The Nagoya Conference on System Design and Patient-Ventilator Interactions During Pressure Support Ventilation*

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Editor's Note:
This report is a summary of a conference held in Nagoya, Japan in December 1988. The purpose of this conference was to bring together a group of active researchers in Japan to discuss how pressure support design features interact with patient neuromuscular function and ventilatory demands. Dr. Shimada served as moderator of the proceeding. Dr. MacIntyre functioned as both a speaker and as an editor of this final report. Drs. Nishimura, Usada, Tokioka, and Takezawa each led discussions regarding specific aspects of patient interactions with pressure support ventilation design characteristics.

**PSV** = pressure support ventilation

**DEFINITION AND POTENTIAL APPLICATIONS OF PSV**

Pressure support ventilation is an assist mode of ventilation that supplies the clinician a set level of positive airway pressure during spontaneous inspiratory efforts. Unlike volume-assisted breaths (which deliver a clinician set flow and tidal volume to the patient), PSV allows the patient to maintain control of inspiratory and expiratory time and to interact with the set pressure to determine the ultimate flow and tidal volume.1

PSV can either totally or partially unload ventilatory muscles during spontaneous breaths.12 Total unloading occurs when the only patient effort is that which is required to trigger the breath. Muscle contractions beyond this point are accompanied by enough positive airway pressure and machine flow such that no appreciable muscle tension generation or mechanical work is performed. Total unloading is reflected by virtually no ventilatory muscle oxygen consumption.3 Clinically, total unloading correlates with levels of inspiratory pressure assist that result in tidal volumes (Vt) of 10 to 12 ml/kg (so called PSVmax).4 Note that when PSV is used at levels sufficient to virtually totally unload muscles, it has similar muscle resting effects to volume controlled ventilation.

Partial unloading occurs when levels less than PSVmax are used. Under these circumstances, ventilatory muscles perform only a portion of the pressure generation and mechanical work required for breathing.2 The actual load on the muscles under partial unloading conditions is determined by the level of inspiratory pressure assist applied and the ventilatory system impedances.

Partial unloading is indicated in two situations. First, in patients requiring prolonged ventilatory support, complete muscle rest beyond 72 to 96 hours may predispose to muscle atrophy and subsequent weaning difficulties.5 Thus, some nonfatiguing load should probably be applied under these circumstances. The exact level of this is not known, but some data would suggest that near normal work loads (eg, up to 10 J/min) are well tolerated in such patients and do not precipitate EMG evidence of overload/fatigue.3 Second, the weaning process involves a gradual return of the breathing loads to the muscles. With PSV, this is accomplished by reductions in the applied inspiratory pressure-assist level. The rate of reduction of support is guided by the patient's ability to handle the loads imposed by ventilation demands. Clinically, this can be monitored well by following the respiratory rate.2
In these partial reloading situations, PSV has several theoretic advantages over other reloading approaches (ie, t piece trials, IMV). First, the pressure-volume "shape" of the muscle load is more normal in configuration. This is a more energy-efficient form of load and may encourage mitochondrial development and endurance conditioning. Second, load is applied with every breath and the flow is servo-controlled to synchronize with both the patient's own neural intensity (ie, VT/Ti) and timing (ie, TV/Tot) characteristics. Better patient-ventilator interactions should result in improved comfort and less sedation needs.

PSV DESIGN FEATURES: OPTIMAL PATIENT-VENTILATOR INTERACTIONS

In order to provide the effects noted above, the inspiratory pressure assist must be designed to do the following: (a) begin simultaneously with onset of a patient's inspiratory effort; (b) provide flow in synchrony with the patient's inspiratory effort; (c) provide a level of airway pressure during the inspiratory effort sufficient to accomplish proper muscle unloading; and (d) terminate simultaneously with the cessation of the patient's effort. Current design characteristics and the importance of these characteristics in providing optimal patient-ventilator interactions during PSV are illustrated in Figure 1 and discussed below.

Pressure Support Initiation (Trigger) (Fig 1A)

As with any form of support that is designed to respond to patient effort, the inspiratory pressure assist of PSV requires a signal to trigger the demand valve to initiate flow. Most current systems trigger off an airway pressure sensor (ie, an inspiratory effort is sensed as a drop in circuit airway pressure). It is important to note, however, that this sensor is physically separated from the ventilatory muscles by a series of tubes (ie, endotracheal tube and airways) and tissue barriers (ie, alveolar walls and pleura). Thus, inherent insensitivity and unresponsiveness exist with all current PSV systems (as well as other assist modes). Furthermore, this inherent insensitivity and unresponsiveness is compounded by the sensitivity and response characteristics of ventilator demand valves. At best, these factors can produce an uncomfortable isometric load on patients' muscles at the beginning of an inspiratory effort. At worst, these imposed loads can be of such magnitude that patient-ventilator dyssynchrony and muscle fatigue can develop.

Improved triggering of the inspiratory pressure assist could be accomplished by moving the trigger sensor physically closer to the inspiratory muscles (eg, the distal endotracheal tube or even into the pleural space). Recent work in this area, for instance, has shown that pleural pressure changes required to initiate an inspiratory pressure assist can be reduced by several centimeters of water if the trigger sensor is located in the pleural space. Inexpensive monitoring catheters with acceptable signal-noise characteristics, however, are not currently available for these purposes. Note that the ultimate sensing location would be a direct link to the patient's neuromuscular system. This could be accomplished by phrenic nerve sensors or muscle EMG signals. Unfortunately, clinically reliable sensors such as these do not exist at the present time.

Machine Delivered Flow to Achieve the Set Pressure Level (Fig 1B and C)

As noted above, the inspiratory pressure assist is triggered by a patient's effort. The patient's ventilatory drive, however, does not cease with the initiation of this breath. Specifically, studies have shown that once the patient has begun to contract the ventilatory muscles, this contraction continues during the assist cycle. Ideal PSV, therefore, should respond not only to a patient trigger, but should also provide inspiratory flows and an ultimate tidal volume that are synchronous with the muscle contraction pattern.

Current systems usually set the initial flow as the maximal flow capability of the ventilator. While this

![Figure 1](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21614/.../06/27/2017)
often appears to produce a rapid and comfortable attainment of the selected airway pressure, in some patients this flow may be too fast and cause airway pressure overshoot ("ringing") (Fig 1B-1). In others, this flow may be too slow and result in excessive patient effort during the initial phase of the assisted breath (Fig 1B-2). Since patient-ventilator synchrony is one of the advantages of the pressure support concept, an adjustable initial flow control might therefore be an appropriate mode enhancement. With such a control, the "shape" of the airway pressure curve could then be set to provide rapid ventilator response without overshoot.10,14

Once the set pressure level is attained, subsequent flow delivery is servo-adjusted continuously through the inspiratory cycle to maintain this airway pressure (Fig 1C). Flow is thus matched to patient demand. Indeed, this is thought to be one of the major reasons pressure supported breaths appear to be more comfortable to patients than fixed flow, volume assisted breaths. For example, a recent clinical study on eight patients clearly showed that with an inspiratory pressure assist level comparable to the peak pressure of the control volume-assisted breaths, patients had larger volumes, slower rates, and much less "fighting" of the ventilator.15

Magnitude of Pressure Support During the Inspiratory Effort (Fig 1C)

The proper level of ventilatory muscle unloading is often not zero and, in fact, depends upon a number of factors that include muscle strength and endurance, cardiovascular function and gas exchange. Conceptually, the proper level of muscle unloading is that which encourages reconditioning and prevention of atrophy while avoiding the development of fatigue.4,5 Recommendations on how to achieve this level of unloading with PSV involve setting a level of inspiratory pressure assist that keeps the respiratory rate below 30 (respiratory rate is a useful marker of load detection); avoids sternocleidomastoid retractions; or avoids diaphragmatic EMG power spectrum shifts.2,3,16

An alternate approach to the determination of the proper inspiratory pressure assist level is to titrate it to a pleural pressure measurement.12 A recommendation is to maintain a pleural pressure of zero (referred to as "pleural pressure support"). This results in unloading patient muscles of virtually all of the work of lung inflation and leaves only the loads associated with inflation of the chest wall. This may be a reasonable load to maintain while underlying lung and muscle abnormalities resolve to the point that extubation is possible. Clinical trials to test this approach are needed.

Computer programmed feedback loops utilizing pressure, end tidal CO₂ (PetCO₂), and inspiratory rate input have also been proposed as a way to optimize the inspiratory pressure assist level. The goal of this approach is to provide the minimal inspiratory pressure assist necessary to prevent tachypnea and/or hypercapnia. In using this approach, a standard sampling tidal volume (interspersed as "sigh" breaths) should probably be used since the arterial-end tidal CO₂ gradient depends heavily on the tidal volume. In addition, it should be noted that while Pet CO₂ clearly reflects alveolar ventilation, it is a poor early indicator of muscle fatigue.17 For this reason, automated feedback loops should probably use respiratory rate as the primary sensing criteria with Pet CO₂ being used as a "safety check."

Pressure Support Termination (Fig 1D)

Ideally, an inspiratory pressure assist should terminate when the patient's inspiratory effort has ceased. Premature termination will leave the patient with sudden loss of support during continued muscle contraction and a consequent abrupt increase in load (Fig 1D-2). Conversely, delayed termination will leave positive airway pressure present while the patient is trying to exhale (Fig 1D-1). This will create a load on the patient's expiratory muscles.

Current pressure support systems use various criteria for support termination. A common termination signal is to use a percent of inspiratory peak flow (usually 25 percent). An alternative approach is to use a fixed flow criteria (usually 5 L/min) as this signal. Preliminary data comparing flow criteria from 25 to 50 percent of peak flow do not appear to show much difference,14 although a reduction to 3 percent appears to substantially increase the VT.18 An additional approach has been to use a pleural pressure increase as the trigger for expiration,12 but no clinical trial has been performed evaluating this.

PSV Design Features: Potential Hazards

Although there appears to be a number of potential advantages to pressure support ventilation, there may also be potential hazards in its use, especially when used by clinicians who do not properly understand the concept or design characteristics of inspiratory pressure assist. Summarized below are some of the more important potential hazards.

1) Varying minute ventilation delivery in unstable patients. Because PSV is an assist mode, patients with unreliable ventilatory drives may not trigger the ventilator at appropriate times to assure an adequate breathing frequency. Similarly, an unreliable inspiratory effort may cause fluctuations in inspiratory times and consequently, the effective VT. Rapidly changing lung impedances (ie, compliance and resistance) can also rapidly change tidal volumes in a patient with a set level of inspiratory pressure assist. PSV should
thus be used with caution in patients with unstable ventilatory drives or respiratory system mechanics.

(2) Atelectasis from smaller tidal volumes. As smaller levels of inspiratory pressure assist are used during the weaning process, the resulting smaller lung inflations can cause atelectasis in the dependent part of the lung. Under these circumstances, an occasional hyperinflation from a volume cycled breath may be needed to maintain alveolar stability.

(3) Persistent inspiratory pressure assist due to circuit leak. A small circuit leak can produce continued flow “demands” such that expiratory criteria are not met. 19 Most ventilators have secondary breath termination criteria (3 to 5 s) to reduce the potential hazard associated with this. Nevertheless, clinicians need to be aware of this potential problem.

(4) Autocycling caused by circuit leak. A circuit leak in a patient receiving positive expiratory pressure can also cause automated triggering of the demand flow (auto-cycling). Under appropriate circumstances, the ventilator will terminate the demand flow but the baseline pressure may not be maintained due to the small leakage. This pressure decrease can exceed the trigger level and cause the initiation of the next inspiratory pressure assisted breath.

(5) High mean airway pressures when high level PSV is used. An inspiratory pressure assist with every breath means positive airway pressure with every breath. This is in contrast to IMV in which the patient creates intermittent negative pleural pressure which, in turn, may promote cardiac filling. In a hemodynamically compromised patient, a high level of inspiratory pressure assist might therefore be a potential problem. On the other hand, improved patient-ventilator synchrony with PSV may reduce pleural pressure increases associated with unsynchronized volume controlled breaths and thereby improve cardiac filling.

Conclusions and Research Needs

At the present time, PSV remains a theoretically attractive alternative to volume cycled ventilation in clinical situations where muscle factors are important. Studies already exist describing the mode and its ventilatory muscle unloading effects. Needed, however, are further studies on design features for optimal patient-ventilator interactions, proper approaches to muscle unloading and reloading in ventilatory muscle failure, and clinical studies assessing outcome as a function of support mode.

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