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Optimizing high-frequency-oscillation ventilation using acoustic parameters of the newborn lung: A feasibility study

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***Abstract*—Ventilation using high Frequency oscillation (HFO) has become a standard care for the ventilatory management of critically ill newborns. In recent years, there has been growing recognition that maintenance of an optimal lung volume during high-frequency oscillation plays an important role in minimizing ventilator-induced lung injury. The primary variable affecting lung volume is the mean airway pressure (MAP). To effectively maintain lung recruitment and optimal gas exchange without overstretching (or collapsing) the lung, MAP should be set between two well defined points in the pressure-volume curve of the lung. To determine optimal MAP during high frequency ventilation, an acoustic monitoring system was developed and tested. The system was based on transmission of audible acoustic bursts and reception of echoes from the lungs. The results suggest that these acoustic measurements reflect the mechanical properties of the lungs. The acoustic measurements indicated an increase in lung volume following the administration of exogenous surfactant into the lungs as expected. Hysteresis in the amplitude of acoustic reflection was also measured as expected. Despite the fact that we had no "gold standard" to compare with, our results suggest that acoustic properties of the lung as measured by our system, have the potential to indicate the degree of lung recruitment during HFO and to define the optimal region of MAP.**

I. INTRODUCTION

VENTILATION using high-frequency–oscillation (HFO) has become a standard care for the ventilatory management of critically ill neonates [1]. However, only little clinical data is available for the physician while setting ventilator variables of HFO. The value of mean airway pressure (MAP) has a major effect on the degree of lung recruitment during HFO. Choosing MAP outside of its clinical boundaries may decrease oxygenation and expose the neonate to lung damage. The Value of MAP is usually determined by a sequence of trial and error, based on the individual clinical experience of the clinician, and not on objective clinical data evaluating the state of lung recruitment.

A number of mechanisms may explain how lung injury in neonates is associated with ventilation parameters. Ventilation at low or high absolute lung volume is the main cause of lung injury [2]. When ventilation pressure is too low, cyclic recruitment and derecruitment of small airways/ lung units may occur and lead to increased local shear stress. On the other hand, high airway pressure may cause overdistension of the alveoli and expose the lungs to air leaks. Although it is considered as a gross simplification, the static pressure-volume (P-V) curve is often used to illustrate the balance between alveoli overdistension and recruitment. As airway pressure increases over the lung's functional residual capacity (FRC), the lower inflection point (LIP) represents the pressure at which lung units are recruited. The upper inflection point (UIP), at which lung compliance decreases as airway pressure increases, is thought to reflect the point at which alveoli become over-distended, and therefore more susceptible to damage.

During HFO, MAP should be set above LIP and below UIP of the P-V loop to effectively maintain lung recruitment and optimal gas exchange without overstretching (or collapsing) the lung tissue. Values of LIP and UIP may vary, primarily depending on neonate weight and severity of lung disease. Acceptable MAP pressure range is between 5 and 20 cmH_2O. The value of MAP is usually set independently of other variables of HFO, such as ventilation frequency and tidal volume. The selected pressure is evaluated by indirect parameters that reflect lung recruitment. In most cases, there are no direct clinical or physical parameters that can quantify lung recruitment during this process, and S_APO_2 and PCO_2 are the main indices during this process. Thus, an iterative procedure is applied to determine the level of minimal MAP that allows adequate lung recruitment and oxygen transfer.

In this study, we investigated the acoustic properties of the neonate lung to assess the usefulness of the acoustic method as a means of determining optimal MAP during high frequency ventilation. We transmitted a sonic signal into the chest of 6 neonates during HFO and measured sound reflection in variable stages of lung recruitment. Despite the fact that there is no "gold standard" device to assess lung parameters, the results suggest that the system reflects the properties of the lungs. Our study suggests that acoustic measurements of the neonate lung have a potential to indicate the degree of lung recruitment during HFO and to determine the optimal region of MAP.

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II. MATERIALS AND METHODS

The acoustic measurement system consisted of a computer, A/D card (National Instruments PCI-6024), acoustic transducer, acoustic receiver, and an electronic circuit. The electronic circuit was operated by a stable +5V supply, generated by a USB connection between the computer and the electronic circuit. The electronic circuit was tested with a safety analyzer to ensure it meets the safety standards of Israeli Ministry of Health and Israeli Institute of Standards regarding the usage of medical equipment (IEC601-1).

An acoustic signal (sonic frequency) in the form of a series of pulses was generated by the A/D card and transmitted by the acoustic transducer to the subject chest. The acoustic transducer was attached on the right lung, 1cm under the nipple. Each pulse contained spectral energy in frequencies between 200-3500 Hz. The acoustic signal reflected by the lungs was recorded by the receiver and filtered by the electronic circuit (bandwidth of 100-3500 Hz). The signal was sampled and digitized by National Instrument PCI-6024E card.

The study group included 6 newborns who were admitted to the Neonatal Intensive Care Unit at the Edith Wolfson Medical Center. All subjects were in their first day of life, weighing between 600-2334 grams (mean weight of 1431 grams). All subjects suffered from respiratory distress syndrome and required high frequency oscillation ventilation. Acoustic measurements were taken before and/or immediately after the procedure of administration of exogenous surfactant and the setting of MAP. Subjects were included in the study after obtaining parental informed consent.

During standard ventilation, the acoustic receiver and transmitter were attached to the subject chest by non-galvanic contacts. Measurements were carried out between the onset of ventilation and the period of the first 4 hours of HFO ventilation. Period of measurement included the standard process of the adjustment of ventilator parameters (including MAP), the administration of exogenous surfactant, and the process of surfactant absorption by the lungs. Standard medical treatment was not delayed or stopped for the purpose of allowing measurement to be taken. Ventilation parameters (i.e., lung compliance, mean airway pressure, ventilation frequency) were transferred from the Stephanie™ ventilator to the computer using aRS232 communication protocol. All data was saved for offline analysis.

III. RESULTS

Fig. 1 shows, in the frequency domain, the change in the acoustic reflection during lung inflation in all subjects. All measurements were taken in the right lung, after the insertion of exogenous surfactant. Baseline response in all subjects was calculated as the acoustic response in the lowest value of MAP used in the specific subject. Data is displayed in Fig. 1 on a three-dimensional grid, where reflection is a function of MAP and frequency.

In all subjects, the acoustic reflection was of the same pattern, with an increase in reflection with the increase in lung volume. Maximal reflection in all levels of MAP was measured at the frequency of 2500 Hz. These results were in

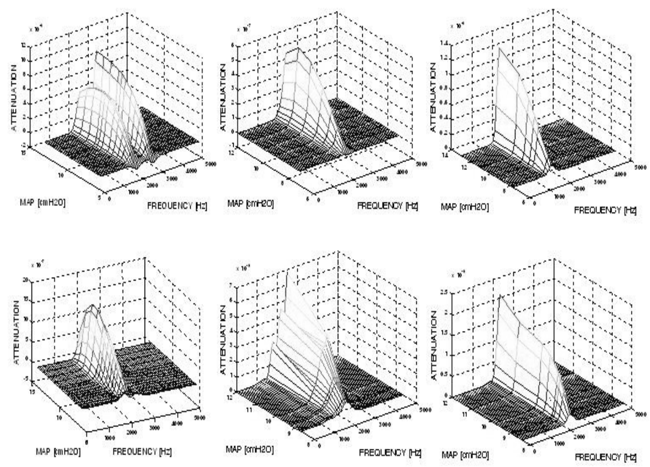

Fig. 1. Average change in the acoustic reflection during lung inflation. Data is displayed on a three-dimensional grid, where reflection is function of MAP and frequency.

accordance with the measurements of the spectral characteristics and signal shape of the acoustic transmitter. In subject No. 1 acoustic reflection was measured also around 3500 Hz. In relatively high levels of MAP (MAP>10 cmH_20) the change in acoustic reflection became more moderate and can be seen as a plateau in the three-dimensional curves.

Fig. 2 presents the normalized reflection-pressure curves of all subjects. These curves represent the relationship between the amplitude of acoustic reflection and lung pressure (MAP). Each curve is normalized by its maximal amplitude of reflection, and presented between the range of 0 and 1. It can be seen that all shapes are of the same pattern, and this is expected since these two-dimensional curves are cross-section views of the 3D curves shown in Fig. 1.

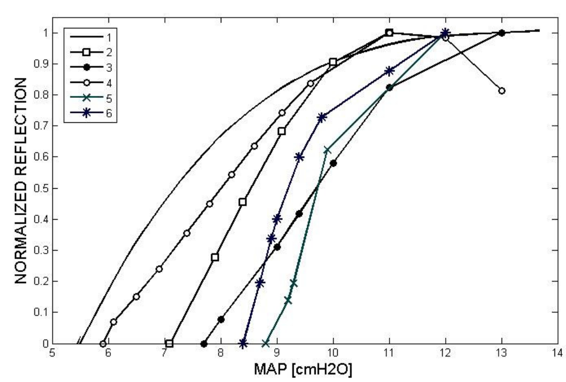

Fig. 2. Normalized reflection-pressure curves of all subjects, by their number

By inspecting Figs 1 and 2, two main findings are disclosed: 1) Energy content of the acoustic signal was concentrated around 2500 Hz; and 2) Acoustic reflection-pressure curves were of the same shape of the mechanical volume-pressure loops, with a linear phase in the middle pressure range. In high values of MAP, the reflection-pressure curve extended into a flattened portion.

In two of the subjects acoustic measurements were taken both before and after the administration of exogenous surfactant. Fig. 3 compares the change in acoustic reflection before and after the administration of surfactant. Top panel (a) presents the data of subject No. 4, whereas the bottom panel (b) presents the data collected from subject No. 6. In this Fig., the data presented is the percentage of change in acoustic reflection (percent change). Baseline for all curves was defined as the amplitude of acoustic reflection of the 'empty' lung. As can be seen, in both subjects, maximal amplitude of lung reflection was higher after the administration of surfactant.

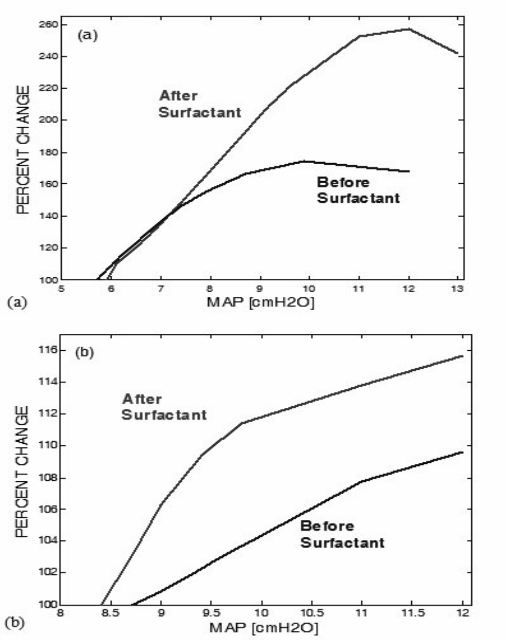

Fig. 3. Acoustic reflection before and after the administration of exogenous surfactant. Top panel (a) shows results of subject No. 4, bottom panel (b) shows results of subject No. 6.

In subject No. 4 (32 weeks, 2000 grams) the change in acoustic reflection was more pronounce than in subject No. 6 (29 weeks, 1169 grams). Percent change in maximal reflection point was 250% in subject No. 4, compared to only 17% in subject 6.

Lung hysteresis was measured in some of the subjects, where MAP was both decreased and increased during the same measurement. The effect of such maneuver of MAP is expected to be a decrease, followed by an increase in lung volume. In the first phase, lung volume is decreased (along the deflation limp of the volume-pressure curve) to a value that reflects lung volume in the respective value of MAP applied. In the second phase, lung volume is increased (along the inflation limb of the volume-pressure curve), until it reaches it final volume, which is again determined by the value of MAP. In the second phase, each value of lung volume is expected to be lower than in the deflation limb, which is a result of lung hysteresis. Fig. 4 shows how a cyclic change in lung pressure was expressed by the acoustic reflection, in subjects 1 and 4. In the left panel (subject No. 1), mean airway pressure was decreased from 14 cmH2O to 6 cmH_2O and than increased again to 12 cmH_2O. The acoustic reflection was decreased in the first phase and than increased again, but remained at lower amplitude than its initial value. In the right panel (subject No. 4), a cyclic change in MAP was applied, in which MAP was decreased from 10 cmH_2O to 5.5 cmH_2O, than increased to 14 cmH_2O, and decreased again to 9 cmH_2O. Sound reflection decreased with the decrease in MAP, and increased with the increase in MAP. However, level of sound reflection was higher along the deflation limb of the lung.

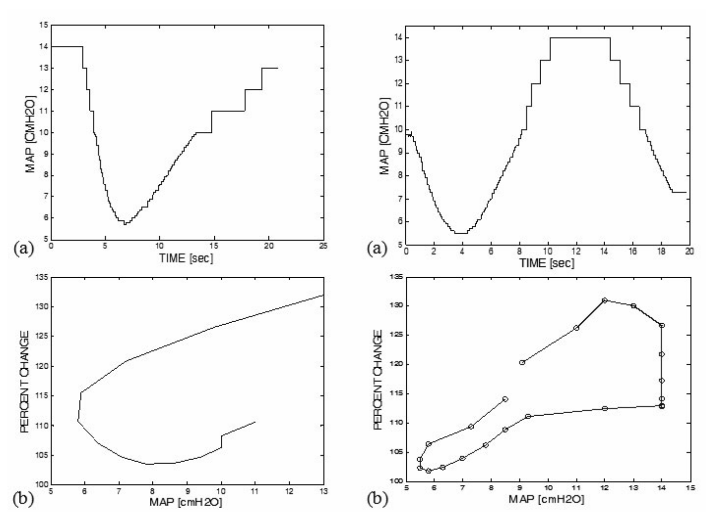

Fig. 4. Acoustic reflection during cyclic maneuver in MAP, in subjects No. 1 (left) and 4 (right). Top panel (a) shows the change in MAP, bottom (b) shows percent change in acoustic reflection.

IV. DISCUSSION

In this study, the acoustic properties of the newborn lungs were shown to reflect the degree to which the lungs were inflated. Our study suggests that reflection of audible sound from the lung has potential as a means for determining optimal value of mean airway pressure (MAP) for a specific subject, to a value that maintains adequate lung recruitment with minimal risk of overinflation or underinflation.

In this study, the amplitude of sound reflection was assumed to be correlative to the parenchymal density. This assumption was based on previous results in the field, indicating of such correlation between sound reflection and the degree of lung volume. The first to demonstrate how lung volume effects sound transmission in the parenchyma was Rice [3], and his work has been followed by extensive work in the field (see Wodicka et al [4], Berger [5] and Leung [6]) who showed that sound attenuation through lung parenchyma has strong relationship with lung density. During HFO, it has been shown that the parenchymal density is mostly affected by the mean airway pressure. We calculated how sound reflection during HFO was affected by the mean airway pressure and used the reflection-pressure curve to estimate the volume-pressure curve.

Our study of the acoustic properties of the lung was motivated by a desire to find a method for monitoring lung inflation during high frequency oscillation. The principal finding that emerged from our study was that lung inflation resulted in a pronounced change in the acoustic properties of the newborn lung. More specifically, we demonstrated that the reflection of audible sound increased with the increase in lung recruitment. The relation between sound reflection and mean airway pressure, as shown in Figs. 1 and 2 was of the same pattern of the known static volume-pressure curve. In the medium-high airway pressures sound reflection increased linearly to the expected change in lung volume. In the high pressures, around the UIP, sound reflection reached a plateau, indicting that maximal lung recruitment was achieved.

Exogenous surfactant reduces the surface tension throughout the lung, more at lower lung volumes and less at higher volumes, leading to alveolar stability. Surfactant is usually inserted via the tracheal tube. During the procedure, there is no way to estimate where surfactant was absorbed. Such estimation is made only by indirect clinical parameters such as the increase in oxygenation and the decrease in MAP and FiO_2 following the procedure. Also, surfactant may be absorbed unevenly between the lungs, with lower amount of surfactant absorbed in collapsed or distal lung. However, since the absorption of surfactant results in a decrease in alveolar surface tension and increase in lung volume, it can be assessed by acoustic measurements of the lung. Comparison of lung acoustics before and after the procedure may be beneficial in this case. Our results of lung acoustics before and after the administration of exogenous surfactant (Fig. 3) indicated of an increase in lung volume and lung compliance following the procedure.

Acoustic reflection was measured during instances of cyclic decrease, followed by increase in MAP. During such maneuver in MAP, lung volume is expected to decrease in the first phase and than increase again, but to a lower degree, as result of lung hysteresis. This effect on lung volume was also quantified by the acoustic measurements, shown in Fig. 4. In these examples, sound reflection followed the increase and decrease in MAP. However, amplitude of sound reflections was lower along the inflation limb of the of the volume-pressure curve of the lung, compared to its value along the deflation limb of the curve. In these instances of pressure change, an acoustic hysteresis was measured. This result further supports the hypothesis that lung acoustics reflect lung volume.

Some limitations of the method presented here should be noted. Because the acoustic signal is of sonic frequency, there is an inherent limitation in resolution. This method can provide a reliable assessment of recruitment in the lung as a unified unit while local phenomena such as uneven expansion of lung units may not be detected. Improving the spatial resolution still poses a significant technical challenge. Also, since the acoustic measurements are taken in the very first minutes of ventilation simultaneously with other procedures, ambient noise and movements of the subject may affect the acoustic measurements. The rate in which MAP is changed during this process is a crucial factor for the SNR since it determines the amount of impulses averaged in each pressure segment.

Further clinical experiments are needed to establish objective criteria for determining the optimal value of MAP during HFO. Also, some improvements in the measurement system can help obtaining more information on the acoustic properties of the lung. An acoustic transmitter with wider frequency response is needed for determining the iso and maximal sensitivity frequencies of the neonate lung during HFO.

V. CONCLUSIONS

In summary, an acoustic system was developed and tested to study the acoustic properties of the newborn lung during HFO. Despite the fact that there is no "gold standard" device to assess lung parameters during the procedure, the results suggest that the system reflects the properties of the lungs. The acoustic measurements indicated an increase in lung volume following administration of exogenous surfactant into the lungs as expected. Our study suggests that this system has a potential to indicate the degree of lung recruitment during HFO ventilation and to define the optimal region of MAP.

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