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Advances in Positive Airway Pressure Treatment Modalities for Hypoventilation Syndromes

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SYNOPSIS

Rationale—Positive airway pressure therapy for hypoventilation syndromes can significantly improve health-related quality of life (HR-QOL), healthcare costs, and even mortality. The sleep-disordered breathing in such individuals are quite complex and require sophisticated devices with algorithms that are designed to accurately detect and effectively treat respiratory events that includes hypoventilation, upper airway obstruction, lower airway obstruction, central apneas and central hypopneas and reduce the work of breathing while maintaining breathing comfort.

Objectives—The therapeutic physiological rationale for the various advanced PAP modalities and the details about the principles of operation and technology implementation are provided here.

Conclusions—The physiological rationale for advanced PAP modalities is sound considering the complexity of sleep-disordered breathing in patients with hypoventilation syndromes. Although such devices are increasingly used in clinical practice, the supporting clinical evidence – specifically comparative-effectiveness studies in real-life conditions -- needs to be performed. Moreover, there is much opportunity for further refining these devices that include the ability of the device to reliably monitor gas-exchange, sleep-wakefulness state, and for reducing variability in device efficacy due to provider-selected device-settings.

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Keywords

Hypoventilation syndrome; obesity; sleep; obstructive sleep apnea; continuous positive airway pressure; positive airway pressure; artificial respiration; algorithms

Introduction

Positive airway pressure therapy for hypoventilation syndromes can significantly improve health-related quality of life (HR-QOL), healthcare costs, and even mortality (1–3). Such important patient-centered and healthcare related outcomes are effected by the beneficial effects of PAP therapy on intermediary physiological endpoints such as improved gas-exchange and better sleep quality accomplished during both sleep and wakefulness (1, 4, 5). While different definitions for advanced PAP therapy may exist, for the purposes of this review, advanced PAP modalities refer to modes other than continuous positive airway pressure (CPAP) therapy administered by non-invasive mask interface during sleep. They could be broadly categorized into bilevel positive airway pressure (bilevel PAP), automated positive airway pressure therapy (autoPAP), volume-targeted pressure assistance (volume assured pressure support), volume control invasive or non-invasive ventilation, or new and emerging devices that administer ventilatory assistance during wakefulness in ambulatory patients. The therapeutic physiological rationale for the various technological options and the details about the technology implementation are provided in this chapter. The supporting randomized clinical trials and other clinical evidence are provided elsewhere in this issue.

Therapeutic options and physiological rationale

The need for advanced PAP modalities should ideally be viewed in the context of the entire gamut of therapeutic options and their respective targets in patients with hypoventilation syndromes (figure 1). While arguably, conventional CPAP could be effective in most cases of obesity hypoventilation syndrome there are instances when CPAP may fail to adequately correct sleep-related hypoventilation (6, 7). Specifically, Piper and colleagues performed a head-to-head study comparing CPAP versus bilevel PAP therapy and came to the conclusion that both treatments were equally effective in improving daytime hypercapnia in a subgroup of patients with obesity hypoventilation syndrome without severe nocturnal hypoxemia (7). The seclusion of patients with severe nocturnal hypoxemia identifies the very subgroup of patients who would need a more advanced form of ventilation. In keeping with such an observation, Banerjee and colleagues have noted that patients with obesity-hypoventilation with four characteristics that includes severe hypoxemia during sleep, namely, greater levels of morbid obesity, restrictive deficit on pulmonary function testing, and greater levels of daytime hypercapnia are also more likely to fail CPAP therapy (6). Failure of CPAP may also be attributable to the fact that CPAP therapy may not measure and therefore effectively abrogate other pathophysiological derangements that underlie the various hypoventilation syndromes (figure 2). In the case of obesity-hypoventilation syndrome, whilst CPAP may have been effective in abrogating the obstructive hypoventilation, the inspiratory assistance required to surmount the *chest wall load due to morbid obesity* may have been insufficient (figure 2). Such differences in efficacy of various PAP therapy modalities may apply not

only to patients with obesity-hypoventilation syndrome but also to other causes of hypoventilation syndromes as well (figure 2).

Morbid obesity may be associated with expiratory airflow limitation (8–10). Such expiratory flow limitation can contribute to gas exchange abnormalities that could be benefited by application of positive end-expiratory pressure (PEEP)(10). Such expiratory flow limitation in morbidly obese individuals may be due to mechanical compression of the smaller airways. However, different levels of PEEP may be required to provide ventilatory assistance versus adequately treat upper airway obstruction during inspiration. But, excessive administration of PEEP may cause hyperinflation and consequently increase inspiratory threshold load. To make matters more complex, such pressure requirements may differ with body position and sleep stage. Advanced PAP modalities may potentially be able to measure and target such physiological variables; however the additional benefit gained needs to translate into clinically significant outcomes.

A similar situation can be said to exist in sleep-related hypoventilation secondary to chronic obstructive pulmonary disease (COPD) in whom significant expiratory flow limitation occurs (11). In patients with COPD, however, there is greater end-expiratory lung volume or hyperinflation which, in turn, exerts a certain level of increased traction on the upper airway that could conceivably protect against inspiratory flow limitation and obstruction (12). Such a physiological “traction” effect on the upper airway of the increased lung volume (hyperinflation) in patients with COPD may be a potential mechanism by which a lack of association between mild COPD and obstructive sleep apnea in a community-based population (13). It follows that application of moderate levels of PEEP that does not exceed the level of intrinsic PEEP (PEEPi; “waterfall effect”) would be more relevant in this population than the level of positive airway pressure needed to treat upper airway obstruction. However, current technology in advanced PAP modalities cannot measure PEEPi nor titrate pressure levels in an automated manner. Conceivably, such advanced PAP modalities that are capable of measuring and treating PEEPi would constitute an improvement over current technology, but whether such advanced PAP modalities can effect improvements in relevant patient outcomes remain to be seen. For example, in patients with COPD, nocturnal non-invasive ventilation in addition to long term oxygen therapy (LTOT) appeared to reduce mortality when compared to those treated with LTOT alone, but such an intervention was accompanied by reduced HR-QOL (14). The mechanisms for such reduced HR-QOL (manifesting as confusion and reduced vigor) was variably attributed to survivor effect and complexity of device therapy, but additional factors such as worsening hyperinflation due to excessive application of PEEP may be an additional and unmeasured contributor. Non-invasive ventilation does not improve lung function, gas exchange, or sleep efficiency in patients with COPD (15). A knowledge-gap exists in this area of study, in that despite multiple clinical trials of nocturnal non-invasive ventilation, whether physiologically titrated PEEP and pressure assist aimed at alleviating PEEPi and inspiratory work of breathing can effect improvements in clinical outcomes remains unclear.

Central apneas may complicate the management of sleep-disordered breathing in patients with obesity hypoventilation syndrome, neuromuscular disease, or concomitant heart failure (figure 2)(16–19). Central apneas in the setting of hypoventilation syndromes could occur in

the setting of hypercapnia (due to respiratory muscle weakness or restrictive thoracic disease) or hypocapnia (in the setting of concomitant heart failure). Additionally, patients with severe obstructive sleep apnea may suffer from unstable ventilatory control (high loop gain) and manifest central apneas during PAP therapy (termed complex sleep apnea) and therefore require advanced PAP modality to more effectively treat their sleep-disordered breathing (16, 20, 21). Specifically, advanced modes such as servo-ventilation or bilevel PAP with a back-up rate can help abrogate the sleep-disordered breathing in such instances (22).

Other disease related factors that create the need for advanced PAP modalities and features that are responsive to specific disease-related factors include bulbar involvement by neuromuscular diseases, diaphragm weakness, and weakness of upper extremities and rate of disease progression (figure 2). Bulbar involvement and accompanying aspiration risk due to dysphagia requires the need for invasive ventilation through a trachesostomy and attendant features to advanced PAP modalities such as the ability to switch between modes of ventilation (pressure- or volume-assisted modes); active or passive exhalation ports; sip and puff features for triggering ventilators. Disease progression in neuromuscular conditions such as Amyotrophic Lateral Sclerosis could predicate the need for “volume-assured” advanced modality of ventilation that would guarantee adequate ventilator assistance despite worsening neuromuscular weakness over the 1–2 month period of time between provider visits. In such instances, volume-assured modality would adjust the level of pressure assist to ensure that minute ventilation is above a threshold determined as a function of ideal body weight and assuring a minimum level of adequate ventilation (17, 23).

The Achilles heels of advanced PAP modalities are the presence of air leak (usually from noninvasive mask or mouthpiece interface) and failure to sense the trigger that switches the ventilator from exhalation to inhalation mode. Advanced PAP modalities have tackled such limitation by tracking basal flow (leak) rates, tracking flow contours, and other sophisticated algorithms aimed at assessing the state of the air column connecting the device and the patient. However, knowledge of the nuances of how a device is set is important to enable such advanced features of leak detection and compensation (24). Flow contours allow devices to “anticipate” when the next inspiratory breath is going to occur and allow triggering of a device-delivered breath in a timely manner to enable adequate and comfortable ventilatory assistance (25).

While the technology of advanced PAP modalities continues to evolve significantly with efficacy of the device in sharp focus, there has been renewed and well-justified push, for improving the adherence to PAP therapy that includes advanced PAP modalities. A major limitation of any PAP technology is adherence to such therapy, which, in turn, deleteriously affects the effectiveness of such therapy. Various monitoring connectivity through wireless, modem-based, or SD card-based technology have allowed for remote monitoring and facilitation of PAP adherence (26). Additionally, tracking technology that allows for reminders and remote monitoring of mask fit, leak levels, and even breath-by-breath visualization of breathing have become possible (27, 28). PAP adherence can be improved with the use of a web-based telemedicine system at the initiation of treatment (26). With

such a physiological and psychological rationale in mind we will now consider each of the advanced PAP technologies and assess the technology.

Bilevel PAP technology

Bilevel PAP therapy varies the airway pressure with a greater inspiratory pressure level and lower expiratory pressure level with algorithms that cycle the device from inspiratory-to-expiratory mode (29). The decreased pressure during exhalation decreases the amount of pressure against which the patient exhales and consequently reduce the respiratory discomfort during the expiratory cycle (figure 3). Moreover, during the inspiratory cycle, the greater level of pressure assist would increase tidal volume and therefore the minute ventilation in patients suffering from hypoventilation syndromes (figure 3). The difference between the inspiratory positive airway pressure (IPAP) and expiratory positive airway pressure (EPAP) could be considered as pressure support level. The implementation of bilevel PAP in hypoventilation requires careful titration during polysomnography that would treat persistent hypoventilation that manifests as reduced oxygen saturation (≤ 88% by pulse oximetry) in the absence of evidence of obstruction. Generally, in adults with neuromuscular disorders, the IPAP and EPAP levels are initiated from arbitrary levels of IPAP of 8 cm H_2O and EPAP of 4 cm H_2O and titrated upwards based upon symptomatic improvement in symptoms of hypoventilation such as early morning headache and patient comfort. Others prefer that such titration be performed under the auspices of polysomnography, confirmed by polysomnography, or by utilizing other advanced PAP modalities such as volume-assured pressure assist methods (30). In general, the maximum pressure setting for bilevel PAP is not to exceed 30 cm H_2O in adults (20 cm H_2O in children), and the minimum difference between IPAP and EPAP level should not be less than 4 cm H_2O (31). The goals of such titration includes improving oxygen saturation through increments in tidal volume and minute ventilation while providing comfort; relieving nocturnal dyspnea; improving daytime gas exchange; and providing respiratory muscle rest; and prolonging life (1, 30, 32). The cycling of the device from inspiratory (IPAP) to expiratory phase (EPAP) and vice-versa may be triggered by the spontaneously breathing patient (spontaneous mode) or by a set respiratory rate programmed into the device (timed mode). The device can be set to cycle from inspiratory to expiratory mode based on pressure inflections, flow-contour, set-timing for inspiratory time, or a combination of such measures. In the spontaneous-timed or timed mode, a back-up respiratory rate of 10 breaths per minute could be initiated and titrated upwards by 1–2 increments and generally do not exceed 16 breaths per minute. The back-up respiratory rate could be initiated when a patient with hypoventilation syndrome manifests central apneas or inappropriately low respiratory rate and consequent low minute ventilation (30).

Dyssynchronous cycling between the patient and the device can be uncomfortable and in the presence of COPD could lead to hyperinflation and further dyssynchronny (33, 34). In the past, the triggering sensitivities for cycling of the device between inspiration and expiration could be adjusted by the therapist or physician, but in most modern bi-level PAP devices the technology has been automated with emphasis on remaining resilient to air leak. Similarly, the rate of pressurization (“rise time”) from EPAP to IPAP level can be adjusted to make the

pressure increase briskly or slowly, but besides individual patient comfort the clinical implications of such adjustments is less clear.

Automation

Self-adjusting, automatic, or auto-adjusting PAP devices are considered an advanced PAP modality but although they could be utilized in hypoventilation syndromes there is not much data of the use of such a device in this particular condition. However, it is worth considering the technological approach of the automation involved in managing hypoventilation syndromes that includes respiratory events such as hypoventilation, obstructive events (apneas and hypopneas), central apneas and central hypopneas.

The purposes of such automation may be to serve as an alternative to in-laboratory manual titration to determine adequate pressure setting (31); to achieve lower mean pressures levels that may conceivably promote adherence (35); or for affecting therapy on a long-term basis while being responsive to various aspects of sleep-disordered breathing (hypoventilation, obstruction, and central) events that occur and that includes changes in weight, sleep state, body position, or even alcohol ingestion.

The principles of automation has evolved, and continues to evolve, over multiple generations and comprises enhancements to sensing events of sleep-disordered breathing (*sensors*), automated computing and analysis of the sensed signals (*analysis)*, and hierarchal set of algorithms that will determine the action taken by the device in response to the conditions exposed (*effectors)*. The sensors include measurement of changes in pressure and flow that can detect snoring (as pressure oscillations) to signify obstructive events and flattening of inspiratory flow curves (indicating inspiratory flow limitation of the upper airway). Devices can even send pulses of air or oscillations to detect the state of the upper airway (open or closed) based upon the presence or absence of reflected (echo) pressure waves in order to differentiate central from obstructive apneas. They can identify Cheyne-Stokes respiration (by detecting breath-by-breath variation in peak flow), identify hypoventilation (by measuring tidal volume or minute ventilation using calibrated flow sensors), and compensate for air-leaks (using sophisticated flow-based algorithms) (36).

The *effector* arm of the auto-PAP device has undergone changes as well. Newer generation devices can not only increase the CPAP level, but can also increase the inspiratory positive airway pressure (IPAP) alone in order to ameliorate obstructive events (Auto Bi-level PAP), correct hypoventilation (averaged volume assured pressure support [AVAPS], or iVAPS) or combat central apneas in patients with complex sleep apnea or CPAP-emergent central apneas (Servo-Ventilation)(17, 37–39). The servo-ventilators may also introduce a back-up rate to prevent central apneas, and even though they are not called auto-PAP devices, they function using similar principles and can be judged as the latest generation of auto-PAP devices (38, 39).

An important aspect of such technology is that different manufacturers of such devices may incorporate different algorithms that lead to significant differences in performance. Bench studies have consistently shown varied performance when comparing devices made by different manufacturers (40–44). We have shown, for instance, that the range of pressure

response of four automated-PAP devices was wide as large as 10 cm H_2O (40). Moreover, bench studies have shown that some devices are more resilient to the effects of air-leak than others (40). Despite such bench studies, the clinical implication of such differential performance of various manufacturers is less clear. It should be noted that most of the randomized controlled trials that involved the utilization of automatic CPAP devices excluded patients with hypoventilation syndromes such as obesity hypoventilation syndrome, co-existent heart failure, neuromuscular weakness and chronic obstructive pulmonary disease (COPD)(45, 46).

Volume-assured pressure assistance

Advanced PAP modalities that targets minute ventilation and tidal volume are ideal for patients with hypoventilation syndromes (17, 37). These devices are unlike auto-bi-level PAP device, which targets obstructive events like the auto-PAP, and the servo-ventilator that targets central apneas and Cheyne-Stokes respiration. Volume assured pressure support technology has been used in critically ill patients receiving mechanical ventilation before it made inroads into managing patients with sleep-disordered breathing and hypoventilation syndromes (47). In patients with acute respiratory failure, volume-assured pressure support ventilation was able to assure a minimum preset target tidal volume and reduced patient workload while improving synchrony between the patient and the ventilator (47). While such technology was geared to assess tidal volume breath-by-breath, the devices that address hypoventilation in patients with hypoventilation syndromes assesses the tidal volume (or minute ventilation) over a variable (1–5 minute) time window. Specifically, the principles of operation of volume-assured pressure support or assist is shown in figure 4. Essentially, when the patient's tidal volume (or minute ventilation) decreases below a certain threshold that passes below a threshold which, in turn, is detected by the device that correspondingly responds by increasing the inspiratory positive airway pressure (IPAP) or pressure support and restores the tidal volume (or minute ventilation; measured over a certain time window) to approximate that of the selected target volume. Previous versions of these devices required an EPAP level setting, but more recent versions have combined the autoPAP technology for optimal EPAP setting determination. Therefore, such devices have an EPAPminimum and EPAPmaximum range that needs to be prescribed. The pressure assistance delivered during inspiratory phase – that is above the operating EPAP level – is aimed at assuring a certain tidal volume that is calculated as a function of ideal body weight (usually 8 ml/kilogram ideal body weight or at 110% of patient's tidal volume)(17). The operating IPAP (or pressure assist) level is then allowed to fluctuate between a minimum and maximum pressure support level in order to assure the target tidal volume.

The selection of target tidal volume is left to the provider with variable targets of 8–10 ml/kg ideal body weight or as a function of patient's own ambient tidal volume. Notably, the choice of tidal volume may be influenced by the sleep-wakefulness state of the patient (17, 48). In patients with chronic respiratory insufficiency (obesity-hypoventilation and neuromuscular disease) receiving averaged volume-assured pressure support, patients preferred (measured as dyspnea score) 110% of ambient tidal volume during wakefulness, but the patients slept better (when measured as sleep efficiency) when receiving tidal volume based on ideal body weight (48). Such data suggests that the choice of device setting

is to a certain extent arbitrary and conceivably, devices that can measure sleep-wakefulness state and adjust their algorithms may be superior to current conventional devices that operate in a similar fashion regardless of sleep-wakefulness state of the patient. Additional settings may include spontaneous or timed respiratory rate settings, and some newer technology has automated the respiratory rate selection based upon patient's minute ventilation and proportion of breaths that are triggered versus spontaneous over a period of time.

Laboratory-based short-term efficacy studies using volume-assured pressure support devices have failed to demonstrate advantages over conventional bi-level PAP settings with regards to improvements in sleep quality (17, 37, 49). Some of the lack of demonstrable difference between such an advanced PAP modality and bilevel PAP may be due to the carefully adjusted "optimized" setting in research study conditions. Studies that assess the performance of such devices in less expert hands (in the "real world") may identify differences that were not discerned in such controlled experiments. Additionally, the advantage of such advanced PAP modalities in adjusting for changes in clinical situations needs to be further explored. Such clinical situations may include rapid weight loss in morbidly obese individuals following bariatric surgery or patients with Amyotrophic Lateral Sclerosis who are experiencing rapidly progressive respiratory muscle weakness. Nevertheless, even current data seems to suggest that such assurance of tidal volume has advantages with regards to lower transcutaneous PCO_2 readings (37) and greater minute ventilation (17), and that they afford resilience against changes attributable to changes in body position and sleep state. More research of these devices, however, needs to be performed to better understand the role of these devices.

Servo ventilation

Servo-ventilation devices can identify and treat central apneas. Servo ventilation can treat Cheyne-Stokes respiration, central sleep apnea, and emergent central apneas in patients with hypoventilation syndromes. The principle of operation of such technology is a servo-controlled pressure support adjustment (*effector*) that is inversely related to the changes in peak flow levels over a moving time window (*sensor*)(figure 5). The device calculates an average peak flow level over a period of time, subsequently, if the instantaneous peak flows are lower than such an average peak flow rate that was derived from the previous moving time window, then the device recognizes this as the decrescendo pattern that precedes a central apnea, and responds by increasing the pressure support level. Conversely, if and when the peak flow rate is significantly higher than the previously calculated average peak flow levels, the device assumes that the patient is manifesting a hyperpneic phase, and correspondingly reduces the level of pressure assist. Therefore, the servo system dampens the inherent oscillatory behavior of the patient's breathing pattern and smoothens respiration (figure 5).

The instantaneous IPAP level is determined by the device algorithm within a set range of minimum (PSmin) and maximum (PSmax) pressure support levels. Previously, the terminology for servo-ventilation was based upon IPAPmin and IPAPmax (figure 5). However, considering that the EPAP level can change in later generation of the devices, the corresponding PS levels are better descriptors of the setting because PS levels are a function

of the EPAP levels. Essentially, the instantaneous IPAP level minus the instantaneous EPAP is the instantaneous pressure support level. Generally, the maximum pressure levels are not to exceed 30 cm H_2O in these advanced PAP devices. The back-up rate can either be set to adjust automatically or be set at a manually determined rate which is usually determined during a sleep study. Servo-ventilation can successfully treat central apneas, central hypopneas, and Cheyne-Stokes respiration (38, 39, 50, 51). Investigators have variably used manual back-up rates set at 15 breaths per minute (39, 51) or employed automatic backup rate (38, 50). They have used EPAP levels of 5 cm H_2O in patients with Cheyne-Stokes respiration and central sleep apnea (39, 51) or titrated the EPAP level to treat obstructive apneas in patients with emergent central apneas (38, 50). Although small studies have demonstrated improvement in physiological measures such as sleepiness and urinary levels of catecholamines in patients with Cheyne-Stokes respiration and central sleep apnea (51), large studies on tangible patient outcomes such as hospitalization or all-cause mortality are awaited.

Summary

The physiological rationale for advanced PAP modalities is sound considering the complexity of sleep-disordered breathing in patients with hypoventilation syndromes. Various advanced PAP devices are available to assist breathing during sleep and wakefulness in patients with hypoventilation syndromes. Although such devices are increasingly used in clinical practice, the supporting clinical evidence warranting the use of such devices needs further study. Currently, there is an evolving body of literature that supports the beneficial effect of advanced PAP modalities on health-related quality of life, physiological end-points, and even mortality. However, more comparative-effectiveness research of such advanced PAP modality devices against conventional CPAP therapy in “real-world” situations and without the requirement of titration polysomnography needs to be conducted. Moreover, there is much opportunity for further refining these devices that include the ability of the device to reliably monitor gas-exchange, sleep-wakefulness state, and reducing variability in device efficacy due to provider-selected device-settings.

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Key points

1. The physiological rationale for advanced PAP modalities is sound considering the complexity of sleep-disordered breathing in patients with hypoventilation syndromes
2. The therapeutic physiological rationale for the various advanced PAP modalities and the details about the principles of operation and technology implementation need to be well understood by the prescribing healthcare provider.
3. The sleep-disordered breathing in such individuals are quite complex and require sophisticated devices with algorithms that are designed to accurately detect and effectively treat respiratory events that includes hypoventilation, upper airway obstruction, lower airway obstruction, central apneas and central hypopneas and reduce the work of breathing while maintaining breathing comfort.
4. There is much opportunity for further refining these devices that include the ability of the device to reliably monitor gas-exchange, sleep-wakefulness state, and for reducing variability in device efficacy due to provider-selected device-settings.

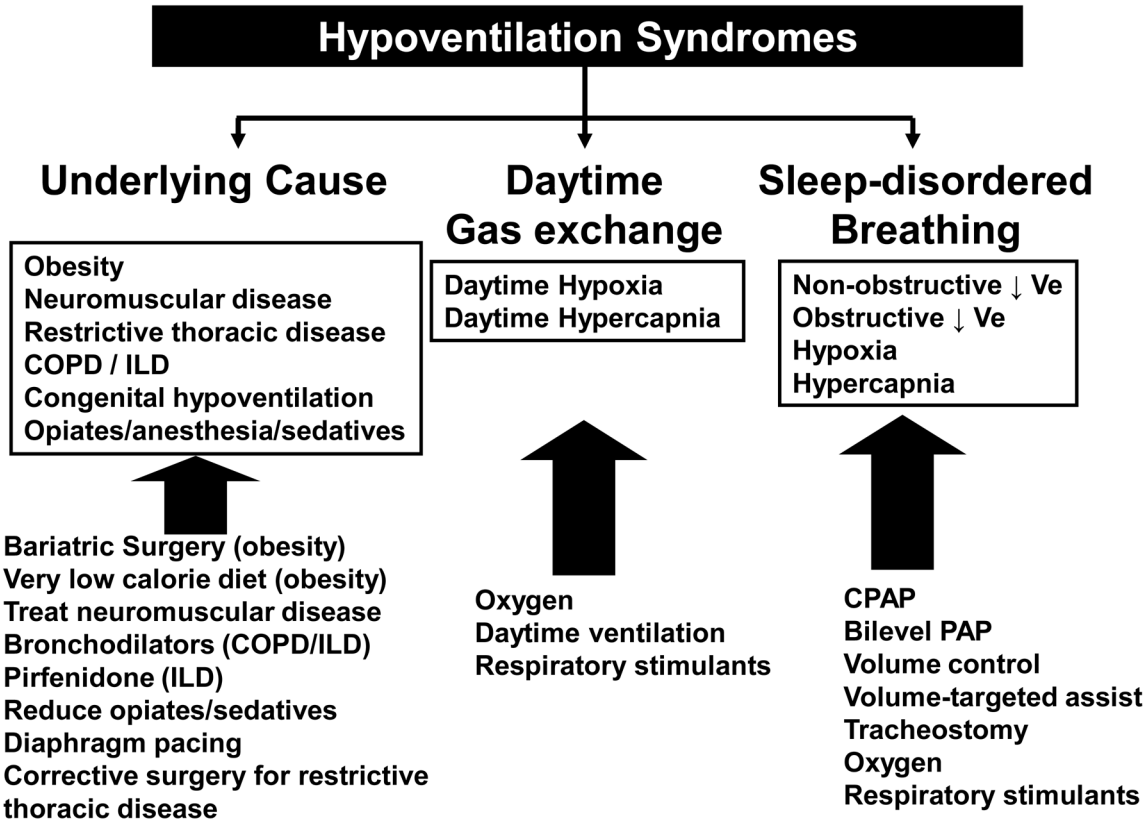

Figure 1.

The underlying pathophysiological characteristics of hypoventilation syndromes and various therapeutic interventions that could be used to provide targeted treatment. Positive airway pressure therapy is one of many treatment modalities that are available.

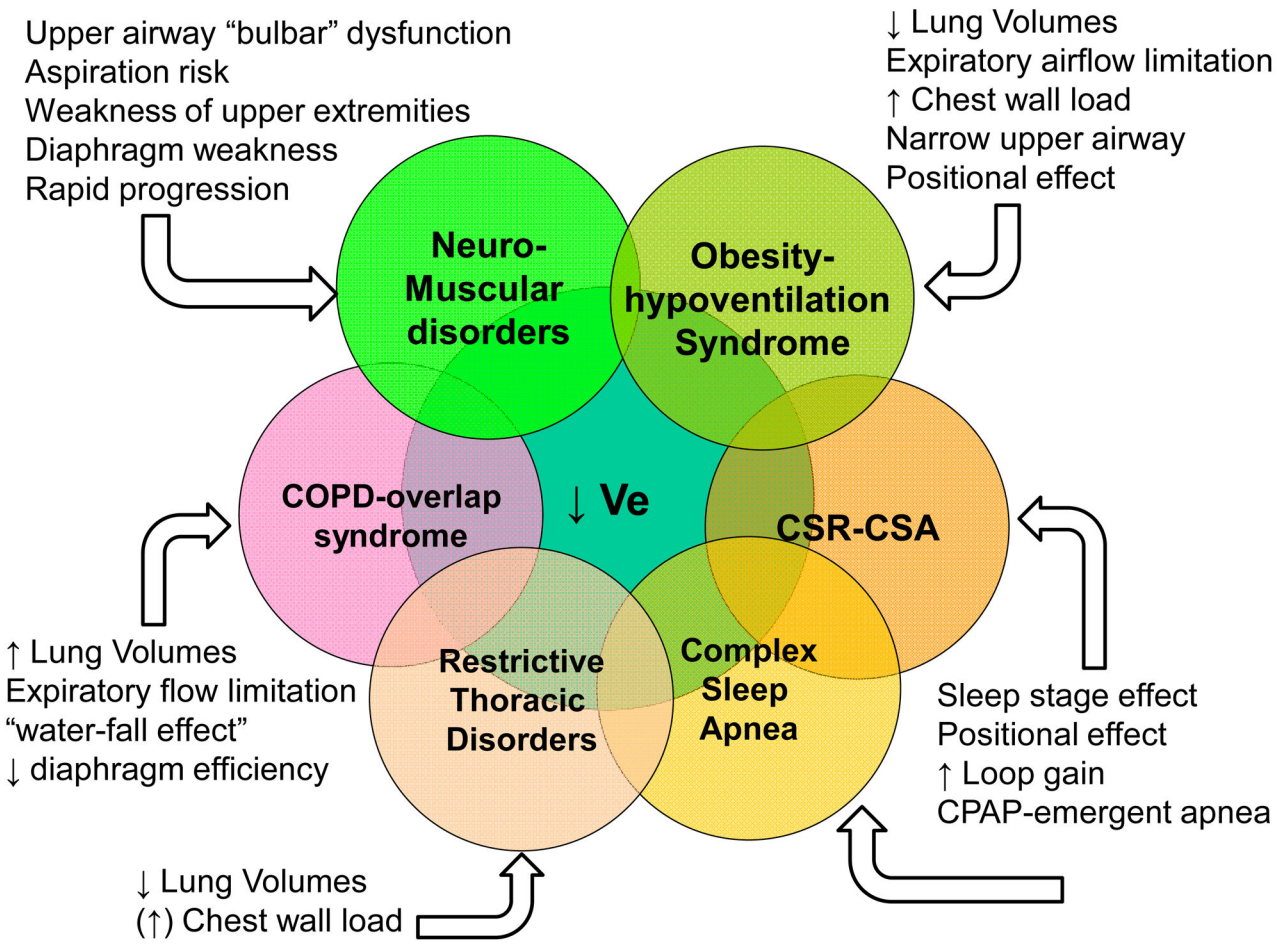

Figure 2.

A schematic representation of the overlapping pathophysiological traits that may manifest in patients with hypoventilation syndromes of various causes.

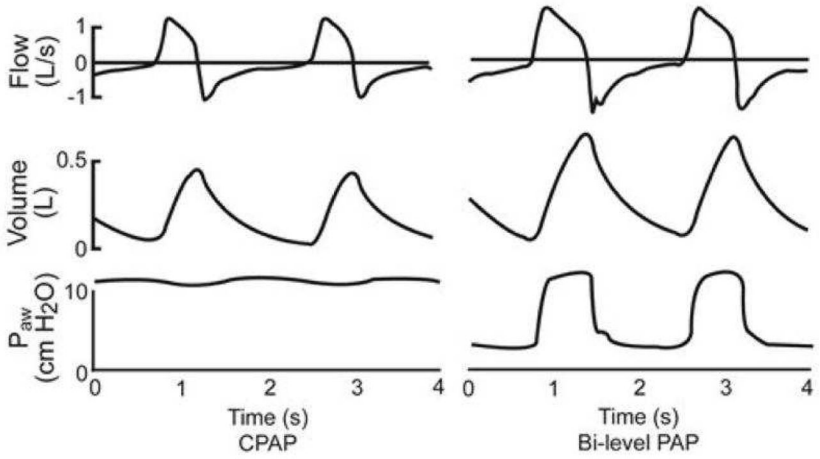

Figure 3.

Representative tracings of flow, tidal volume, and airway pressure (Paw) during administration of continuous positive airway pressure (CPAP) and bi-level PAP. In the left panel note that there are small undulations in the CPAP level that is generated by the patient's inspiratory and expiratory effort, and the consequent displacement of inspiratory and expiratory tidal volume. Such inflections are usually negligible in a responsive CPAP device. In this instance the CPAP is set at 14 cm H2O. In the right panel there are large decrements in the pressure during exhalation (expiratory positive airway pressure [EPAP], which is set at 4 cm H2O), whereas during inspiration the inspiratory positive airway pressure (IPAP) is set at 14 cm H2O, which would conceivably provide the same level of airway splinting as a CPAP of 14 cm H2O. Note the larger tidal volumes and flow patterns consequent to the pressure assist provided by the bi-level PAP device that would benefit a patient suffering from hypoventilation. In this instance, a pressure support or assist level of 10 cm H2O (IPAP minus EPAP) is being administered, with consequently greater tidal volume and inspiratory flow. Reproduced with permission from reference (21).

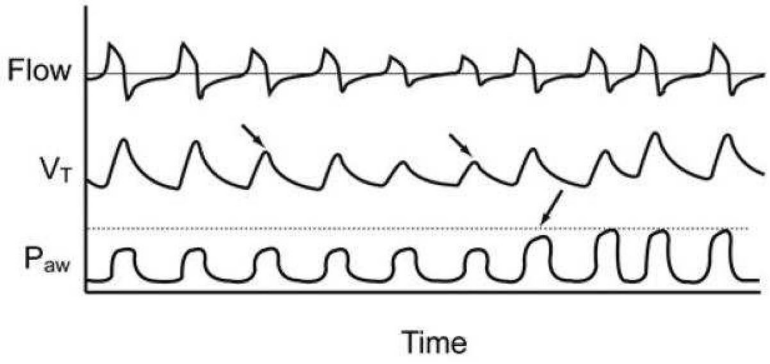

Figure 4.

Principles of operation of volume-assured pressure support or assist. Flow, tidal volume (VT), and airway pressure (Paw) tracings are shown. Note that in this instance the VT and flow decrease progressively between the 2 shorter arrows. The device detects such a VT drop and responds by increasing the inspiratory positive airway pressure (IPAP) (longer arrow) and restores the VT to near the target. The new, yet higher, IPAP is better shown by the difference between the dashed line and the pre-existing IPAP prior to the increment. Conversely, the IPAP could decrease if the measured VT were to exceed the target VT prescribed by the provider. Reproduced with permission from reference (21).

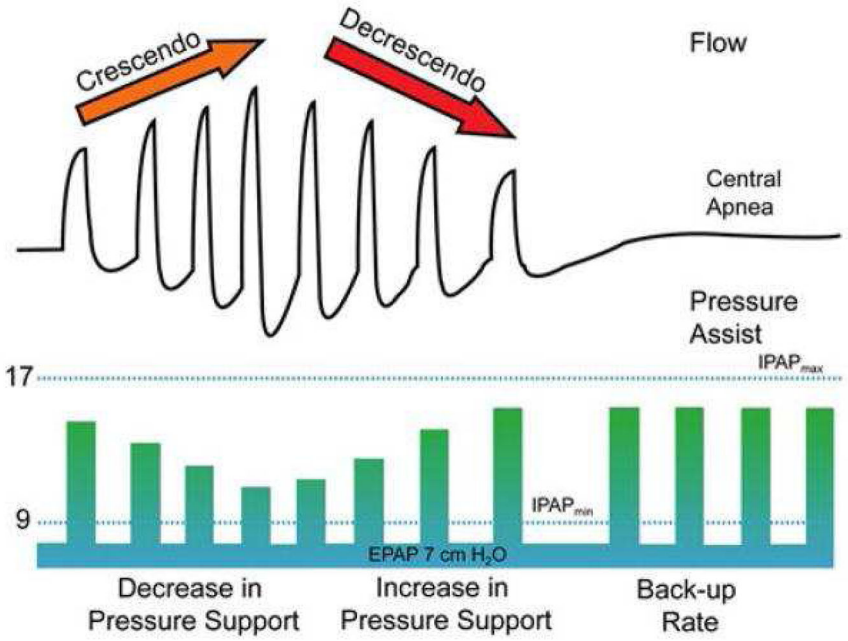

Figure 5.

Principles of operation of servo ventilation. The air flow tracing depicts a classical crescendo (orange arrow) and decrescendo (red arrow) pattern of Cheyne-Stokes respiration, followed by an ensuing central apnea. The servo-controlled automatic adjustment of the inspiratory positive airway pressure [I PAP] level is inversely related to the changes in peak flow over a moving time window. Specifically, during the crescendo pattern of peak flow rates (orange arrow) the pressure assist (or I PAP) level decreases in order to dampen the rise in inspiratory peak flow rate (or tidal volume). Conversely, during the decrescendo pattern of peak flow rates (red arrow) the pressure assist (or I PAP) level increases in order to dampen the fall in inspiratory peak flow rate (or tidal volume). Therefore, the servo system dampens the inherent oscillatory behavior of the patient's breathing pattern and smoothens respiration. During a central apnea, however, the device backup rate kicks in and ventilates the patient (right side of the figure). The maximum and minimum IPAP (IPAPmax and IPAPmjn) are set at 17 cm H2O and 9 cm H2O (dashed blue lines). The expiratory positive airway pressure (EPAP) is set at 7 cm H2O. During any given breath the pressure assist or pressure support is equal to the IPAP minus the EPAP. Reproduced with permission from reference (21).