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# Simulation of Spontaneous Breathing Synchronization under Non-Invasive Positive Pressure Ventilation with a Helmet-Type Interface: Comparison of Two Ventilators under Three Different Lung Conditions

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## ABSTRACT

**Purposes:** Few studies have investigated the synchronization of different ventilators with spontaneous breathing under non-invasive positive pressure ventilation (NPPV) delivered by helmet interface to the diseased lung. The aim of this study is to investigate ventilator synchronization under pathological conditions by testing the difference of trigger sensitivity between an ordinary ICU ventilator and an NPPV ventilator which are used in our intensive care unit.

**Methods:** A simulator was used to set three lung conditions: (1) normal: compliance (C) of 50 mL/cm$H_2O$ and airway resistance (R) of 5 cm$H_2O$/L/sec; (2) obstructive: C50, R20; and (3) restrictive: C20, R5, respectively. To test trigger sensitivity, pressure support ventilation (PSV) mode and spontaneous/time (S/T) mode were selected for the ordinary and NPPV ventilators. We tested multiple positive end expiratory pressure (PEEP; 5, 10, 15 cm$H_2O$) and pressure support (PS; 5, 10, 15 cm$H_2O$) settings, and recorded the inspiratory and expiratory trigger delays under each lung condition.

**Results:** With an ordinary ICU ventilator, neither inspiratory nor expiratory trigger delays were significantly affected by PEEP or PS under any lung conditions. In contrast, with an NPPV ventilator, auto-triggers were frequently recorded for some combinations of PS and lung conditions at 5 cm$H_2O$ of PEEP; inspiratory trigger delays worsened at peak inspiratory pressures $\geq$ 25 cm$H_2O$, and under obstructive conditions, expiratory trigger delays were prolonged in accordance with increasing PS.

**Conclusions:** An ordinary ICU ventilator is superior to an NPPV ventilator in achieving synchronization with spontaneous breathing, especially under obstructive condition and with combination of low PEEP and high PS. We consider that an ordinary ventilator is better choice for such situation than an NPPV ventilator.

**Key words:** Non-invasive positive pressure ventilation, Interface, Helmet, Inspiratory trigger, PS termination

## Background

Non-invasive positive pressure ventilation (NPPV) is widely used in the treatment of acute and chronic respiratory failure as a mechanical ventilation method that does not require endotracheal intubation[1), 2)]. This reduces the risk of complications associated with endotracheal intubation and facilitates weaning from artificial ventilation[3)]. However, there are some potential downsides related to NPPV. The interfaces commonly used with NPPV, especially

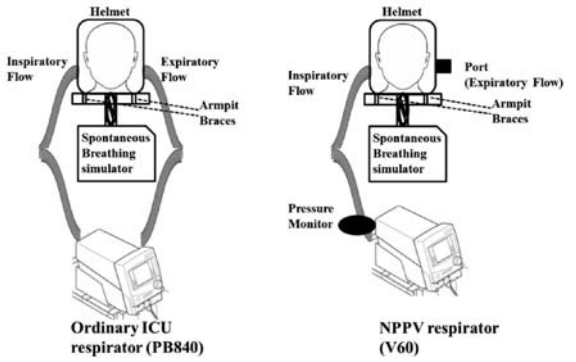



**Fig. 1.** Helmet-type interface was connected to each respirator

the facemask[4), 5)], can lead to NPPV failure. Air leakage[6), 7)], patient discomfort[8)], and pressure-related ulcerations of the nose[9), 10)] can all limit the duration of NPPV and account for failures. To avoid these complications, a helmet-type interface was developed and has been tested under different clinical situations[9)−12)]; the helmet has the potential to improve patients' tolerance of NPPV and decrease the rate of interface-associated complications.

Despite these advantages, few studies have investigated synchronization with spontaneous breathing under NPPV and pathological lung conditions with a helmet-type interface. Our objective was to investigate ventilator synchronization with a patient's spontaneous breathing under various conditions.

A helmet-type interface can also provide a closed circuit between the ventilator and the patient, which enables the effective use of an ordinary ICU ventilator in addition to an NPPV ventilator. Therefore, we tested the inspiratory trigger and expiratory termination sensitivity of an ordinary ICU ventilator (Bennett 840; Covidien) compared with an NPPV ventilator (V60 ventilator; Philips Respironics). We postulated that the ordinary ICU ventilator would be superior to the NPPV ventilator with regard to synchronization because of its closed respiratory circuit.

## Materials and methods

Measurements were conducted with a large-sized helmet (Starmed Caster R; Mirandola; Modcua, Italy) placed on a mannequin head, which is made to replicate a human's airway, connected to a spontaneous breathing simulator (LUNGOO; Air Water Inc.; Shinagawa-ku; Tokyo, Japan). Two underarm laces, which were attached to a ring at the lower side of the helmet, prevented it from lifting when inflated. A plastic collar fit around the neck prevented leakage during ventilation. Inspiratory and expiratory tube connectors were fitted to the lower part of the helmet.

We used three lung models capable of simulating spontaneous breathing. The active servo lung consisted of an electrically driven pneumatic lung simulator that allowed for adjustment of respiratory rate, compliance, resistance, inspiratory effort (total pressure of respiratory muscles), inspiratory to expiratory ratio, and inspiratory pattern (i.e., rise time and plateau). During the study, data were gathered by sensors (flow and pressure) placed in the respiratory circuit, not by the lung model itself (Fig. 1).

A normal lung was simulated using compliance (C) of 50 mL/cm$H_2O$ and an airway resistance (R) of 5 cm$H_2O$/L/sec. We also simulated two types of lung pathology, obstructive lung disease and restrictive lung disease. Obstructive lung disease was simulated using a normal compliance of 50 mL/cm$H_2O$ and a high resistance of 20 cm$H_2O$/L/sec. Restrictive lung disease was simulated using a low compliance of 20 mL/cm$H_2O$ and a normal resistance of 5cm$H_2O$/L/sec (Table 1). The other settings were as follows for all lung conditions: total pressure of respiratory muscles (Pmus), 5 cm$H_2O$; inspiratory time, 1.0 seconds; and

**Table 1.** The settings of three lung conditions (normal, obstructive and restrictive)

| Lung Condition/ Settings | Compliance(mL/cm$H_2O$) | Resistance (cm$H_2O$/L/sec) |
|---|---|---|
| Normal | 50 | 5 |
| Obstructive | 50 | 20 |
| Restrictive | 20 | 5 |

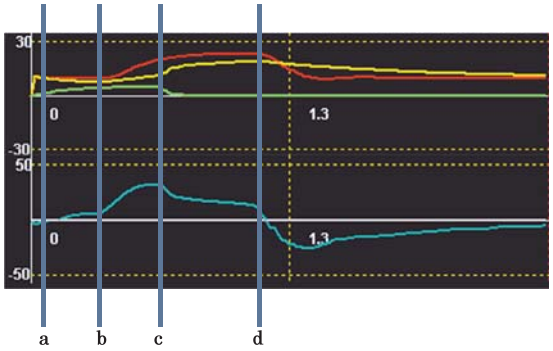



**Fig. 2.** Representative waveforms of airway pressure (red), alveolar pressure (yellow), total pressure of respiratory muscles (Pmus; green), and flow (blue). The time required to trigger inspiration (inspiratory delay: a-b) and to terminate pressure support (expiratory delay: c-d) was recorded

respiratory rate, 15 breaths per minutes (bpm).

To test trigger sensitivity, the Bennett 840 was set in non-invasive ventilation (NIV) mode and pressure support ventilation (PSV) mode, with an inspired oxygen fraction ($F_IO2$) of 0.21, an inspiratory trigger set at 3 L/minute, and a cycling-off flow threshold of 25% of the peak inspiratory flow. The V60 was set in the spontaneous/timed (S/T) mode, with $F_IO2$ of 0.21 and a rise time of 0.1 second. Both ventilators' settings also included positive end expiratory pressures (PEEPs) of 5, 10, and 15 $cmH_2O$ and pressure support (PS) settings of 5, 10, and 15 $cmH_2O$.

We recorded inspiratory trigger delays, calculated as the time lag between the onset of inspiratory effort and the start of ventilator support, and expiratory trigger delays, calculated as the time lag between the end of inspiration and the termination of ventilator support, ten cycles in all settings. Then, we plotted the average value. Those two measurements indicate dis-synchrony between the simulator and the ventilator and are considered to represent increased work of breathing as prolonged. These measurements were recorded for both ventilators at different levels of PEEP and PS under all three lung conditions: normal, obstructive, and restrictive (Fig. 2).

***Statistics:***

All calculations of average value were performed by Microsoft Excel 2010™.

## Results

***ICU ventilator***

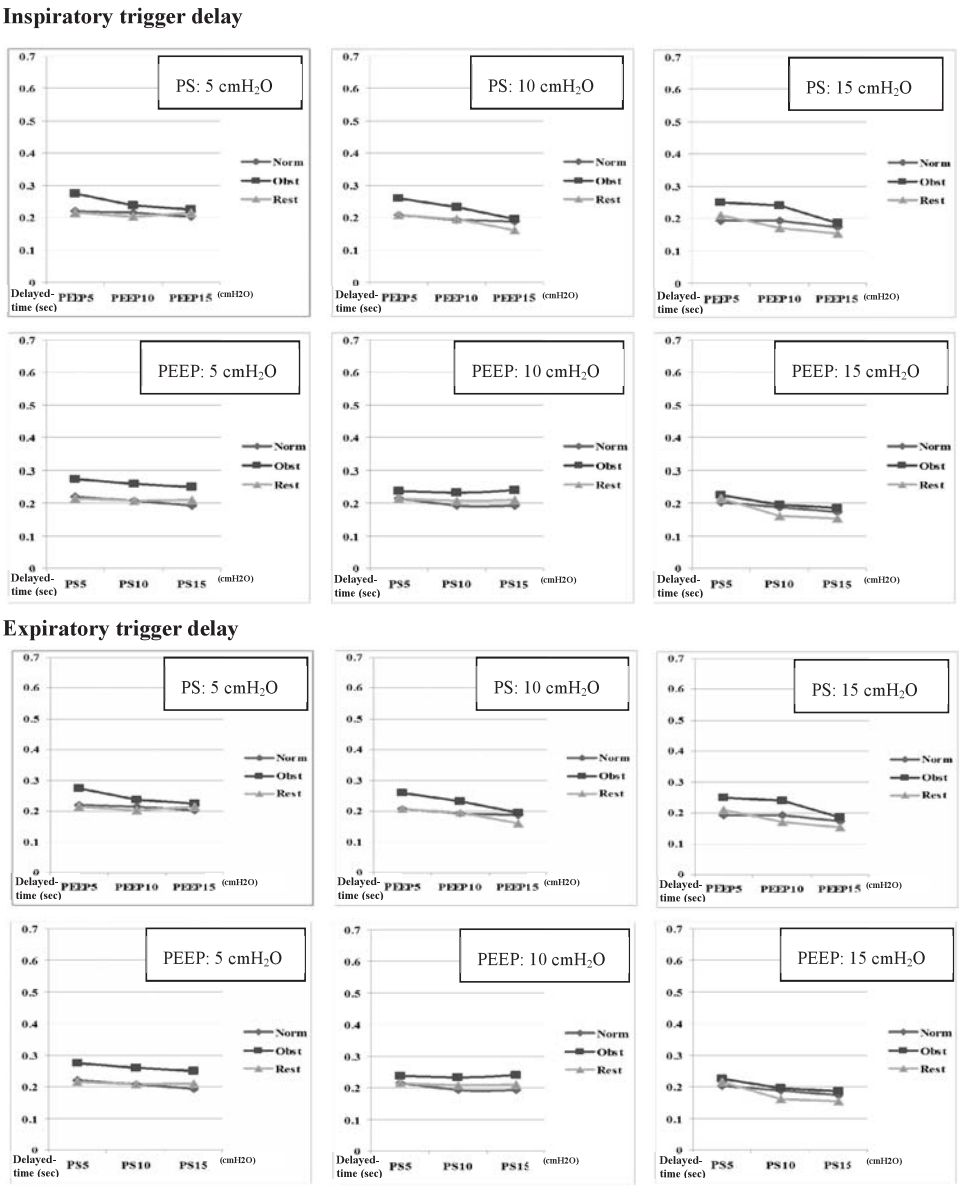
Using an ICU ventilator (PB 840), the inspiratory trigger delays were 0.15− 0.25 seconds and were not significantly affected by PEEP or PS under any lung conditions (Fig. 3). Regarding expiratory trigger delays, although slightly earlier PS terminations (less than 0.1 seconds) occurred under restrictive conditions and trivial delays in PS termination (less than 0.2 seconds) occurred under normal and obstructive conditions (Fig. 3), expiratory trigger delays were less affected by PEEP and PS than they were with the NPPV ventilator.

***NPPV ventilator***

In contrast, with the NPPV ventilator, auto-triggers were recorded for six of nine combinations of PS and lung conditions at 5 $cmH_2O$ of PEEP; they were especially frequent under restrictive conditions (Fig. 4). Inspiratory trigger delays were 0.2− 0.24 seconds under normal and restrictive conditions and were not significantly affected by PEEP or PS, with the exception of auto-triggers. However, inspiratory trigger delays worsened to over 0.3 seconds under obstructive conditions, particularly when peak inspiratory pressure was $\geq$ 25 $cmH_2O$ (Fig. 4). Expiratory trigger delays were trivial, ranging from 0.01 to 0.24 seconds under normal and restrictive condition, but significant delays were found when PS was increased during obstructive condition. The delays were notably prolonged as peak inspiratory pressure increased under obstructive condition (Fig. 4).

## Discussion

Our results showed the ordinary ICU ventilator to be superior to the NPPV ventilator in achieving synchronization with spontaneous breathing with the use of a helmet-type interface, especially under obstructive conditions and with combinations of low PEEP (5 $cmH_2O$) and high PS. We found two major problems with the NPPV ventilator: auto-triggered ventilation and prolonged trigger delay.




Norm: normal lung conditions; Obst: obstructive lung conditions; Rest: restrictive lung conditions

**Fig. 3** Inspiratory trigger and pressure support (PS) termination times are shown under different lung conditions and levels of positive end expiratory pressure (PEEP) and PS for the ICU ventilator (Bennett 840): The data of auto (double)-triggers could not be plotted on the graph due to the inappropriate results

***Auto-triggered (Double-triggered) ventilation***

Auto-triggered ventilation seemed to be caused by up-and-down motion of the helmet-type interface. We think that this motion was related to the cycle of collapse and expansion at the helmet surface and to higher air flow within the helmet.

The helmet surface is made of polyvinyl chloride, which has high compliance. A PEEP of 5 $cmH_2O$ was not enough to maintain expansion of the helmet's surface; collapse of the surface caused vertical movement of the helmet, which caused auto-triggering even though the underarm laces should have prevented the helmet from lifting when it was inflated. In addition, the open circuit of the NPPV ventilator may have facilitated higher air flow within the helmet because the NPPV ventilator circuit is a one-tube device that requires a hole for air leakage to avoid overly high pressure. The helmet has a large

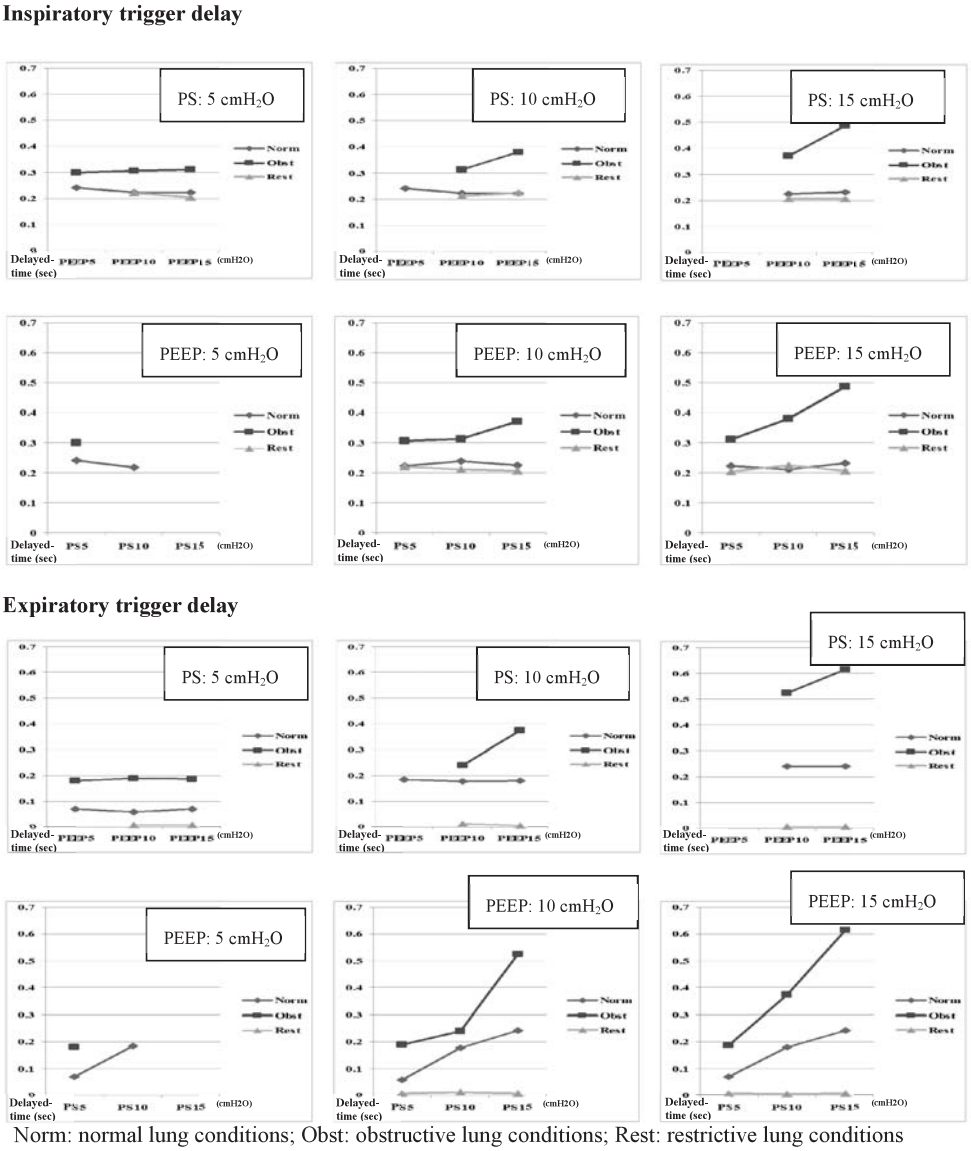



**Fig. 4** Inspiratory trigger and pressure support (PS) termination times are shown under different lung conditions and levels of positive end expiratory pressure (PEEP) and PS for the NPPV ventilator (V60): The data of auto (double)-triggers could not be plotted on the graph due to the inappropriate results

internal volume of 7.5 L with inflated cuffs[13]; although this internal volume is reduced to approximately 2.4 L when a head is inserted into the helmet, the internal volume of the helmet is much larger than that of any other NPPV interface[13]. Therefore, the ventilator needed to use a higher air flow to maintain airway pressure within the helmet. This higher air flow facilitated the up-and-down motion of the helmet. In stark contrast to the NPPV ventilator, the ICU ventilator (PB 840) showed a stable response to spontaneous breathing in this study because it formed a closed circuit without a hole.

***Prolonged trigger delay***

As a past study pointed out, inspiratory and expiratory trigger delays are prolonged when using a helmet[14]. In terms of synchrony, an endotracheal tube or face mask is better than a helmet at a given ventilator setting. The helmet-type interface necessitates both higher PEEP and higher PS to improve delay times[15]. In our study, the helmet required a

higher PEEP (≥ 10 $cmH_2O$) to eliminate auto-triggering, but we did not find any improvement in trigger delay with increased PS. Between the two ventilators, the ICU ventilator showed better results than the NPPV ventilator. Air leakage may have affected the trigger sensitivity.

***Pathological lung conditions***

The settings for obstructive lung disease (compliance, 50 $cmH_2O$; resistance, 20 $cmH_2O$) created the worst trigger delay at every setting for both the ICU and NPPV ventilators. This can be explained by higher airway resistance in the circuit, it took much more time for the ventilator's trigger to detect sufficient air flow. Significant delays in both inspiratory and expiratory triggers were recorded with the NPPV ventilator under obstructive conditions; the trigger delays showed a trend to increase with increases in PEEP and PS. Because the ICU ventilator showed better results, we hypothesize that these delays may have been caused by air leakage from the ventilator circuit.

Under the settings for restrictive lung disease (compliance, 20 $cmH_2O$; resistance, 5 $cmH_2O$), auto-triggering occurred frequently at a PEEP setting of 5 $cmH_2O$ with the NPPV ventilator. The reason for this is unclear, but we theorize that lower lung compliance may have led to lower airflow at the inspiratory phase and higher air flow at the expiratory phase. Those changes of airflow facilitated up-and-down movement of the helmet.

The problems of auto-triggering and trigger delays may be reduced by improvements in the helmet-type interface[16] and circuit[17), 18)], but at present, an ICU ventilator (PB 840, closed circuit) is more reliable in terms of synchronization with patients' spontaneous breathing.

***Limits of this study***

This was a simulation study, and it had several limitations that should be highlighted. First, the study was designed to focus on synchronization with spontaneous breathing; therefore, the clinical impact of the study findings is unknown, especially regarding patients' gas exchange. There have been several previous papers that referred to higher $PaCO_2$ with the use of a helmet-type interface[19), 20)]. Thus, when using a helmet-type interface in clinical practice, patients' gas exchange should be carefully monitored. Second, this study involved limited ventilator settings and lung conditions. From the study, we were able to identify tendencies in synchronization with spontaneous breathing for ordinary (PB 840) and dedicated respirators (V60) using a helmet-type interface under NPPV conditions, but the study was not designed to determine the best settings for each lung condition[21)]. We used just two ventilators (ordinary ICU and NPPV dedicated) for our study, which varied widely regarding triggers for spontaneous breathing[21)]. In addition, several previous reports have indicated that some ICU ventilators do not correctly resume their action after helmet collapse[22)]; therefore, it is important to check patients carefully when using ICU ventilators with a helmet-type interface. We need to assess a wider range of ventilators in the future. Third, we used a helmet with arm laces, but a new type of helmet that does not require arm laces may reduce auto-triggering and PS termination delays[16)].

Despite these limitations, our simulation study showed the efficacy of using an ICU ventilator for NPPV with a helmet-type interface in terms of synchronization with spontaneous breathing. To our knowledge, this is the first study to compare popular ventilators (PB 840 and V60) under normal and pathologic (restrictive and obstructive) lung conditions using NPPV with helmets. Therefore, the results of our study provide useful suggestions for clinicians when choosing ventilators for NPPV. More studies are needed to clarify the selection of ventilators and settings and to achieve optimal synchronization between patients and ventilators.

***Clinical relevance***

It is currently unknown whether patient-ventilator asynchronies due to air leaks can affect the clinical course of NPPV and influence a clinician's choice of ventilators. However, there are multiple reasons to optimize synchronization during NPPV. First, it is reasonable to assume that auto-triggering and delayed cycling will reduce patient tolerance of ventilation, which is a key to NPPV success[23), 24)]. Second, the occurrence of delayed cycling can lead to dynamic inflation and contribute to ineffective efforts[25), 26)]. We cannot quantify to what extent these

differences may be clinically relevant, and there is a need for further studies addressing the impact of different devices, ventilators, and settings on the outcomes of different groups of patients receiving NPPV to formulate more useful recommendations.

## Conclusion

In conclusion, we found an ICU ventilator (PB 840) to be superior to an NPPV ventilator (V60) in achieving synchronization with spontaneous breathing, especially under obstructive conditions and with combinations of low PEEP and high PS. We consider that an ordinary ventilator is better choice for such situation than an NPPV ventilator.

## Availability of supporting data

The data sets supporting the results of this article are included within the article and its additional file.

## List of abbreviations

(In the figures)
Norm: normal lung conditions; Obst: obstructive lung conditions; Rest: restrictive lung conditions

## Conflict of interest statement

Sources of financial support: none
The authors declare that they have no conflicts of interest.

## Author's contributions

TK and MN participated in the design of the study. TK performed data interpretation and statistical analysis and drafted the manuscript. KazukiK, NM, MO collected the patient data. MN, SO, and KaneyukiK revised and edited the manuscript. All authors read and approved the final manuscript.

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The authors are affiliated with the Department of Anesthesiology and Critical Care Medicine, Yamagata University Faculty of Medicine, Yamagata, Japan.

This study was performed in the same place as above.

This data was presented in poster in the 41st critical care congress of Society of Critical Care Medicine (4-8th February 2012, Houston, Texas, USA)
Presenter: Tadahiro Kobayashi M.D.

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