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Original Research

# Effect of High Flow Nasal Cannula on Thoraco-abdominal Synchrony in Adult Critically Ill Patients

Taiga Itagaki MD[1], Nao Okuda MD[1], Yumiko Tsunano MD[1], Hisakazu Kohata MD[1],

Emiko Nakataki MD PhD[1], Mutsuo Onodera MD[1], Hideaki Imanaka MD PhD[2],

Masaji Nishimura MD PhD[1]

1. Department of Emergency and Critical Care Medicine,

The University of Tokushima Graduate School, Tokushima, Japan

2. Department of Emergency and Disaster Medicine,

Tokushima University Hospital, Tokushima, Japan

**Running Head:** Effect of High Flow Nasal Cannula on Breathing Pattern

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its accuracy. All authors had full access to the data. All authors participated in drafting and critically revising the manuscript. All authors approved the final version of the manuscript.

**Corresponding Author:** Masaji Nishimura MD PhD

Department of Emergency and Critical Care Medicine,

The University of Tokushima Graduate Shool

3-18-15 Kuramoto-cho, Tokushima, Japan 770-8503

Telephone: +81 88 633 9347    Fax: +81 88 633 9339

E-mail address: nmasaji@tokushima-u.ac.jp

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## Abstract

***Background:*** High flow nasal cannula (HFNC) creates positive oropharyngeal airway pressure and improves oxygenation. It remains unclear, however, whether HFNC improves thoraco-abdominal synchrony in patients with mild-to-moderate respiratory failure. Using respiratory inductive plethysmography (RIP), we investigated the effects of HFNC on thoraco-abdominal synchrony.

***Methods:*** We studied 40 adult patients requiring oxygen therapy in the intensive care unit. Low-flow oxygen (up to 8 litre $\text{min}^{-1}$) was administered to the patients via face mask for 30 min followed by HFNC at a flow of 30–50 litre $\text{min}^{-1}$. RIP transducer bands were circumferentially placed, one around the rib cage (RC) and one around the abdomen (AB). We measured the movement of RC, AB and used the sum signal to represent tidal volume ($V_T$) during face-mask breathing and at 30 min after start of HFNC. We calculated two quantitative indexes; maximum compartmental amplitude/$V_T$ ratio (MCA/$V_T$); and phase angle. We assessed arterial blood gas and vital signs at each period, and mouth status during HFNC. To clarify factors associated with improvement in thoraco-abdominal synchrony, multiple regression analysis was applied to the data.

***Results:*** Respiratory rate statistically significantly decreased from 25 (22-28) to 21 (18-24) breath $\text{min}^{-1}$ after the start of HFNC ($P < 0.001$). With HFNC, patients showed

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significant improvement in $MCA/V_T$ ($P < 0.001$) and phase angle ($P < 0.05$).

***Conclusions:*** HFNC improved thoraco-abdominal synchrony in adult patients with mild-to-moderate respiratory failure.

**Abstract word count**: 232 words

**Key Words**: high flow oxygen therapy, nasal cannula, thoraco-abdominal synchrony, respiratory inductive plethysmography, acute respiratory failure, critical care

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## Introduction

Face-mask oxygen therapy and noninvasive positive pressure ventilation (NPPV) are widely used in critical care settings. NPPV is often poorly tolerated due to the close fitting of the mask, which hinders speech and oral intake.[1, 2] While nasal cannulae are less obstructive and easily allow speaking and drinking,[3] conventional nasal cannulae cannot be used with high flow, which would cause nasal soreness or bleeding.[4]

High flow nasal cannula (HFNC) can deliver adequately heated and humidified oxygen at a maximum flow of 60 litre $\text{min}^{-1}$ of gas[5-7] and has become a routine treatment in intensive care units (ICUs) for spontaneously breathing patients with respiratory failure.[5, 6, 8, 9] The beneficial effects of HFNC have been widely reported: heated humidification during HFNC improves patient comfort;[8] flushing of anatomical dead space reduces $CO_2$ levels;[5, 10] and the expiratory resistance produced by continuous high flow causes a low level of positive oropharyngeal airway pressure.[5, 11–13]

In patients with respiratory failure, coordinated movement of rib cage and abdominal wall is often impaired. Lack of coordination increases the work of breathing and causes respiratory muscle fatigue.[14, 15] Patients displaying asynchronous thoraco-abdominal movement have increased risk of ventilatory failure necessitating mechanical ventilation and, subsequently, poorer prognoses.[16, 17] To our knowledge, studies on thoraco-abdominal movement during HFNC are limited. In premature neonates, Saslow and colleagues compared phase angle between during HFNC and during nasal continuous positive airway pressure.[18] In adults, HFNC was found to improve thoraco-abdominal synchrony, but was not quantitatively evaluated.[19] The primary aim of this clinical study was to clarify the effects of HFNC on thoraco-abdominal synchrony in adult ICU patients with mild-to-moderate respiratory failure.

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## Methods

### Study population

We conducted a prospective comparative study in a university hospital ICU. The study protocol was approved by the Human Ethics Committee of Tokushima University Hospital. Before the measurement was started, informed consent was obtained from each patient's next of kin. Adult patients exhibiting mild-to-moderate respiratory failure requiring oxygen therapy were included in the study. We calculated $PaO_2/FiO_2$ ratio during face mask by using corresponding $FiO_2$ values according to flow of oxygen (3 litre $min^{-1}$ = 0.3, 5 litre $min^{-1}$ = 0.4, 7 litre $min^{-1}$ = 0.5).[20] Inclusion criteria were: $PaO_2/FiO_2$ ratio less than 300; respiratory rate more than 25 beats $min^{-1}$; dyspnea or accessory muscle use; asynchronous or paradoxical breathing pattern; and post thoracotomy. Exclusion criteria were: mean blood pressure less than 50 mmHg; $PaO_2/FiO_2$ ratio less than 150; facial trauma or nasal obstruction; inability to tolerate HFNC; and GCS score of less than 12.

### Study protocol

We recorded demographic data, GCS and Acute Physiology and Chronic Health Evaluation (APACHE) II score. Thoraco-abdominal movements were evaluated by means of respiratory inductive plethysmography (RIP) (Respitrace, Ambulatory Monitoring Inc., Ardsley, NY). Two elastic transducers (respibands), which recorded changes in cross-sectional area, were attached to the body at the start of face-mask oxygen therapy. One respiband was placed around the rib cage (RC), with the upper edge at the level of the axilla, and the other around the abdomen (AB) with the upper edge at the level of the umbilicus. Initially, oxygen was administered to each patient via face mask at 3–8 litre min$^{-1}$ for 30 min, and then we measured thoraco-abdominal movement, heart rate, blood pressure, and respiratory rate, and drew samples for arterial blood gas and $SpO_2$. Next, 30 litre min$^{-1}$ oxygen was given via HFNC (Optiflow system; MR850 humidifier, RT319 heated delivery tube and OPT544 Optiflow nasal cannula, Fisher & Paykel Healthcare, Auckland, New Zealand). Flow was titrated according to the patient tolerance. At 30 min after the start of HFNC, we acquired the same data as during face-mask breathing. During HFNC, mouth status was monitored and rated on a three-point scale (poor, almost continuously open; fair, open for about half the time; good, almost always closed). HFNC was continued until, according to the judgment of attending physicians, there was no need to give oxygen.

## Measurement of thoraco-abdominal movement

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RIP evaluation was derived as follows. The motions of RC and AB were recorded from changes in the inductance of each respiband during face mask and HFNC. Maximum compartmental amplitudes (MCAs), results of summing the maximal peak-to-trough amplitudes of RC and AB excursion, were assessed. Ratios of MCA to tidal volume ($V_T$) ($MCA/V_T$) were obtained. In this calculation, we used the maximal amplitude of the sum signal of RC and AB to resemble $V_T$. *Konno-Mead* diagrams were obtained by plotting AB motion against RC motion. Phase angle ($\theta$) was calculated according to the formula $\theta = \sin^{-1}(M/S)$, where M was horizontal distance of the *Konno-Mead* diagram at halfway between the maximal and minimal RC excursion and S was the maximal AB excursion (Fig. 1).

## Statistical analysis

Parameters before and after HFNC were compared by the Wilcoxon signed-rank test. To discover independent factors that improve thoraco-abdominal synchrony, univariate and stepwise multiple regression analysis were performed. Changes in $MCA/V_T$ and phase angle were used as dependent variables. The following continuous and nominal variables of categorical and measured items were analyzed. Patient age, BMI, $PaO_2/FiO_2$ ratio during face mask, gas flow during HFNC and the change in respiratory

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rate between face mask and HFNC were used as continuous variables. We created dummy variables that took on the values 1 and 0 for nominal variables such as sex (1, male; 0, female), consciousness disturbance (1, GCS 15; 0, GCS between 12 and 14) and mouth status during HFNC (1, good or fair; 0, poor). We included the variables with a level of significance of 0.1 in univariate analysis or the variables possibly associated with the effect of HFNC into stepwise multiple regression analysis. We considered gas flow and mouth status during HFNC and the change in respiratory rate between face mask and HFNC as possible confounding factors. Statistical calculation was carried out with statistical software (SPSS version 11.0.1, SPSS, Chicago, IL). Data are expressed as median and interquartile range values. $P < 0.05$ was considered statistically significant.

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## Results

Fifty patients were eligible for inclusion into the study, however, consent was not obtained for three patients, and seven patients were too restless to record thoraco-abdominal movement: consequently, forty patients were included. The characteristics of the patients are summarized in Table 1. There were more males than females and more surgical patients, half of whom underwent cardiothoracic procedures. The most frequent inclusion criterion was hypoxia (19 patients).

Table 2 shows measurements taken during face mask and during HFNC. No statistically significant differences between the two oxygen therapies were found for measured items such as pH, $PaO_2$, $PaCO_2$, mean blood pressure, and heart rate. Respiratory rate significantly decreased after the start of HFNC ($P < 0.001$). With HFNC, patients showed statistically significant improvement in $MCA/V_T$ ($P < 0.001$) and phase angle ($P < 0.05$).

Results of stepwise multiple regression analysis showed that any items were not associated with improved $MCA/V_T$. No items independently affected the improvement of phase angle, either.

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## Discussion

The major findings of this study were that HFNC improved thoraco-abdominal synchrony, as shown by statistically significant improvement of MCA/$V_T$ and phase angle. HFNC also statistically significantly decreased respiratory rate. This study is the first quantitative investigation of the short-term effects of HFNC on thoraco-abdominal synchrony in adult patients with mild-to-moderate respiratory failure. While Sztrymf and colleagues reported how HFNC affects thoraco-abdominal synchrony, they did not quantitatively evaluate the effects.[19] Using MCA/$V_T$ and phase angle, which are superior to other indices for quantitatively assessing breathing pattern,[21, 22] we evaluated thoraco-abdominal synchrony.

When patients are not mandated to close their mouths, HFNC delivers a low level (less than 3 cm $H_2O$) of positive airway pressure.[5, 11–13, 23] It is not fully understood, however, whether the beneficial effects of HFNC are induced solely by positive airway pressure.[8] Even though HFNC has been found to increase positive airway pressure,[5, 9, 11, 24] we found no correlation of breathing pattern improvement with female gender, mouth closure, and high gas flow. These findings suggest that positive airway pressure is not the only HFNC mechanism contributing to the improvement of breathing pattern. It is likely that enhanced patient comfort from heated humidification,[8] flushing of anatomical dead space, and reduction of airway resistance[5, 10] contribute to lessening the work of breathing, and thus to improve thoraco-abdominal synchrony.

Corley and colleagues reported that as the body mass index of the patients increased, so did end-expiratory lung volume with HFNC. They speculated that obese patients might derive more benefit from HFNC because they have more recruitable alveoli.[25] The BMI of our population were all within normal range compared to the study by Corley and colleagues and may explain why no correlation between MCA/$V_T$ improvement and BMI was observed. Further study with actual measurements of oropharyngeal airway pressure may reveal how positive airway pressure affects the respiratory mechanics of patients with different body sizes.

The statistically significant short-term decrease in respiratory rate in our study is consistent with previous studies.[7, 19, 25, 26] While improved thoraco-abdominal synchrony could possibly be a mechanism of respiratory rate reduction, we did not find any statistically significant reduction in $PaCO_2$. Roca and colleagues similarly reported that HFNC produced a statistically significant reduction in respiratory rate but no reduction in $PaCO_2$. We did not perform quantitative calibrations for RIP, so we were unable to obtain accurate $V_T$ of each patient from RIP. Even so, the product of the sum signal and respiratory rate was statistically significantly reduced by HFNC ($P < 0.001$). If minute

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volume was reduced by HFNC without any change in alveolar ventilation, it was likely that HFNC reduced anatomical dead space.

Our study has several limitations. First, it was not a controlled trial and we did not conduct the two oxygen therapies at random. A randomized cross-over trial, incorporating sufficiently long washout periods would reveal changes with HFNC and enable a clearer view of the effect of HFNC on thoraco-abdominal synchrony. Second, it is uncertain whether 30 minutes for each oxygen therapy was adequate. Long study duration makes it more difficult to clarify the effects of HFNC due to the effect of other treatments as antibiotics, bronchodilators and so forth. Third, beginning with a higher flow could have given different results on the studied end point. Fourth, we studied a small population of mixing medical and surgical patients (n = 40), and only those with mild-to-moderate respiratory failure, which makes it imprudent to extend our findings directly to other patients with difficult backgrounds. Had we studied larger numbers of patients with different categories of background disease and compared values between those populations, multivariate analysis may have revealed that HFNC is more beneficial for specific types of patient. Finally, we were unable to elucidate the mechanisms by which HFNC improved thoraco-abdominal synchrony. Actual

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measurements of oropharyngeal airway pressure and transpulmonary pressure derived from esophageal pressure may help clarify this question.

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## Conclusions

HFNC immediately improved thoraco-abdominal synchrony as demonstrated by reduction in MCA/$V_T$ and phase angle as well as respiratory rate in adult patients with mild-to-moderate respiratory failure.

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**Figure Legend**

Fig. 1. Two quantitative indexes for thoraco-abdominal synchrony using respiratory inductive plethysmography.

Fig. 1a. The motion of the rib cage (RC), the abdomen (AB), and their sum signal (SUM). SUM represents tidal volume ($V_T$). Maximum compartmental amplitude (MCA) is the sum of the maximal peak-to-trough amplitudes of RC and AB excursion. MCA/$V_T$ approaches to 1.0 with progressive synchrony.

Fig. 1b. *Konno-Mead* diagram obtained by plotting abdominal motion against rib cage motion. Phase angle ($\theta$) is calculated according to a formula $\theta = \sin^{-1}(M/S)$. Asynchrony produces a wide open loop. Synchronous rib cage/abdominal motion has a phase angle of 0° and paradoxical motion has a phase angle of 180°.

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Table 1 Patient characteristics

| | n = 40 |
|---|---|
| Age, yr | 72 (63–76) |
| male/female, n | 25 / 15 |
| Height, cm | 162 (151–168) |
| Weight, kg | 58 (49–67) |
| Body mass index | 23 (20-25) |
| APACHEIIscore | 20 (17–23) |
| Surgical/Medical, n | 27 / 13 |
| Surgical | |
| Cardiovascular | 8 |
| Thoracic | 5 |
| Upper abdominal | 2 |
| Lower abdominal | 5 |
| Brain | 5 |
| Orthopedic | 2 |
| Medical | |
| Heart failure | 6 |
| Sepsis | 2 |
| COPD | 4 |
| Neuromuscular disease | 1 |
| Inclusion criteria, n | |
| Hypoxia | 19 |
| Tachypnea | 9 |
| Dyspnea / Forced breathing | 10 |
| Abnormal breathing pattern | 2 |
| Consciousness disturbance | 16 |
| Post thoracotomy | 9 |

Values are median and interquartile range unless otherwise stated. Hypoxia is defined as $PaO_2/FiO_2$ ratio less than 300. Tachypnea is defined as respiratory rate more than 25 breath $min^{-1}$. Asynchronous or paradoxical breathing patterns are considered abnormal. Consciousness disturbance is defined as Glasgow Coma Scale between 12 and 14. APACHE, acute physiology and chronic health evaluation; COPD, chronic obstructive pulmonary disease; GCS, Glasgow Coma Scale.

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Table 2 Measurement variables during face-mask oxygen therapy and high-flow nasal cannula

| | Face mask | HFNC | P value |
|---|---|---|---|
| Gas flow, litre $min^{-1}$ | 5 (5–5) | 40 (35–40) | <0.001 |
| $FiO_2$ | 0.39 (0.40-0.40) | 0.36 (0.34–0.40) | <0.05 |
| Respiratory rate, breath $min^{-1}$ | 25 (22–27) | 21 (18–24) | <0.001 |
| pH | 7.46 (7.41–7.50) | 7.46 (7.41–7.50) | 0.06 |
| $PaO_2$, mm Hg | 97 (78–130) | 101 (77–116) | 0.75 |
| $PaCO_2$, mm Hg | 36 (33–40) | 36 (34–40) | 0.22 |
| Mean blood pressure, mm Hg | 88 (77–101) | 87 (73–97) | 0.21 |
| Heart rate, beats $min^{-1}$ | 89 (78–104) | 91 (79–102) | 0.32 |
| Mouth closure; poor/fair/good, n | NA | 17/12/11 | NA |
| $MCA/V_T$ | 1.02 (1.01–1.05) | 1.00 (1.00–1.02) | <0.001 |
| Phase angle, degrees | 19.3 (11.0–26.8) | 12.6 (6.4–25.9) | <0.05 |

Values are median and interquartile range unless otherwise stated. $PaO_2/FiO_2$ ratio during face mask was calculated by using corresponding $FiO_2$ values according to flow of oxygen. P values compare face-mask oxygen therapy versus high-flow nasal cannula. HFNC, high-flow nasal cannula; NS, not significant; NA, not applicable; $MCA/V_T$, ratio of maximum compartmental amplitude to tidal volume.

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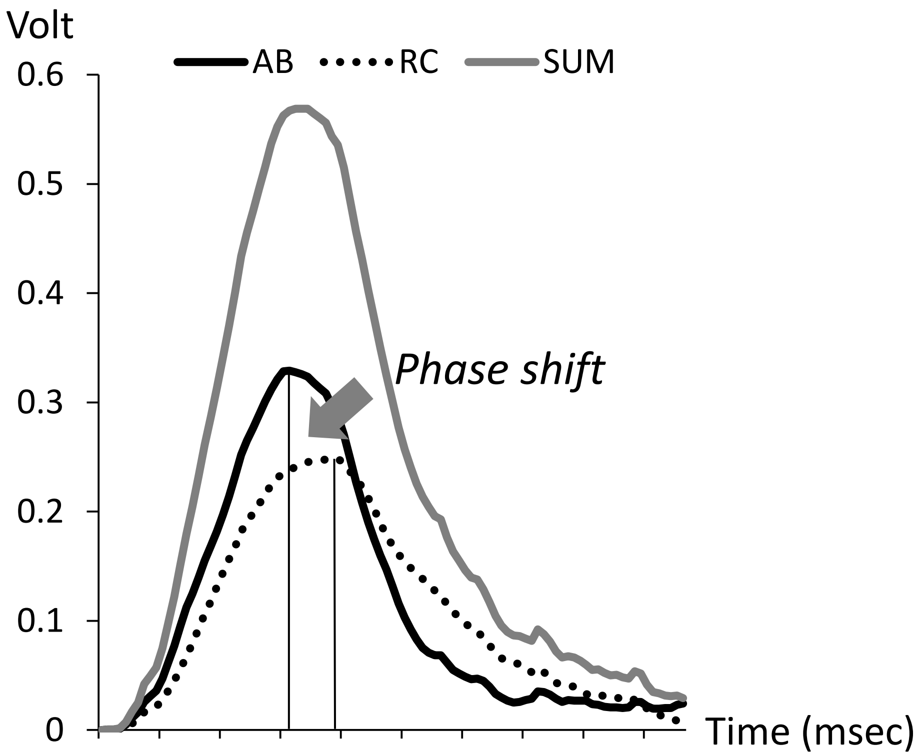

$$MCA/V_T = AB_{max} + RC_{max} / SUM_{max}$$

Figure 1a

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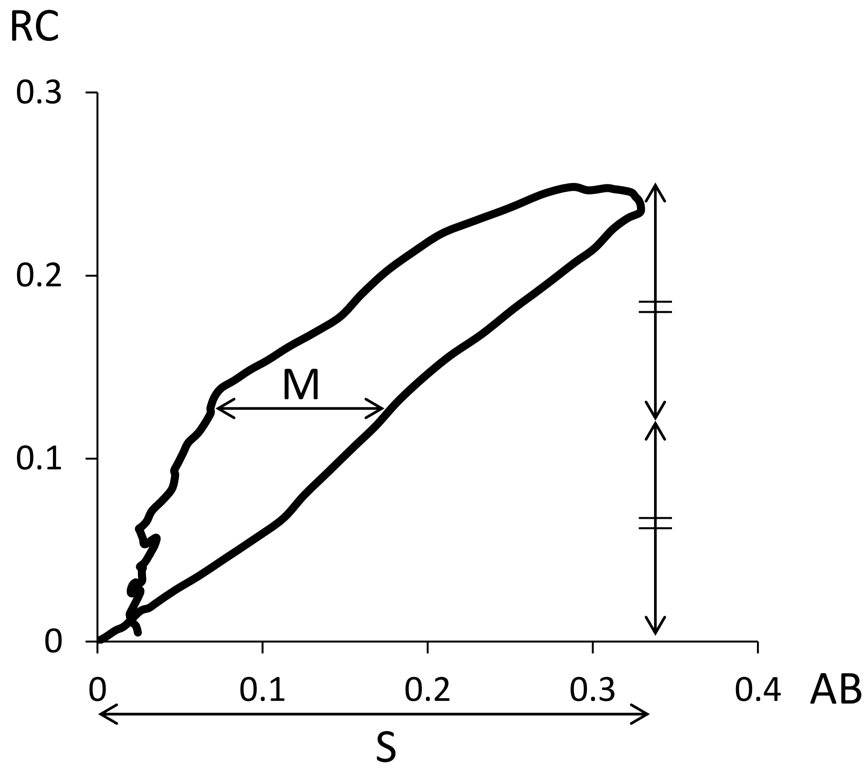

Phase angle = $\sin^{-1}(M/S)$

Figure 1b