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Ventilation distribution measured with EIT at varying levels of pressure support and Neurally Adjusted Ventilatory Assist in patients with ALI

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Abstract *Purpose:* The purpose of this study was to compare the effect of varying levels of assist during pressure support (PSV) and Neurally Adjusted Ventilatory Assist (NAVA) on the aeration of the dependent and non-dependent lung regions by means of Electrical Impedance Tomography (EIT). *Methods:* We studied ten mechanically ventilated patients with Acute Lung Injury (ALI). Positive-End Expiratory Pressure (PEEP) and PSV levels were both 10 cm H_2O during the initial PSV step. Thereafter, we changed the inspiratory pressure to 15 and 5 cm H_2O during PSV. The electrical activity of the diaphragm (EAdi) during pressure support ten was used to define the initial NAVA gain (100 %). Thereafter, we changed NAVA gain to 150 and 50 %, respectively. After each step the assist level was switched back to PSV 10 cm H_2O or NAVA 100 % to get a new baseline. The EIT registration was performed continuously. *Results:* Tidal impedance variation significantly decreased during descending PSV levels within patients, whereas not during NAVA. The dorsal-to-ventral impedance distribution, expressed according to the center of gravity index, was lower during PSV compared to NAVA. Ventilation contribution of the dependent lung region was equally in balance with the non-dependent lung region during PSV 5 cm H_2O, NAVA 50 and 100 %. *Conclusion:* Neurally Adjusted Ventilatory Assist ventilation had a beneficial effect on the ventilation of the dependent lung region and showed less over-assistance compared to PSV in patients with ALI.

Keywords Electrical Impedance Tomography · Intratidal gas distribution · NAVA · Mechanical ventilation · Acute lung injury · Pressure support ventilation

Introduction

One of the main reasons for admission to the intensive care unit (ICU) is the requirement for mechanical ventilation [1]. During mechanical ventilation the dependent lung region is of special interest, due to the high risk for development of atelectasis. During controlled mechanical ventilation, air is pushed into the lungs and the diaphragm is passively moved to the abdomen with as result that tidal volume is mostly distributed to the non-dependent lung region due to better compliance of this area [2]. In contrast during spontaneous breathing, there is a contraction of the diaphragm, with more displacement of the posterior part, leading to more homogenous ventilation distribution [3]. Spontaneous breathing has been shown to lead to better ventilation/perfusion ratio [3, 4] and less atelectasis [5].

Pressure Support Ventilation (PSV) and Neurally Adjusted Ventilatory Assist (NAVA) are commonly used partial ventilatory assist modes. The PSV uses flow- or pressure-triggering in the ventilator circuit and a pre-set, constant, amount of pressure assistance is delivered with a decelerating flow pattern. The NAVA uses a special feeding tube in order to measure the diaphragm electrical activity (EAdi), and the amount of pressure assistance is proportional in relation to the measured EAdi. This enables the patient to control their tidal volume by regulation of their EAdi signal. Several studies [6–13] have shown that NAVA improves patient-ventilator synchrony compared to PSV. In addition, it has been found that NAVA reduces the risk of over-assistance due to down regulation of the EAdi signal [7, 9, 12, 14–18].

Electrical Impedance tomography (EIT) is a non-invasive, bedside, radiation-free monitoring technique. Small currents are passed through the skin by using 16–32 electrodes on the thoracic cage skin surface [19, 20]. We have shown that EIT is a reliable tool to discriminate aeration between the dependent and non-dependent lung region [19, 21]. During a decremental Positive-End Expiratory Pressure (PEEP) trial, we have shown that ventilation was lost in the dependent lung region in both healthy and diseased lungs at lower PEEP levels [19].

The purpose of this study was to visualize the effect of varying levels of pressure support and NAVA gain on the aeration of the dependent lung region by means of EIT at the bedside. Our hypothesis was that NAVA leads to more ventilation of the dependent lung region compared to PSV.

Materials and methods

Study population

In the present study, ten patients admitted to the ICU were studied during mechanical ventilation. The protocol was approved by the local institutional human investigations committee. The inclusion criteria were: >18 years of age, PSV, weaning phase of mechanical ventilation, respiratory failure according to the New Berlin ARDS criteria (mild ARDS: PaO_2/FiO_2 200–300 mmHg; moderate ARDS: PaO_2/FiO_2 100–200 mmHg; severe ARDS: PaO_2/FiO_2 <100 mmHg).

Study protocol and measurements

The EIT measurements were performed with a 16-electrode silicon belt placed around the patient's thoracic cage, just below the nipples between the 6th and 7th intercostal spaces [21] (Pulmovista 500, Dräger Medical, Lübeck, Germany). Data were gathered with a sample frequency of 20 Hz. At the time of enrollment, all patients were pressure support ventilated (PSV), using the Servo-I (Maquet, Solna, Sweden), according to our local ventilation protocol. All included patients had already a NAVA catheter for clinical reasons. Each patient received three different assist levels during pressure support and NAVA. During each assist level, EIT measurements were performed. For more detail, see the electronic supplement.

Statistics

All statistical analyses were carried out using SPSS 20 (Chicago, IL, USA). The values are stated as mean ± SD unless specified otherwise. We assessed the distribution of our data using the Kolmogorov–Smirnov one sample test for goodness of fit, and the homogeneity of variance between two distributions by means of the Brown–Forsythe test. The primary endpoint of the study was to investigate changes in ventilation distribution in the dependent lung region between NAVA and PSV. We performed a mixed linear model for repeated measures (assist levels as independent factor) to analyze changes in the average of COG index and TIV (dependent variables). Our secondary endpoint was to assess over-assistance of the non-dependent region during one breath, between the different assist levels during both NAVA and PSV. Therefore, we analyzed the intratidal gas distribution. Since the intratidal gas distribution data did not meet the assumption of normality, we analyzed the difference of the intratidal gas distribution between dependent and non-dependent lung regions by means of non-parametric statistical tests.

In addition we analyzed the differences in EAdi, peak pressure, respiratory rate, mean inspiratory pressure, expiratory tidal volume (Tve) and Tve/kg predicted body weight values between PSV and NAVA by means of mixed linear models. For both PSV 10 cm H_2O and NAVA 100 %, there were no significant differences between the three baseline periods. Therefore, the data of the three baseline periods for both PSV 10 cm H_2O and NAVA 100 % are averaged for the statistical analysis. Differences are considered to be significant when $p < 0.05$.

Results

Entry characteristics of the study population are presented in Table 1 (electronic supplement). The ventilatory data including the amount of pressure support given and the resulting EAdi values during each PSV and NAVA step are shown in Table 1. At the lowest assist level, the peak pressure was significantly lower during PSV compared to NAVA (Table 1). Increasing the level of assist, tidal

Table 1 Respiratory parameters varying pressure support and NAVA assist levels

Ventilator mode	50 %	100 %	150 %
PSV			
Assist pressure (cm H_2O)	6 ± 1*	10 ± 1	16 ± 1
Ppeak (cm H_2O)	16 ± 0	21 ± 0	26 ± 0
Mean inspiratory pressure (cm H_2O)	11.5 ± 0.3	13.2 ± 0.2$^{\$}$	14.3 ± 0.6**
EAdi (µV)	17 ± 13	14 ± 12	12 ± 9
Respiratory rate (ventilatory) (BPM)	22 ± 8	21 ± 7	18 ± 7**
Tve (mL)	508 ± 160	581 ± 188$^{\$}$	681 ± 210**
Tve (mL/PBW)	7.5 ± 2.5	8.6 ± 2.9$^{\$}$	10.1 ± 3.0**
NAVA			
Gain (cm H_2O/µV)	0.6 ± 0.7	1.3 ± 1.4	2.0 ± 2.1
Assist pressure (cm H_2O)	10 ± 5	9 ± 3	19 ± 6
Ppeak (cm H_2O)	19 ± 1	22 ± 2	28 ± 2
Mean inspiratory pressure (cm H_2O)	11.2 ± 0.3	12.3 ± 0.2	12.6 ± 0.3
EAdi (µV)	16 ± 10	14 ± 12	13 ± 9
Respiratory Rate (ventilatory) (BPM)	23 ± 8	21 ± 7	21 ± 7
Tve (mL)	532 ± 152	539 ± 165	557 ± 166
Tve (mL/PBW)	7.9 ± 2.3	8 ± 2.6	8.3 ± 2.6

Tve Expiratory tidal volume, *Ppeak* Peak pressure, *EAdi* Electrical activity of the diaphragm, *PBW* Predicted body weight, *BPM* breaths per minute

* Significant different versus NAVA 50 %; $^{\$}$ significant different versus NAVA 100 %; ** significant different versus NAVA 150 %

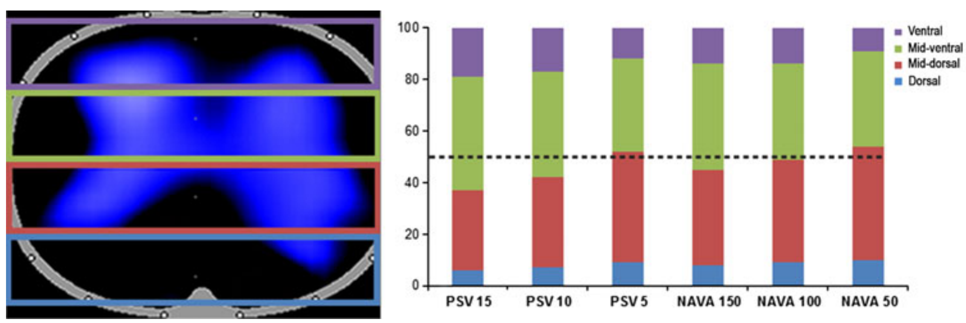

Fig. 1 Impedance distribution. The EIT image is divided in four regions of interest (*purple* ventral, *green* mid-ventral, *red* mid-dorsal, *blue* dorsal). The *bars* on the right side represent the percentage of the total tidal impedance variation located in each region, for each assist level. The *dashed-line* represents the 50 % border

volume ($p < 0.0003$) and mean inspiratory pressure ($p < 0.027$) increased significantly, whereas respiratory rate decreased significantly ($p < 0.008$) during PSV whereas not during NAVA (Table 1). During NAVA, respiratory rate and tidal volume were comparable despite the different levels of assist (Table 1). At the highest applied ventilatory assist, tidal volume was significantly higher with PSV compared to NAVA (Table 1).

The dorsal-to-ventral impedance distribution, expressed as center of gravity index, was higher during NAVA compared to PSV which means that more tidal impedance variation (TIV) was located in the dependent lung region (Fig. 1). Higher levels of assist resulted in more TIV in the non-dependent lung region (Fig. 1).

Figure 2 shows the results of the intratidal gas distribution between the dependent and non-dependent regions for both NAVA and PSV. During NAVA 150 %, PSV 10 and 15 cm H_2O the non-dependent lung region was responsible for the greatest part of the tidal ventilation and this contribution further increased during the time period of a breath for both PSV 10 and 15 but not during NAVA 150 % (Fig. 2). On the other hand, during NAVA 100, 50 % and PSV 5 cm H_2O the dependent and non-dependent lung region had an equal contribution to the tidal ventilation (Fig. 2).

Discussion

In the present study, NAVA 100 % ventilation showed an improved ventilation of the dependent lung region compared to PSV 10 cm H_2O at the same pressures. Reduction of ventilatory assist during PSV led to less ventilation of the lung whereas not during NAVA. The contribution of the dependent lung region was in-balance with non-dependent lung region during PSV 5 cm H_2O and NAVA 50 and 100 % (Fig. 2), indicating more homogenous ventilation. During PSV 10 and 15 cm H_2O, the contribution of the non-dependent lung region increased during the time period of a breath, indicating over-assistance.

Löwhagen and colleagues [22] introduced the intratidal gas distribution based on EIT measurements during a

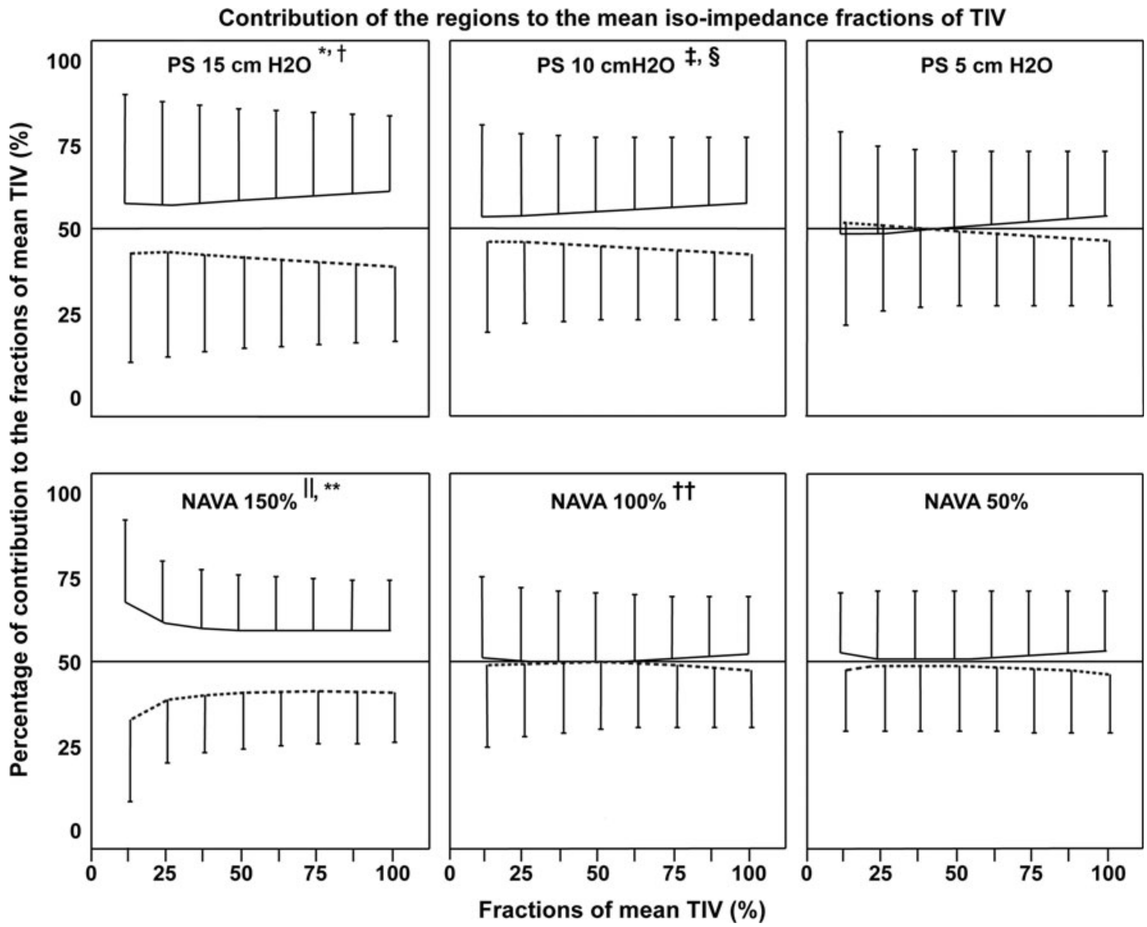

Fig. 2 Mean Intratidal gas distribution in eight iso-volume steps during inspiration at the varying levels of pressure support ventilation (PSV) and neurally adjusted ventilatory assist (NAVA). The intratidal gas distribution is calculated from one breath. The total contribution of the non-dependent and the dependent lung regions to each iso-volume step is 100 %. Significant difference in distribution by the Mann–Whitney *U* test: $^{*}p = 0.002$ between PSV 15 and PS 10 cm H2O, $^{\dagger}p = 0.001$ between PSV 15 and PS 5 cm H2O, $^{\ddagger}p = 0.001$ between PSV 10 and PS 5 cm H2O, $^{\S}p = 0.001$ between PSV 10 and NAVA 100 %, $^{\|}p = 0.001$ between NAVA 150 % and NAVA 100 %, $^{**}p = 0.001$ between NAVA 150 % and NAVA 50 %, $^{\dagger\dagger}p = 0.027$ between NAVA 100 % and NAVA 50 %. *Solid line* non-dependent lung region, *dashed line* dependent lung region

PEEP trial in 16 volume-controlled ventilated patients. They used the intratidal gas distribution to analyze how the tidal volume was distributed within the lung during inspiration and found that the gas distribution in the dependent lung region improved when PEEP was increased. In the present study, we performed the intratidal gas distribution analyses and found a homogenous gas distribution at the lowest ventilatory assist for both NAVA and PSV (Fig. 2). Tidal ventilation was also homogenously distributed with NAVA 100 % (Fig. 2) and had more ventilation in the dependent region (Fig. 1) compared to PSV 10 cm H_2O, despite that these two ventilator settings had comparable inspiratory peak pressure and EAdi values (Table 1). At the highest applied ventilator assists for both NAVA and PSV, the gas distribution in the dependent lung region was less compared to the contribution of the non-dependent lung region, and this was also seen at PSV 10 cm H_2O. In addition, the gas contribution of the non-dependent lung region increased even during inspiratory phase during both PSV 10 and 15 cm H_2O whereas not during NAVA 150 %. During NAVA, tidal volume was comparable despite the different levels of assist, whereas tidal volume increased during increasing levels of pressure support (Table 1). This can be explained by down-regulation of the EAdi signal at higher assist levels. Like previous articles [9, 16–18] we found a suppression of the EAdi signal when the assist levels are increased during both NAVA and PSV. Because NAVA uses the EAdi signal to define the assist level, the amount of increase in pressure was less due to down-regulation of the EAdi signal. In contrast during PSV, the patient will receive a constant, pre-chosen amount of pressure assist that is independent of the activity of the diaphragm. Therefore, tidal volumes will increase at higher support levels. The upslope of the non-dependent intratidal gas distribution curves during PSV 10 and 15 means that the increased tidal volume during support ventilation may lead to ventilation of the more compliant part of the lung, i.e., the non-dependent lung region, with risk of over-inflation of this lung region. This indicates that during pressure support there is more risk for over-assistance whereas this is less with NAVA.

Several [6, 9–11, 13] studies have shown that NAVA has a beneficial effect on patient-ventilator synchrony. Colombo et al. [9] compared the effect of different ventilatory assists during NAVA versus PSV on blood gases and respiratory parameters, and showed that NAVA has the advantage to reduce both patient-ventilator asynchrony and over assistance compared to PSV. This was also seen in the present study in which NAVA resulted in more homogenous ventilation compared to PSV and with less over-assistance of the non-dependent lung region (Fig. 2). Also TIV at the different used ventilatory assists during NAVA was more comparable for both dependent and non-dependent lung regions compared to PSV (Fig. 1) (electronic supplement).

There are also limitations in this study. The EIT measurement covered a cross-sectional slice of 5–10 cm of the lung depending on the placement level of the electrodes [21]. We have chosen to place the electrodes just above the diaphragm, because this is the predominant site of atelectasis in the ventilated patient in supine position. Data obtained by EIT measurement depend on many factors (patients' posture, impedance of the electrode-patient contacts, etc.) and; therefore, the absolute TIV values cannot be used to compare differences between patients directly but only the absolute changes of the effect of the different ventilatory support within a patient can be used (Fig. 1, electronic supplement). Therefore, avoiding electrode dislocation during EIT registration is important and in this study the belt with the electrodes was not disconnected during the entire measurement period of around 1.5 h.

Conclusion

Neurally Adjusted Ventilatory Assist ventilation has a beneficial effect on the ventilation of the dependent lung region compared to PSV at the same pressure in patients with Acute Lung Injury (ALI). Reduction of ventilatory assist during PSV led to less ventilation of the lung but the ventilation distribution improved in the dependent region. This indicates that levels of assist should be titrated in the individual patient in order to avoid over-assistance as seen at the highest used assist levels. During NAVA, we found less over-assistance compared to PSV and with less variation in tidal volume and TIV despite the different used ventilator assists, indicating that the patient chooses his own optimal tidal ventilation and adjusts to the imposed ventilatory assist. Despite ventilation of the dependent lung region being more pronounced with NAVA, it is unclear whether this may lead to shorter length of stay on the ventilator. Therefore, outcome studies are needed.

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