Case Report

Respiratory Distress Associated With Inadequate Mechanical Ventilator Flow Response in a Neonate With Congenital Diaphragmatic Hernia

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The incidence of congenital diaphragmatic hernia has been reported as 0.17–0.66 per 1,000 births. Despite advances in neonatal intensive care, congenital diaphragmatic hernia is associated with high mortality and morbidity. We report a neonate who was born with a left congenital diaphragmatic hernia and underwent surgical repair. The lack of ventilator flow response and flow cycling was identified via interpretation of the ventilator graphic and clinical assessment. Presumably, the ventilator failed to respond to the patient's peak inspiratory flow demand, despite the clinician's setting the highest peak flow available. A time-cycled pressure-limited mode with adjustable peak flow rate was the only option that met the infant's flow requirement, and alleviated the respiratory distress. This clinical finding follows bench research that raises the concern that so called "cradle-to-grave" ventilators may not optimally support all neonates. *Key words: neonate; mechanical ventilation; ventilator flow.* [Respir Care 2010;55(3):342–345. © 2010 Daedalus Enterprises]

Introduction

The incidence of congenital diaphragmatic hernia has been reported as 0.17–0.66 per 1,000 births.[1] Despite advances in neonatal intensive care, congenital diaphragmatic hernia is associated with high mortality and morbidity, from pulmonary hypoplasia, pulmonary hypertension, chromosomal defects, and associated malformations. The main underlying pathophysiology consists of a combination of lung hypoplasia and persistent pulmonary hypertension. Despite improvements in neonatal mechanical ventilation, clinical assessment and liberation from mechanical ventilation remain difficult. Preservation and synchronization of spontaneous breathing is associated with the highest tidal volume (V_T) for a given pressure in patients with congenital diaphragmatic hernia,[2] so, in 1996, Children's Hospital Boston adopted a ventilation strategy that includes permissive hypercapnia and the preservation of spontaneous breathing.

Historically, we used the VIP Bird (Carefusion [formerly Viasys Healthcare], Yorba Linda, California) in the assist-control mode, with adjustable flow-triggering and flow-cycling, which delivered a breath similar to pressure-support ventilation (eg, patient-triggered, pressure-limited, flow-cycled), yet maintained a minimum respiratory rate. Our primary ventilator today is the Avea (Carefusion, Yorba Linda, California), which has some of the same characteristics as the VIP Bird. Initially we used the standard pressure-support mode, but we were concerned about periodic apnea, in which the ventilator switches to a back-up mode and supplies only continuous mandatory ventilation. The related change in minute volume could negatively affect the cardiopulmonary interaction, such as in a patient with pulmonary hypertension. Therefore we adopted the same approach used previously with the VIP Bird and employed the pressure assist-control mode with flow-cycling, which allows patient control over inspiratory time, but with a minimum back-up respiratory rate. Thus, a minimum respiratory rate in the setting of periodic breathing is maintained without creating an apnea alarm

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or forcing the ventilator to go into apnea mode ventilation. The only difference is that we chose the variable flow option of pressure assist-control ventilation, as it may improve patient comfort.[3-6]

Case Report

We saw a 39-week gestational age, 3.8-kg white male, prenatally diagnosed with left congenital diaphragmatic hernia, who was transferred to our medical-surgical intensive care unit for further management. A 3.5-mm oral endotracheal tube was in place, and ventilator settings were: intermittent mandatory ventilation mode, peak inspiratory pressure 20 cm H_2O, positive end-expiratory pressure 4 cm H_2O, respiratory rate 30 breaths/min, and fraction of inspired oxygen (F_{IO_2}) 0.4. Upon admission he was hemodynamically stable and without the need for vasoactive medications.

He was transitioned to an Avea ventilator, in pressure assist-control mode with flow-cycling at the same peak inspiratory pressure, positive end-expiratory pressure, respiratory rate, and F_{IO_2}. Effective V_T was 3–4 mL/kg, arterial oxygen saturation (measured via pulse oximetry) was ≥ 94%, and end-tidal partial pressure of carbon dioxide was 42–48 mm Hg. Via echocardiography we confirmed a mildly hypoplastic aortic arch with right-ventricular hypertension, consistent with pulmonary hypoplasia or hypertension, and on day 4 of life a successful thoracoscopic primary repair of the diaphragm was completed. In the immediate postoperative period a slightly higher peak inspiratory pressure (25 cm H_2O) was required to achieve the target V_T of 3–5 mL/kg, but was subsequently weaned to 18 cm H_2O because of improved lung compliance and respiratory effort. The respiratory rate remained set at 30 breaths/min. Over the next several days the patient recovered well, and sedation was weaned to promote ventilator liberation.

During a routine ventilator assessment on postoperative day 4, a respiratory therapist noted respiratory distress, described as moderate intercostal and substernal retractions, with paradoxical breathing. The F_{IO_2} requirement was stable at 0.40, and ventilator support had been weaned 4 hours previously to a peak inspiratory pressure of 14 cm H_2O and a respiratory rate of 15 breaths/min. Sedation and analgesia had been tapered, which led to concern that pain and/or withdrawal may have been a source of distress. Upon further investigation it was noted that the inspiratory phase was no longer flow-terminating and that the inspiratory tracings appeared abnormal (Fig. 1). The flow appeared to scalp or concave approximately a third of the way through the inspiratory phase, and the pressure did not reach the target (set) until the end of the breath. There were no active ventilator alarms. The endotracheal tube was assessed for correct position and patency. Adjustments in the inspiratory flow delivery failed to reduce the patient's distress, even at the fastest flow delivery setting (rise profile 1).

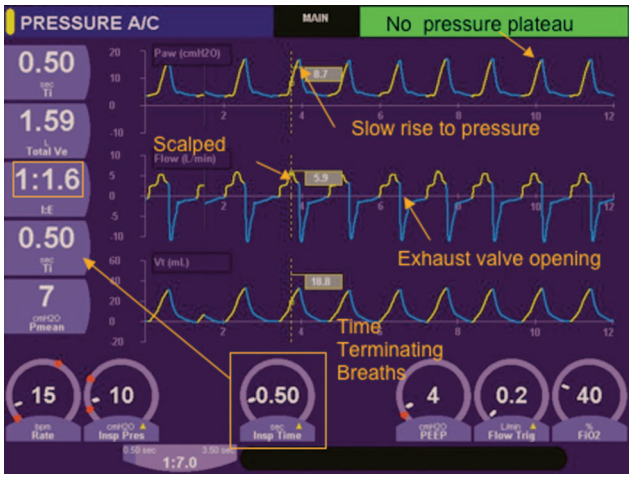

Fig. 1. Ventilator display during assist-control mode. The spontaneous respiratory rate is 45 breaths/min. There is no pressure plateau, an abnormal flow pattern, a maximum flow of 5.9 L/min, and time-cycling of the breaths despite a flow-cycle setting of 20%. A scalped inspiratory flow pattern is present, and the peak inspiratory pressure reaches the setting late in the breath. This suggests flow starvation.

These findings led us to the hypothesis that there was insufficient flow in the current ventilation mode. To test this hypothesis, we switched to the pressure-limited, time-cycled mode (which many ventilators no longer offer) and set the peak flow to 12 L/min, which was 2 times higher than the previous mode. This strategy proved successful, as the patient's distress decreased significantly and he appeared more comfortable without the need for additional sedation. The inspiratory flow graphics were consistent with flow-cycling, and the inspiratory time was more physiologic (Fig. 2). The patient was successfully extubated 6 hours later to high-flow nasal cannula and did not require further mechanical ventilation.

Discussion

In 1972 Kirby et al invented a new mode of ventilation for neonates, using what they called "continuous flow."[7] This was a form of pressure control that generated inspiratory pressure by directing a constant flow of gas from a flow meter through a pressure relief valve, allowing unrestricted spontaneous breathing throughout the ventilatory cycle (remarkably similar to airway pressure release ventilation introduced in 1987).[8] During the 1970s and 1980s, the mode became the standard of care in neonatal intensive care units around the world. This was because volume control for neonates, requiring precise control of flow and volume, was beyond the capability of most ventilators of the era (with the notable exception of the Bourns LS104-150). The term "continuous flow, time cycled, pressure limited (TCPL)" became attached to this mode of neonatal ventilation and has per-

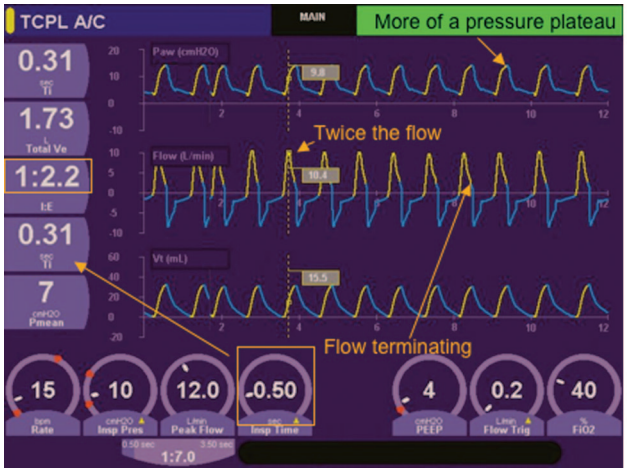

Fig. 2. Ventilator display during a pressure-limited, time-cycled ventilation mode, with the flow set 2 times higher (12 L/min) than the previous mode. There is a faster rise to pressure. The flow pattern appears normal, and the breaths are flow-cycled.

sisted to this day. As ventilators evolved, electronic feedback control of the pressure waveform gradually replaced the old mechanical pressure relief valves on most ventilators. However, with the switch to electronic control valves, the mode underwent a subtle transformation that has not been recognized in the literature before this report.

Electronic valves allow the delivery of a relatively rectangular shaped pressure waveform. For a perfect rectangular pressure waveform (ie, instantaneous rise from end expiratory pressure to peak inspiratory pressure), peak inspiratory flow is equal to the inspiratory pressure change divided by the respiratory system resistance.[9] Some ventilators allow adjustment of the pressure rise time such that making the pressure rise more gradual will decrease the peak inspiratory flow. The implication here is that if a ventilator has a relatively slow flow control valve, then the pressure rise will be relatively slower and thus peak inspiratory flow will be less than a ventilator with a faster flow valve. This form of pressure targeting scheme is called setpoint control, meaning that a pressure target is set as a goal for each breath by the operator.[10]

In contrast, TCPL is a form of dual control, meaning that the primary control variable switches between pressure and volume within a breath.[10] In this case, inspiration starts out with volume control (ie, using an operator preset constant inspiratory flow), and when a preset inspiratory threshold is met, inspiration continues in pressure control at that constant pressure until inspiration is time cycled. The main difference between these 2 targeting schemes is that while both are forms of pressure control (ie, tidal volume varies with lung mechanics), set point pressure control does not allow the operator to directly set the peak inspiratory flow, whereas dual control allows setting of the *maximum* peak inspiratory flow *below* the theoretical maximum peak inspiratory flow determined by inspiratory pressure change and respirator system resistance. The *actual* inspiratory flow with this form of dual control can be much less than the set flow.

For example, in this case study, during TCPL on the Avea ventilator, the peak flow control could have been set as high as 30 L/min, but the actual inspiratory flow would be much less. To illustrate, suppose the inspiratory resistance is 100 cm H_2O/L/s and the inspiratory pressure is 10 cm H_2O. The peak inspiratory flow would be 10/100 = 0.1 L/s or 6 L/min achievable using a rectangular pressure waveform. But if the operator set the peak flow to 4 L/min, then that would be the peak inspiratory flow (and the pressure waveform would not be rectangular, but show a more gradual rise to peak inspiratory pressure). If the peak flow was set to 12 L/min, the peak inspiratory flow would be only 6 L/min, but the pressure waveform would be rectangular. In the lower limit, the peak flow could be set equal to the desired tidal volume divided by the set inspiratory time, and then the inspiratory flow waveform would be rectangular, the inspiratory pressure waveform would be triangular, and indeed, the inspiration would have switched from pressure control to volume control.[11] In the upper limit, peak flow could be set to its maximum value, the pressure waveform would be approximately rectangular, and the inspiratory flow waveform would be a decaying exponential.[9]

It is common for infants following congenital diaphragmatic hernia repair to exhibit episodes of increased respiratory distress in the immediate postoperative period because of lung hypoplasia, pulmonary hypertension, diaphragm dysfunction, and pain. Sakai et al reported that the surgical repair alone reduced lung compliance by 10–77% in 7 of 9 infants.[12] The defect in our patient was considered minimal, it was thoracoscopically corrected, an artificial diaphragm patch was not needed, and lung hypoplasia and pulmonary hypertension were relatively mild. We anticipated a smooth postoperative course and rapid ventilator liberation. The respiratory distress emerged following a decrease in sedation in preparation for extubation. The atypical inspiratory flow pattern, marginally attainable pressure target, and time-cycling suggested insufficient flow delivery and led the respiratory therapist to suspect a ventilator malfunction.

Actual inspiratory flow at any point in time with any form of ventilation can be expressed as a function of the pressure waveform[13] that results from the set flow pressurizing the patient circuit and the patient's respiratory system mechanics. The higher the set flow, the more rectangular the pressure waveform and the closer the peak inspiratory flow gets to the theoretical maximum determined by inspiratory pressure and resistance. This feature of dual control on the Avea ventilator was the key to success in this patient. On this ventilator, the flow control mechanism was not fast enough to generate a rectangular pressure waveform when set in pressure assist-control, and

hence the delivered peak inspiratory flow and tidal volume were less than they could be in ideal pressure control with a rectangular pressure waveform (ie, tidal volume is inspiratory pressure change divided by respiratory system compliance).[9,13] Neonatal practitioners have historically set the continuous flow in the range of 8–12 L/min arbitrarily for neonates with RDS because this gives a nearly rectangular pressure waveform. Increasing the peak inspiratory flow with TCPL mode with the same inspiratory time necessarily increased the tidal volume as well. The higher flow and tidal volume were probably the major factors in reducing the patient's stress.

Arguing that neonates are not small adults, we remain concerned that any ventilator, regardless of manufacturer, can meet the extreme needs of the entire patient population. Marchese et al[14] reported that 5 intensive-care ventilators with neonatal ventilation modes are generally equivalent to the performance of a Babylog neonatal ventilator (Dräger, Telford, Pennsylvania) set for its TCPL. They also reported that the time between trigger and return of pressure to baseline, and time from start of breath to 90% of peak pressure, were delayed with the Avea. The present case provides clinical confirmation of those findings. After the presently reported case we observed similar findings in 7 additional patients. The majority of these cases were neonates in our cardiac intensive care unit, where many of the patients are intubated for corrective surgery and have little to no lung disease. In 4 cases there was apparent respiratory distress, whereas 3 others were observed with no obvious distress. In the patients with distress, one was successfully extubated and the other two were successfully switched to TCPL.

We informed the ventilator manufacturer (Carefusion) of the concern. They developed a solution that requires an upgrade to a new flow-delivery system, which we bench tested, and it appears to respond more appropriately. The original flow-delivery system was designed to reduce pressure overshoot, which is a concern. However, a slight pressure overshoot may be preferred to flow starvation. The pressure overshoot is attenuated by the highly resistive endotracheal tube and is unlikely to be transmitted to the alveolus unless inspiratory flow reaches zero.

Chatmongkolchart et al[15] found that the inspiratory rise time of 5 ventilators differed significantly at similar settings, which suggests that the clinician also needs to be aware of the nuances of a ventilator's operation. Regardless of whether the cause is ventilator design or improper flow setting, clinicians must be vigilant in understanding the limitations of their ventilator fleet and the modes those ventilators provide.

This case makes the argument for good clinical assessment, using the ventilator graphics to augment that assessment, and the importance of understanding a ventilator brand's limitations. Without correct interpretation of the ventilator graphics, the ventilator settings might have been escalated, which might have reduced the flow starvation but delivered a much larger V_T than required. We were able to use pressure-limited, time-cycled ventilation with adjustable peak flow, which made available additional flow that reduced respiratory distress. It was both interesting and surprising to realize that the peak flow needed to be doubled to meet this patient's demand, particularly with the diagnosis of congenital diaphragmatic hernia. We attribute this to the patient having fairly normal lung mechanics, a strong respiratory drive, and a relatively uneventful postoperative course. These attributes combined created a higher flow requirement at a lower pressure than is typically seen in patients who acquire lung disease severe enough to require mechanical ventilation.

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