Back to Basics

Rob Graham, R.R.T./N.R.C.P.

I dedicate this column to the late Dr. Andrew (Andy) Shennan, the founder of the perinatal program at Women's College Hospital (now at Sunnybrook Health Sciences Centre). To my teacher, my mentor and the man I owe my career as it is to, thank you. You have earned your place where there are no hospitals and no NICUs, where all the babies do is laugh and giggle and sleep.

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The efficacy of mechanical ventilation is determined by the laws of physics related to gas flow. Resistance (R) and compliance (C) are most often referenced. However, the determinants and dynamics thereof are not necessarily understood or considered in and of themselves.

Overview

Whether spontaneous or mechanical, breathing is subject to physics and gas flow laws. The nature of each is very different and directly affects how these laws influence ventilation.

Negative pressure produced by the diaphragm excursion produces the pressure differential required for gas to flow into the lungs during normal spontaneous breathing. Aside from producing gas flow, this negative pressure also has other effects, particularly in premature infants.

When inhaling, negative pressure increases airway diameter, which directly and exponentially affects airway R; the larger diameter increases gas flow dramatically since R decreases by the fourth power as the diameter increases. The result is that the time required to fill the lungs decreases.

Conversely, positive pressure within the lungs provides the differential necessary for gas to leave. This pressure is also exerted on the airways, decreasing airway diameter and increasing airway resistance. In the adult, this is not a significant concern as airways are mature and well supported, but in the premature infant, this is not the case, and the airways are prone to collapse during expiration if the pressures are insufficient to maintain patency. This may happen whether breathing is spontaneous or the baby is mechanically ventilated.

Mechanical ventilation requires positive pressure to blow gas into the lungs during the inspiratory phase, increasing airway diameter just as in spontaneous breathing, possibly more so. The expiratory phase of mechanical ventilation (in conventional modes) is essentially the same as in spontaneous breathing, and the effect on airways is the same.

Because airway diameter is greater during inspiration than expiration, it takes less time for a given volume of gas to enter the lungs than to leave. Normally, people do not breathe with a one-to-one inspiratory to the expiratory ratio (I:E ratio) but rather at a 1:3 and 1:5 I:E ratio (1), allowing sufficient time for the lungs to empty.

"A newborn's respiratory rate is faster than that of an adult, typically 40 – 60 breaths per minute, though a recent study found that about 5% of healthy newborns breathe at a rate of 65 (2). This provides less time for gas to enter and exit the lung; the infant's normal I:E ratio of 1:1.5 – 1:2 (3) mitigates this to an extent. "

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Compounding these factors is a physiological difference in newborns and particularly premature infants:

> ***"While typical term newborn tidal volumes are the same per kilogram as adults, the newborn's anatomical dead space is higher (approximately 3mls/kg c.f. 2.2 mL/kg in the adult) (4) this is not the case with the premature infant, whose Vt is smaller (in one study 50th percentile mean Vt was 4.2-5.8 mL/kg although there was wide variation, particularly during the first hour of life) (5)."***

Dead Space

While typical term newborn tidal volumes are the same per kilogram as adults, the newborn's anatomical dead space is higher (approximately 3mls/kg c.f. 2.2 mL/kg in the adult) (4) this is not the case with the premature infant, whose Vt is smaller (in one study 50th percentile mean Vt was 4.2-5.8 mL/kg although there was wide variation, particularly during the first hour of life) (5).

Physiological dead space is also increased partly due to shunting. (4)

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Chest Wall and Respiratory Mechanics

Chest wall compliance increases in the newborn because the rib cage is more cartilaginous than the adult, decreasing chest recoil during expiration. This increases the time required for exhalation since recoil is one factor that facilitates exhalation.

Aside from being less mature, the newborn's ribs are more horizontal. This places the respiratory muscles at a mechanical disadvantage compared to the adult. A smaller number of type 1 muscle fibers makes the diaphragm more prone to fatigue. (4)

Respiratory Control

Even at term, the respiratory centre is not entirely mature, and there is a wide respiratory rate and pattern variation. There is a decreased response to hypercarbia, a *decrease* in the respiratory rate with hypoxia, and a maximal increase in response to hypercarbia in the face of hyperoxia. These responses are opposite to those of an adult (4,6).

Work of Breathing

The aforementioned factors all increase the work of breathing. There is a point at which ventilatory efficiency is ideal. An old reference (1957) ranges between 30-50 breaths/minute (4). In the premature infant, this is more pronounced as much efficiency is lost to a chest wall prone to retraction.

Oxygen Transport

The oxyhemoglobin disassociation curve is shifted to the left in the newborn due to fetal hemoglobin's increased affinity for oxygen. This makes it more efficient at picking up oxygen in the lungs but decreases its ability to offload oxygen at the tissue level. Cardiac output in the newborn can only be increased by increasing heart rate, further limiting the ability to respond to inadequate oxygenation; shunt in the presence of a patent ductus arteriosus blunts this response.

Oxygen consumption is higher in the newborn and more so in the premature infant due to increased work of breathing and decreased ventilatory efficiency (4).

Implications for Mechanical Ventilation and Respiratory Support

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Non-Invasive Ventilation (NIV)

Aside from higher R, immature airways are prone to collapse, and adequate CPAP/PEEP/MAP is required to help decrease airway R and maintain patency. These decrease work of breathing, but the limited range of efficiency remains unchanged, and even moderate pressures often lead to gastric and abdominal distention ("CPAP belly"), further reducing efficiency and increasing the work of breathing.

While NIV has decreased the incidence of chronic lung disease overall, the limitations must not be ignored, and clinicians must recognise and respond appropriately when those limitations are reached. This is most often demonstrated by increasing FiO_2 requirements and increased apneic and bradycardic episodes.

Conventional Ventilation (CV)

Mechanically ventilation does not change the laws of diminishing returns. There is an optimal respiratory rate above which efficiency decreases and ventilation deteriorates, just as in spontaneous breathing. As the rate increases, the respiratory cycle time decreases, and there comes the point at which further increases are either ineffective or lead to further deterioration. This is often due to gas trapping.

Due to limitations in its ability to respond to changes in hemodynamics, the cardiovascular system's ability to maintain adequate perfusion and, thus, tissue oxygenation may be exceeded at higher MAP.

In the extremely immature lungs of the micro-premie, pressures required to achieve optimal inflation may exceed the tolerances of conducting airways, particularly the alveolar ducts, leading to the development of micro-tears. This is the path to fulminant air leak, namely pulmonary interstitial emphysema.

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High-Frequency Oscillation (HFO)

Increasingly HFO is being recognised as being a gentler, more lung-protective mode of ventilation than CV (although not without controversy).

Here the smaller volumes used decrease volutrauma and sheer stresses and require less time to deliver and evacuate, but this is offset by the high rates used. Because the respiratory cycle is very brief, HFO requires negative pressure during the expiratory phase to speed up emptying. This may lead to airway instability or outright collapse if sufficient MAP is not provided.

Newer, 3rd generation ventilators provide for volume targeted ventilation during HFO. Since Vt is no longer a function of frequency, it may be decreased without resulting in higher Vt. This is not the case in places where these machines have yet to be approved (the U.S.); higher frequencies may be required to limit volumes delivered to tiny babies. While HFO/VG does not eliminate the problem of gas trapping, it does decrease the risk. Just as with CV, the law of diminishing return exists with HFO, just at higher rates.

High-Frequency Jet Ventilation (HFJV)

HFJV is unique in its ability to ventilate in the face of high airway R and poor pulmonary compliance. Because the jet "breath" shoots down the centre of the airway at high speed and initially reasonably high pressure, it can better ventilate effectively in a broad range of scenarios.

With the very short inspiratory time (typically 0.02 seconds but as high as 0.034 seconds) and the I:E ratio as high as 1:12, there is much more time available for the lung to empty. Rates used in clinical practice range between 240 – 420/minute, coupled with the effect of double helical bidirectional flow (which allows a small amount of gas to leave the lung during inspiration). HFJV as a mode is the least likely to result in gas trapping. That is not to say it does not occur, particularly with tiny babies.

HFJV has also been shown to provide adequate oxygenation at lower MAP than other modes, a bonus when dealing with the limited capacity of the premature infant's cardiovascular system (7).

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Summary

As the patients we treat in the NICU become ever smaller, the stark differences in their physiology, particularly R, are multiplied. High time constants resulting from high R make ventilating conventionally ever more complex.

High-frequency ventilation can best mitigate the difficulties of ventilating the micro-premie, particularly with volume targeting. HFJV may be the best choice for mode should this feature not be available and should be considered where gas trapping is a concern or is clinically evident.

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Disclosures: The author receives compensation from Bunnell Inc for teaching and training users of the LifePulse HFJV in Canada. He is not involved in sales or marketing of the device nor does he receive more than per diem compensation. Also, while the author practices within Sunnybrook H.S.C. This paper should not be construed as Sunnybrook policy per se. This article contains elements considered "off label" as well as maneuvers, which may sometimes be very effective but come with inherent risks. As with any therapy, the risk-benefit ratio must be carefully considered before they are initiated.

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