detect breathing. Different techniques to filter the signal are described.[9,13–15] Currently, we are working on the reduction of the time delay introduced by the gating technique we used for filtering the raw dEMG signal. At this moment this filtering delay time is about 50 ms. Even with this delay the dEMG signal is still much faster than the GC. Second, the heart rate of preterm infants is relatively high which might also influence the delay time of a trigger. The heart rate of the infants measured in this study might be the explanation for the wider IQR of the calculated delay time in this study for the dEMG signal compared to the GC signal. Furthermore, a new algorithm

for triggering of nIPPV needs to be incorporated in a ventilator. This will introduce additional delay because of the reaction time of the ventilator to initiate an inflation when a breath is detected.[12] However, this additional delay will be similar when using dEMG or the GC.

Several limitations of our study need to be addressed. First, the new breath detection algorithms used in this study are developed for research purposes. Before the algorithms can be used in clinical care they need to be tested and optimized. Second, we used the RIP_{AB} signal as reference signal for spontaneous breathing in this study which is only used for research purposes. However, RIP is currently the only non-invasive tool to assess spontaneous breathing in preterm infants. Furthermore, we used RIP as the reference signal for both the GC and dEMG signal, which makes comparison of these two methods still valid. Third, all infants were measured in supine position and therefore we do not have information on breath detection in other positions. However, the dEMG and RIP measurements can be done in supine, side as well as prone position in preterm infants and in our experience this does not influence the signal quality.

In conclusion, suboptimal triggering of the Infant Flow® SiPAP™ system using the GC signal is mainly caused by limitations of the built-in breath detection algorithm. Breath detection can be improved by developing new algorithms based on abdominal expansion. Transcutaneous dEMG provides similar breath detection but with the advantage of detecting the onset of inspiration earlier than the GC. These findings suggest that dEMG is a promising technique for non-invasive synchronization of nIPPV in spontaneous breathing preterm infants. Further research is needed to optimize the algorithm and the filtering of the dEMG signal before it could be used in clinical care.

Acknowledgements

The authors thank Leo A. van Eykern, Tom Leenhoven and Hilbert Koetsier for the technical assistance in this study.

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