ORIGINAL ARTICLE

Monitoring the respiratory rate by miniature motion sensors in premature infants: a comparative study

S Kohn^{1,6}, D Waisman^{2,3,6}, J Pesin⁴, A Faingersh⁴, IC Klotzman⁵, C Levy¹, G Hirshberg⁴, A Rotschild^{2,3} and A Landesberg⁴**OBJECTIVE:** Existing respiratory rate (RR) monitors suffer from inaccuracy. The study assesses the accuracy of a novel modality that monitors lung ventilation with miniature motion sensors.**STUDY DESIGN:** RR was measured by three methods: impedance technology, motion sensors and visual count, in babies ($n = 9$) that breathed spontaneously or with respiratory support and babies ($n = 12$) that received high-frequency oscillatory ventilation (HFOV).**RESULTS:** A line close to equality (slope = 0.96, $r^2 = 0.83$) was obtained between the motion sensor and the visual count of the RR with narrow 95% limits of agreements (< 14.0 b.p.m.). The relationship between the impedance and the visual count showed a lower correlation ($r^2 = 0.65$) and wider 95% limits of agreements (21.4 b.p.m.). The motion sensor- and the ventilator-determined RRs demonstrated a good agreement during HFOV, whereas the impedance failed to measure the RR during HFOV.**CONCLUSION:** Monitoring RR with motion sensors is more accurate compared with the impedance, in infants, in all ventilation modes.*Journal of Perinatology* (2016) **36**, 116–120; doi:10.1038/jp.2015.173; published online 19 November 2015

INTRODUCTION

The respiratory rate (RR) is one of the five vital signs, and is considered a critical measurement in both the hospital care setting and as a critical parameter for home monitoring.^{1–3} The RR and respiratory patterns are basic tools for prioritizing the required treatment in the neonatal intensive care unit (NICU) as well as for monitoring patients in operating rooms and a wide range of patients in the hospital setting.^{4–7} The most common method for measuring the RR is based on measuring the breath-dependent variations in the transthoracic impedance.^{8,9} Despite the large spectrum of alternative modalities for measuring the RR, existing electrical RR measurement methods, including the impedance technique, have demonstrated poor accuracy;^{8–13} therefore, there is a need for a more accurate method for RR monitoring.

A recently developed novel method for monitoring the changes in the tidal volume and the symmetry of lung ventilation uses miniature motion sensors attached to both chest wall and upper abdomen.^{14–17} This continuous monitoring of respiratory dynamics was suggested to be beneficial in early detection of deteriorating ventilation.^{14,15,17} Preclinical studies have established its ability to provide early detection of developing asymmetric ventilation, such as in one-lung ventilation or progressing pneumothorax.^{14,16,17} A clinical study in premature infants ventilated with high-frequency oscillatory ventilation (HFOV) has revealed the ability to detect deteriorating ventilation as early as 22.4 ± 18.7 min before the recognition of clinical signs of respiratory distress and hypoxemia by the pulse oximeter.¹⁵

Whereas the feasibility of monitoring respiratory dynamics was substantiated,^{14–17} the accuracy of monitoring the RR by this method has not yet been tested. The driving hypothesis of our work was that with three different surface motion sensors

measuring the actual movements of the chest and abdomen, we can achieve higher or at least comparable reliability of the RRs compared with that obtained with the methods currently used in the NICU. Therefore, the objective of the present study is to assess the accuracy of measuring the RR in two groups of newborn infants by this method and to compare it with an existing technique and with visual count of the RR. One group breathing or ventilated at physiological RRs (< 180 b.p.m.), and the second group ventilated using HFOV (> 180 b.p.m.).

METHODS

This study was conducted in the Carmel Medical Center NICU, Haifa, Israel. The study was approved by the Institutional Review Board and the Ministry of Health, and registered at the US National Institutes of Health (NCT00810186), and experiments were performed following parental informed consent.

The clinical study included two separate groups: (1) babies that breathed at a physiological RR (< 180 b.p.m.) and (2) babies that were ventilated by HFOV (≥ 180 b.p.m.). The first group included premature infants that breathed spontaneously, were treated with conventional mandatory ventilation or received respiratory support using nasal synchronized intermittent mechanical ventilation (LEONI PLUS infant ventilator; Heinen Lowenstein, Bad Ems, Germany), or high flow nasal cannula (Vapotherm, Stevensville, MD, USA; HFOV was provided by SLE 2000 or SLE 5000 ventilator; SLE, Croydon, UK).

The following parameters were continuously monitored as part of the routine monitoring in the NICU (Philips IntelliVue MP40 monitoring system, Philips, Boeblingen, Germany): heart rate, blood pressure, pulse oximetry (SpO₂) and ventilation parameters (e.g., flow, FiO₂, ventilation rate). Printouts of the monitor recordings and the medical follow-up sheets were collected for offline analysis.

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Figure 1. Vital signs (heart rate (HR), oxygen saturation (SpO₂) and respiratory rate (RR)) and the raw data from the impedance (RESP) sensors and the right (R), left (L) and abdominal/epigastric (A) motion sensors, recorded from a premature infant during spontaneous breathing (gestational age: 31 ± 4 ; weight: 1436 g). The visual count of the RR during this time interval was 60 b.p.m., the impedance (gray dots) and motion sensors (black rectangles) recordings yielded 76 and 60 b.p.m., respectively, in this same interval.

The inclusion criterion for the study was the need for tight respiratory monitoring. The exclusion criteria were: parental refusal to participate in the study, weight < 700 g, age < 26 weeks, hydrops fetalis, severe hypoxic ischemic encephalopathy, severe intracranial bleeding or skin reactions to the adhesive patches. These criteria were based on concerns of the Institutional Review Board of having extra patches in extremely immature infants, concerns about the possible influence of very thick soft tissues on the new technique explored and the desire not to approach parents of severely compromised infants with a suspected very poor outcome.

Physiological RR

Three independent modalities were used to measure the RR: (A) visual count from video recordings, (B) transthoracic impedance and (C) motion sensors.

A video recording of the chest and abdomen of each subject was acquired at a frame rate of 10 frames per s using a UI-122 LE camera (OpteamX, Azor, Israel). The RR was counted by a trained research assistant while viewing the recording. The RR was determined over 1-min spans, every 5 min. The research assistant was blinded to the RRs determined using the other devices.

The transthoracic impedance was continuously monitored (Philips IntelliVue MP40, Boehringer, Germany) through standard pediatric chest electrodes, as part of the routine monitoring of NICU patients. The measurements were collected into a laptop computer using the iXtrend software (ixellence GmbH, Wildau, Germany) that provides a new data set every second.

The chest wall motion was continuously monitored by three miniature motion sensors (< 1 g, 5 mm diameter, Pneumonitor; Pneumedicare, Yokneam, Israel) that were placed on both sides of the chest wall and on the upper abdomen, as shown in Supplementary Figure 1. The system measures the local tidal displacement of each of the sensors, at 10 s

intervals.^{14–17} Each new RR data point is derived from the analysis of the preceding 30 s of measured chest wall motion.

The RRs derived from the visual counts were compared with those measured using the motion sensors and impedance technology, at the same time intervals that were used for the visual counts. Measurements during periods of crying, or handling, which rendered the visual count from the video recordings impossible, were excluded from the analysis.

HFOV

The RR during HFOV was measured with the motion sensors and was compared with the RR displayed by the ventilator. An infant supported by HFOV is typically ventilated at a fixed frequency, at which the infant is stable.

To further verify the accuracy of the motion sensors in a broader spectrum of frequencies, an additional preclinical study was carried out on rabbits using a video recording. This type of study would not be possible in patients because of the deleterious effects of the changes in the ventilator parameters. The experiments were performed on healthy anesthetized New Zealand rabbits as described in the online Supplementary Data. HFOV was provided with a pressure-controlled ventilator (SLE 2000; SLE). The RR was randomly changed to cover a wide RR range of 3 to 20 Hz at various delta pressure conditions (10 to 30 cmH₂O). The RR measured by the motion sensors was compared with the data displayed on the ventilator and the visual counts from the video recording (Fast video-camera UI-122, OpteamX). The videos were acquired at a frame rate of either 60 or 79 frame per s. Ten-second time intervals were inspected and analyzed every 10 min of recording.

Statistical analysis

Considerations for sample size calculation: a sample size of five experimental subjects per group (according to the type of ventilatory modality), with at least 240 measurements each (each 30 s for 2 h period), were considered to provide a power of at least 90%, with 5% statistical significance to demonstrate comparability between the tested device (PneumonitorTM) and the reference monitor (Philips IntelliVue MP40). A difference of up to 15% between the monitors was defined as comparable (noninferiority). The visual count served as the criterion standard, as was carried out by others.^{10,11} The linear correlation between the impedance or the motion sensor and the criterion standard was calculated to examine whether it is close to the anticipated line of equality and to quantify the R^2 . The absolute relative error (aRE) and the root mean squared error (RMSE) between the tested devices (motion sensors or the impedance sensor) and the visual count were calculated. The limits of agreement method developed by Bland and Altman¹⁸ was used to assess the agreement between the impedance or the motion sensor and the criterion standard. The limits of agreement method presents the difference between the methods, and the variability in those differences within and across individuals.¹⁸

RESULTS

The accuracy of RR determination within the physiological range was tested in nine premature infants (6 males, 3 females) in 11 trial sessions. The mean postmenstrual age was 35.1 ± 3.3 weeks at monitoring (gestational age at birth was 32.5 ± 4.0 weeks), and the mean weight was 2205.6 ± 1150.1 g. The average monitoring duration was 174 ± 67 min per-patient.

In seven sessions, the infants breathed spontaneously without respiratory assistance, and in four sessions, the patients received the following types of respiratory support: conventional mandatory ventilation ($n=1$), nasal SIMV (intermittent mandatory ventilation, synchronized; $n=1$) or high flow nasal cannula ($n=2$). A total of 171 time intervals were visually inspected and were used to evaluate the accuracy of the impedance and the motion sensor modalities.

Figure 1 depicts the signals recorded from a premature infant (gestational age $31+4$ weeks, weight 1436 g) during spontaneous breathing. The raw impedance data (RESP in Figure 1) resemble those obtained from the three motion sensors, that is, the right (R) and left (L) sensors on the chest and the abdominal sensor (A). However, some discrepancy was observed between the

Figure 2. The correlation between the respiratory rate (RR) derived from the impedance (gray dots) or the motion sensors (black rectangles) and the criterion standard determined by visual count.

impedance-based RR measurements and the visual count of the RR. The visual count of the RR during this time interval was 60 b.p.m., whereas the impedance (gray dots) and the motion sensor (black rectangles) recordings yielded 76 and 60 b.p.m. in this interval, respectively. (The impedance- and the motion sensor-determined RRs are the values obtained at the end of the 1-min monitoring interval.) A short, 3-s segment without breath was observed in the impedance recordings, but the recording from the abdominal sensor (A) revealed two spontaneous breaths at the same interval. Supplementary Figure 2 presents an example of similarity between the three modalities in the same premature infant.

Figure 2 depicts the correlation between the RR extrapolated from the impedance or the motion sensors and the visual count. A tight correlation was obtained between the motion sensor modality and the visual count ($r^2=0.83$), with a slope of 0.96, very close to the line of equality. The impedance-based RR determinations had a lower correlation with the visual count ($r^2=0.65$) and a larger deviation from the expected line of equality. The motion sensor-based RR measurements had mean aRE of 9.27% and an RMSe of 6.93, significantly smaller than the mean aRE (13.21%) and RMSe (10.67) of the impedance modality ($P < 0.001$ for both). The RMSe distributions of the two modalities over different breathing frequency ranges (from 20 to 100 b.p.m. divided into four equal ranges) demonstrate (Supplementary Figure 3) that chest wall motion monitoring provided significantly lower error in the respiratory frequency range of 41 to 60 b.p.m. ($P < 0.001$).

The accuracy of the two modalities was quantified using the levels of agreement method as depicted in Figure 3. The RR determined using the motion sensors provided a good level of agreement, with narrow 95% limits of agreement with the visual count of the RR that spanned between -13.89 and 14.83 b.p.m. The transthoracic impedance-based extrapolation yielded a wider 95% limits of agreements that spanned between -22.66 and 20.55 b.p.m. (Supplementary Table 2).

The accuracy of measuring the RR during HFOV (RRs: 10 Hz ($n=8$), 12 Hz ($n=2$) and 15 Hz ($n=2$)) was tested in a second group of 12 premature infants (5 males and 7 females). The mean postmenstrual age was 30.0 ± 2.4 weeks at monitoring (gestational age at birth was 28.4 ± 3.2 weeks), and the mean weight was 1211.5 ± 585.7 g. Each infant was monitored for 4.00 ± 1.43 h. Figure 4 depicts the tight correlation obtained between the RRs measured using the motion sensors and the frequencies displayed on the ventilator ($r^2=0.96$), with a slope close to one (0.96). The

Figure 3. Data collected from premature infants during spontaneous breathing or when on ventilatory support with physiological respiratory rate (RR). The motion sensor-based modality for measuring the RR (black rectangles) provided a better level of agreement with the visual count than did the impedance technology (gray dots) versus the visual count, with narrower 95% limits of agreement (black lines).

mean aRE of 3.40% and an RMSe of 0.71 are below the ventilator display resolution.

The preclinical verification study in rabbits included five rabbits (mean weight 3.70 ± 0.19 kg), tested when ventilated using eight different frequencies: 3, 4, 5, 6, 10, 12, 14 and 20 Hz (see the online Supplementary Data for more details). Various levels of inspiratory delta pressure, from 10 to 30 cmH₂O, were used. The frequency of oscillation and the delta pressure were modified randomly (88 different sets of RR and delta pressure were acquired). A tight correlation ($r^2=0.997$) with a relationship close to equality (1.01) was obtained between the RR determined with the motion sensors and the visual count, as depicted in Figure 5. A similar correlation ($r^2=0.995$) was obtained between the frequency displayed on the ventilator and the visual count. The mean aRE of 1.51% and an RMS error of 0.19 were below the resolution displayed by the ventilator. The ventilator yielded a slightly larger mean aRE (5.64%) and higher RMS error (0.54), as shown in Supplementary Figure 4 and Supplementary Table 1 ($P < 0.001$ for both types of errors). The levels of agreement of the RR calculated from the motion sensors versus by visual count were high, with limits of agreement < 0.5 Hz (-0.31 to 0.41), as shown in Figure 6. The corresponding analysis for the ventilator-determined RR yielded wider limits (-0.01 to 0.97), with a bias of about $+0.5$ Hz.

DISCUSSION

This study validates the accuracy of the RR measured by the motion sensors in neonates. Specifically:

1. There is a strong correlation between motion sensor-determined RR and the visual count; the relationship is close to the line of equality.
2. Both the RMSe and the average aRE measured by the motion sensors relative to the visual count are significantly smaller ($P < 0.001$) compared with that of the RMSe and aRE of the impedance technology.
3. A high correlation exists between the motion sensor-determined RR and both the visual count and the ventilator display at HFOV. The impedance technology cannot measure the RR during HFOV.
4. RR measured using the motion sensor technology lies in better agreement with that determined by the visual count compared

Figure 4. A tight correlation ($R^2 = 0.959$) with a line close to equality (slope of 0.958) was obtained between the respiratory rate (RR) measured by the motion sensors and the ventilator display, in premature neonates ($n = 12$) supported by high-frequency oscillatory ventilation (HFOV).

Figure 5. Tight correlations ($R^2 \geq 0.99$), with lines close to equalities (1.02 and 1.01), were obtained between the respiratory rate (RR) measured by the motion sensors or the ventilator display and the visual count in anesthetized rabbits ($n = 5$, 88 data points) supported by high-frequency oscillatory ventilation (HFOV).

with that determined by the impedance technology, with lower 95% limits of agreement (< 14 versus < 22 b.p.m.).

RR monitors can be classified as those which must be in tight proximity to the nasal airflow, those which apply sensors on the chest and abdomen, and those which exploit non-contact imaging technologies.^{11–13} The first group senses the effects of the air flow and performs capnography, pneumotachography, sound recordings, temperature or condensation monitoring.^{11–13,19} These measurements are cumbersome in the absence of an endotracheal tube, are inconvenient in the spontaneously breathing patients, and are useless in the presence of a low or high flow nasal cannula. The second group includes strain gauge, pressure gauges or inductive plethysmography, requiring belts around the chest, or transthoracic impedance plethysmography.^{8–12} The use of belts is impractical for small premature infants, as it restricts chest expansion and may be irritating to their vulnerable skin. The third group of non-contact imaging technologies has not gained popularity because of the many recording artifacts.¹³

Figure 6. Data collected from anesthetized rabbits ($n = 5$, 88 data points) supported by high-frequency oscillatory ventilation (HFOV) at various frequencies and delta pressures. The motion sensor-based RR measurement modality (black rectangles) provided a better level of agreement with the visual count during HFOV compared with the ventilator display (gray dots), with narrower 95% limits of agreement. Moreover, the motion sensor-based modality for RR determinations had no bias in the measured RR, whereas there was a bias in the ventilator display.

The RR is an important vital sign.^{20,21} In many situations, changes in the RR and signs of respiratory distress are sufficient for diagnosis, independent of pulse oximetry measures, especially when supplemental oxygen is provided. The chemoreceptors in the body measure the O_2 and CO_2 partial pressures, and under normal conditions, the arterial O_2 partial pressure is at the plateau of the hemoglobin saturation curve. Consequently, the chemoreceptors can detect the decrease in O_2 partial pressure and can elicit respiratory distress, even without noticeable change in the oxygen saturation. Therefore, the RR and respiratory effort are important for the early diagnosis of life-threatening clinical situations, such as deterioration due to worsening lung disease, developing lung barotrauma, central or drug-induced hypoventilation, as well as partial airway obstruction or sepsis, where changes in the ventilation can precede changes in the pulse oximetry. Monitoring the RR both from the ventilator and from the patient is very important during mechanical ventilation. Synchronization between the patient's own efforts and mechanical breaths minimizing bar and volutrauma, avoidance of hyperventilation or excessive work of breathing, and controlling the weaning process from ventilatory support, all have a tight correlation to the detection and monitoring in a reliable manner of the spontaneous breathing efforts during assisted ventilation.^{22–26}

The clinical implications of RR have inherent physiological limitations as: (1) there is no simple linear relationship between the RR and the severity of respiratory problems, (2) there is a wide normal range of the RR and (3) the RR is modulated by pain, stress levels, speech, activity or sleep cycles.

In this study, the motion sensor technology was compared with the impedance plethysmography, as the latter is the most common modality for measuring the RR in ICUs.^{8,9} Many studies have confirmed that the impedance-extrapolated RR correlates well with the visual RR counts,^{10,11} as was found in our study as well. However, the following advantages of motion sensors can explain their observed higher accuracy and better agreement with the visual count compared with the impedance technology:

1. Measurements from three independent sensors yield a more accurate measure than impedance measures, which records a single trace of the breath between the electrodes. The motion

- sensor technology computes the RR from three independent traces extracted from three independent sensors.
2. Measurement from three independent sensors reduces the number of artifacts. Loose attachment in one of the impedance electrodes yields artifacts and noises.²⁷ In contrast, disconnecting one of the motion sensors does not affect the signals from the other motion sensors.
 3. Motion-sensing-based RR recordings are applicable over a broader spectrum of frequencies (up to 30 Hz), whereas the impedance technology cannot measure the RR during HFOV, which is an important lung-protective ventilation strategy.
 4. The motion-sensing technology monitors the chest and upper abdomen motions separately. The motion sensor positioned on the epigastrium is highly sensitive to the diaphragm motion, which is the primary respiratory muscle in neonates.

Limitations

This study monitored a small number of infants. However, the RR is highly variable in premature infants, with large fluctuations during the sleep-awake cycles and in response to many handling disturbances. Thus, the recordings spanned a wide distribution of data points.

The present implementation requires placement of three patches on the chest and abdomen; however, in the future, these patches may include the ECG electrodes.

Obviously, further studies are required to confirm these findings in a larger neonatal population and in adults.

CONCLUSIONS

This study validated the accuracy of RR measurements using the motion sensors technology in the NICU. Monitoring the chest wall motion is a simple noninvasive and convenient method that does not require a sensor within the airflow path and registers the symmetry and magnitude of lung ventilation. Measuring the RR with the motion sensors is more accurate compared with the transthoracic impedance in premature infants. The chest wall motion sensor also enables highly accurate RR measurements during HFOV.

CONFLICT OF INTEREST

SK, DW, JP, GH, AF, ICK, CL and AL are involved in the development of a respiratory function monitor in a collaborative effort between the Technion – Israel Institute of Technology, Clalit Health Services and Pneumedicare. AR does not have a conflict of interest to declare.

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Supplementary Information accompanies the paper on the Journal of Perinatology website (<http://www.nature.com/jp>)