Received: 15 October 2021 | Revised: 2 December 2021 | Accepted: 3 December 2021

DOI: 10.1111/pan.14366

EDUCATIONAL REVIEW

Pediatric Anesthesia WILEY

Understanding pediatric ventilation in the operative setting. Part II: Setting perioperative ventilation

Johannes Spaeth[1,2] | **Stefan Schumann**[1,2] | **Susan Humphreys**[3,4]

[1]Department of Anesthesiology and Critical Care, Medical Center - University of Freiburg, Freiburg, Germany

[2]Faculty of Medicine, University of Freiburg, Freiburg, Germany

[3]Paediatric Critical Care Research Group, Child Health Research Centre, The University of Queensland, Brisbane, Qld, Australia

[4]Department of Anaesthesia, Queensland, Children's Hospital, South Brisbane, Qld, Australia

Correspondence
Johannes Spaeth, Department of Anesthesiology and Critical Care, Medical Center University of Freiburg, Hugstetter Str. 55, 79106 Freiburg, Germany.
Email: johannes.spaeth@uniklinik-freiburg.de

Funding information
None.

Section Editor: Britta von Ungern-Sternberg

Abstract

Approaches toward lung-protective ventilation have increasingly been investigated in recent years. Despite evidence being found in adults undergoing surgery, data in younger children are still scarce and controversial. From a physiological perspective, however, the continuously changing characteristics of the respiratory system from birth through adolescence require an approach based on the analysis of each individual patient. The modern anesthesia workstation provides such information, with the technical strengths and weaknesses being discussed in a review preceding the present work (see Part I). The present summary aims to provide ideas on how to translate the information displayed on the anesthesia workstation to patient-oriented clinical ventilation settings.

KEYWORDS
anesthesia, intraoperative care, mechanical, pulmonary ventilation, ventilators

1 | INTRODUCTION

Clinical evidence regarding ventilation strategies for children with healthy lungs during surgery is still scarce. The pediatric anesthetist needs to make individual decisions regarding the patient's treatment, taking into account the wide range of physiological characteristics of the respiratory system, changing from birth through adolescence, including information obtained from the anesthesia workstation (AWS). The primary goal of mechanical ventilation settings is to optimize gas exchange within a physiological range. Configuring ventilation settings in order to achieve this goal requires understanding and skills that go far beyond using automatic presets.

From a physical perspective, ventilation aims at transferring pneumatic energy from the ventilator to the patient's respiratory system. Concerning potential ventilation-related lung injury, setting mechanical ventilation will always be a trade-off between adequate lung ventilation and applying the lowest possible energy transfer. Critically evaluating the following questions in the light of the patient's characteristics and circumstances may help to determine ventilator settings on a rational basis:

1. Is the ventilation mode the most effective?
2. Is the minute ventilation just as low as required?
3. Is the lung open and not overdistended?
4. Is the composition of the breathing gas adjusted to the actual need?

In the following chapters, we aim to address how the information provided by the AWS may be used to answer these questions.

2 | SETTING THE MOST EFFECTIVE VENTILATION MODE

From a historical perspective, pediatric anesthetists prefer pressure-controlled ventilation (PCV). From the evidence available, volume-controlled ventilation (VCV) has been avoided for the reason of mistrusting the precision of tidal volume application and the fear of high airway pressures. As illustrated before, manufacturers made promising efforts to address shortcomings in regard to the precision of tidal volume application. Fresh gas decoupling and compliance compensation are among the most important (see Part I). In regard to airway pressures, it is important to recall that with identical end-inspiratory alveolar pressure, VCV shows a clearly higher peak airway pressure compared with PCV. This is, however, solely due to the flow-dependent resistive pressure gradient across the airways distal to the Y-piece and therefore does not strain the lungs (see Part I, Figure 4). The uncertainty regarding the "true" inspiratory pressure, however, will continue unless manufacturers of AWS imply tracheal (or alveolar) pressure calculation, for example, based on algorithms as discussed.

To date, there is not enough outcome-related evidence favoring decelerating flow waveform during inspiration (ie, PCV) over squared flow waveform (ie, VCV) in the perioperative setting. Nevertheless, selection should target specific circumstances.

PCV appears the preferred ventilation mode if relevant airway leakage is potentially present, for example, during ventilation via an uncuffed endotracheal tube or a laryngeal mask or during lung separation. In the presence of leakage, the inspiratory flow delivery, up to the limit of the ventilator, ensures the pressure amplitude required for insufflation of the targeted tidal volume. For this reason, the mechanical principle of PCV is also the basis for most assisted ventilation and noninvasive ventilation modes. Furthermore, PCV is preferable when there is a risk of dynamic hyperinflation. The retained volume (and increased end-expiratory pressure) diminishes driving pressure of the subsequent breath. Peak inspiratory pressure remains constant; thus, an excessive pressure increase, as it would develop incrementally during VCV, is avoided.

VCV can be an advantage in situations when changes in respiratory system compliance (C_{RS}) are expected, for example, in case of capnoperitoneum or re-positioning. Tidal volume is constant at varying peak inspiratory pressures, avoiding hypoventilation and extensive tidal volumes (which may be associated with volutrauma). Moreover, albeit less obvious, the constant flow during inspiration provides (almost) linear conditions, thus facilitating the analysis of respiratory mechanics.[1]

Newer modes of ventilation are available, combining the strengths of both techniques. These modes provide the benefits of a decelerating flow pattern with a warranted tidal volume. Therefore, peak inspiratory pressure is automatically adjusted to deliver a set tidal volume, in certain ranges. With changes in compliance being continuously determined, alveolar ventilation can be ensured at the lowest possible inspiratory pressure. To date, these modes appear to be the most effective for long-term ventilation of preterm and term neonates. The Volume Guarantee mode (most extensively studied; Dräger Medical, Germany) can significantly reduce death and bronchopulmonary dysplasia, pneumothoraces, hypocarbia, and periventricular leukomalacia as well as severe intraventricular hemorrhage compared with PCV.[2] Modes of comparable functionality are also available for perioperative ventilation with modern AWS. Whereas evidence in regard to improved respiratory mechanics is quite convincing in adults undergoing elective surgery,[3] the evidence is less good developed for ventilation during pediatric anesthesia.

From a biomechanical point of view, patients benefit from assisted spontaneous breathing using pressure support ventilation (PSV). During PSV, inspiratory pressure should at least compensate for the resistive pressure gradient of the artificial airways. As resistance depends nonlinearly on flow, the required compensation varies considerably between specific situations and even within a single breath. For example, in an infant, peak inspiratory flow can be as high as 300 mL/s. In this situation, an endotracheal tube of 4.5 mm inner diameter causes about 5 cmH_2O (Figure 1), the breathing system including connectors about 2 cmH_2O, and the breathing system filter about 0.5 cmH_2O of resistive pressure gradient.[4,5] Accordingly, an inspiratory pressure support of about 3–4 cmH_2O could compensate for about 50% of the resistance of the artificial airways in this example. Caution is required in regard to trigger sensitivity. Artificial airway resistance counteracts the patient's efforts to trigger the ventilator. The trigger threshold should therefore be set to achieve sufficient patient-ventilator synchrony (typically about 1 L/min). In case of severe patient-ventilator asynchrony (eg, coughing just before extubation), continuous positive airway pressure may be better suited than PSV to maintain positive airway pressure.

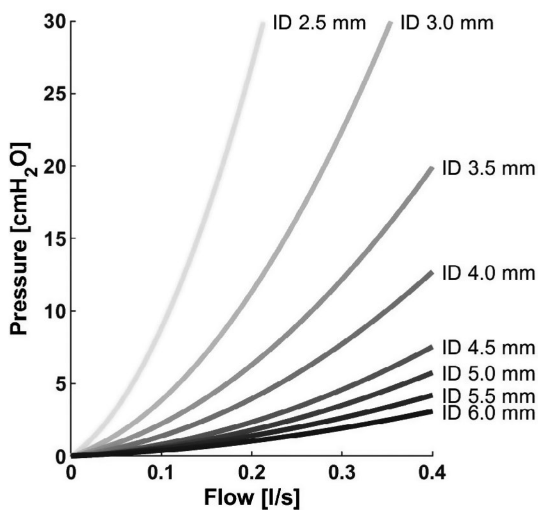

FIGURE 1 Flow-dependent inspiratory pressure gradient across pediatric endotracheal tubes with an inner diameter (ID) from 2.0 to 6.0 mm. Please note that in the knowledge of the current flow rate (eg, 300 mL/s), the corresponding pressure gradient can be roughly estimated from the ordinate

3 | SETTING THE LOWEST REQUIRED MINUTE VENTILATION

Achievement of sufficient alveolar minute ventilation (MV) is the key challenge when setting ventilator variables for pediatric patients. What sounds as simple as just combining two basic variables, VT and respiratory rate, turns out to be difficult in daily practice. The smaller the children, the higher the proportional need for alveolar ventilation. High oxygen consumption, low oxygen diffusion capacity, and low functional residual capacity cause a disproportionally high demand on MV.[6] The need for alveolar ventilation is opposed by the high resistance of the respiratory system, limiting volume exchange with an increased turnover (ie, flow). Postnataly, lungs grow faster than the airways,[6] which accounts for the disproportional high resistance of the respiratory system (R_{RS}). Above that, the ratio of dead space to VT further complicates sufficient gas exchange. Fortunately, the weight-adjusted amount of anatomical dead space remains relatively stable with growing up.

In the past decades, evidence accumulated in regard to low tidal volume diminishing the risk of ventilator-induced lung injury in adults. The observed benefits in outcome encouraged clinicians and researchers to apply these concepts to perioperatively ventilated lung healthy patients as well. Today, it is widely accepted that tidal volume between 6 and 8 ml per kg ideal body weight (IBW) can reduce the risk of postoperative pulmonary complications (PPCs), as part of a bundle of measures referring to so-called lung-protective ventilation. In this context, it has turned out that the risk for PPCs depends on several factors referring to patients' characteristics, comorbidities and type of surgery, for example.

Such evidence is scarce in pediatric patients. Kneyber et al. analyzing evidence in this regard in 2015 is worth reading. The authors conclude that settings of pediatric ventilation are hardly supported by any scientific evidence, and therefore, VT should be close to the physiological range (5–8 mL/kg IBW).[6] Nevertheless, in 2017, the Paediatric Mechanical Ventilation Consensus Conference (PEMVECC) published recommendations for mechanical ventilation of critically ill children, in which it is stated that VT should set below 10 ml/kg IBW.[7] This value should also be reflected in the light of potential sources or error. First, volume measurement in the AWS includes a certain tolerance which may lead to a relevant error, particularly at very small VT; second, between-subject variability of functional characteristics of the respiratory system can be of considerable extent in children. In a 5-year-old child, forced vital capacity (FVC) is considered "normal" within a range of 70%–130% of the predicted value. This range decreases until the age of 15 year, but then still amounts to 80%–120%; third, calculation of IBW in children lacks evidence, if clinically performed at all. The given VT landmarks assume calibration to the patient's individual

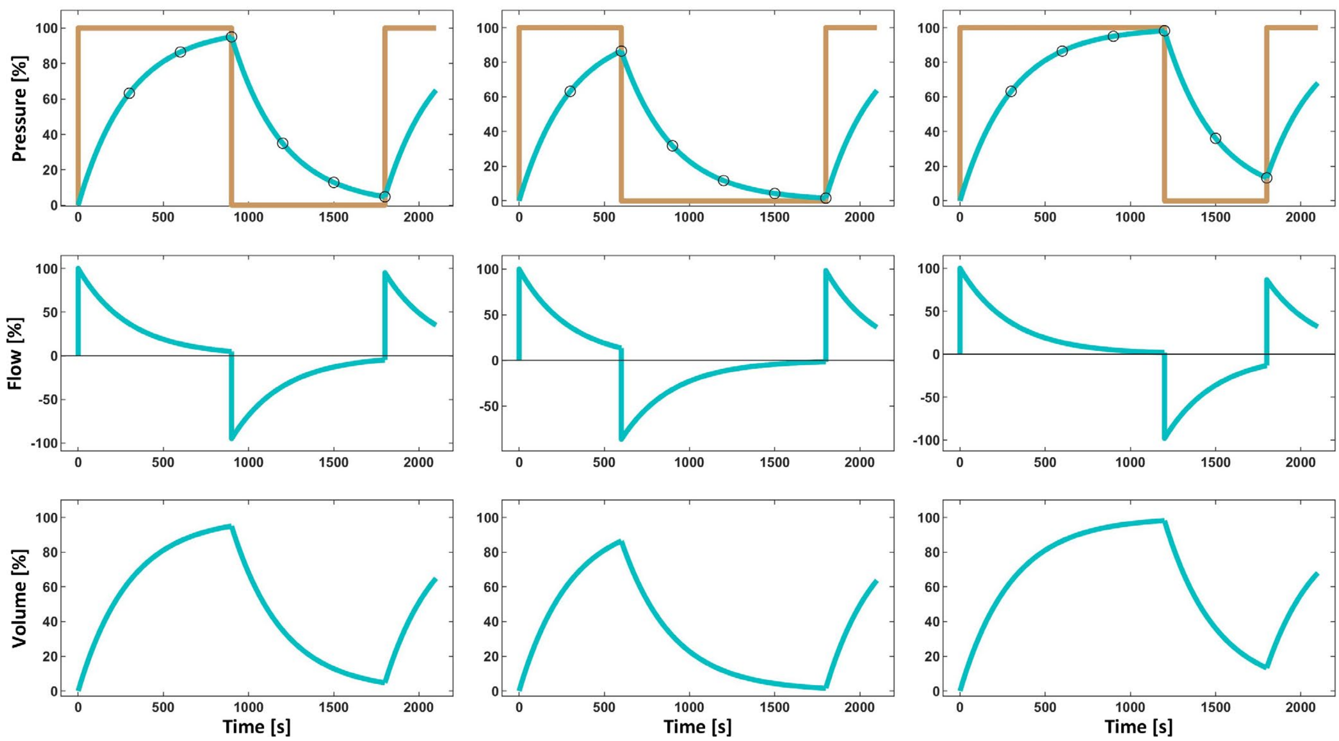

FIGURE 2 Computer-generated simulation of pressure-controlled ventilation curves at constant respiratory rate and inspiratory pressure but different inspiratory to expiratory (I:E) ratios. Airway pressure curve (orange) is superimposed by tracheal pressure curve (blue; upper panel). Please note, that tracheal pressure does not reach airway pressure (set at the ventilator) closely at the end of inspiration at an I:E ratio of 1:2 (middle row). Consecutively, the inspired tidal volume is lower than that at an I:E ratio of 1:1 (left row), at respective inspiratory airway pressures. On the contrary, at an I:E ratio of 2:1 (right row), tracheal pressure does not reach airway pressure at the end of expiration. Consecutively, the expired volume is lower than the inspired volume, indicating dynamic hyperinflation of the lungs and followed by a lower tidal volume with the subsequent breaths

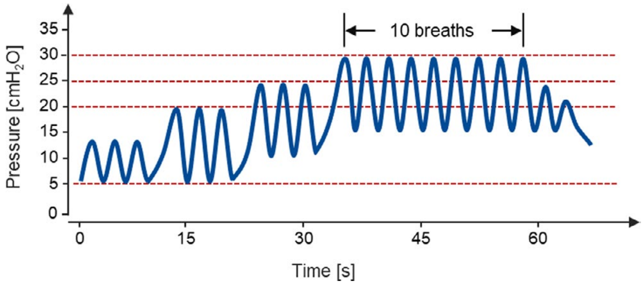

FIGURE 3 Schematic illustration of the course of airway pressure during a lung recruitment maneuver as applied in the study of Acosta and colleagues in 42 lung healthy children aged 6 months to 7 years, before capnoperitoneum.[15] During pressure-controlled ventilation, driving pressure was increased to 15 cmH_2O, and then, PEEP was increased to 10 cmH_2O and consecutively 15 cmH_2O, each condition applied for 3 consecutive breaths. At PEEP 15 cmH_2O and driving pressure 15 cmH_2O, 10 breaths were applied with the effectiveness of the maneuver controlled via lung ultrasound

total lung capacity. Height, and therefore IBW, is accepted as a rough surrogate for TLC. Studies comparing methods of calculating IBW, however, suggest that actual body weight and IBW can differ considerably in children.[8,9] Calculation of IBW should therefore be limited to children above the age of 2 years.[9] Although there is no gold standard equation for calculating IBW in children, Ward et al. found the McLaren-Read method fits, in children with PARDS between the age of 2 and 10 years, and particularly in children above the age of 10 years, where discrepancies between different calculation methods were most distinct.[10] The authors conclude that the McLaren-Read method is relatively easy to calculate using readily available growth charts that compare weight and height in relation to a child's age. The modern AWS may be suited to calculate such complex algorithms and display age-adjusted IBW, in order to increase precision.

Setting appropriate VT in preterm and term neonates requires special attention due to the vulnerability for respiratory distress syndrome. In healthy neonates, the average tidal volume is 4 – 6 ml/kg with a minute ventilation aiming at 0.2–0.3 L/min/kg.[11] In brief, PEEP and volume-targeted ventilation should be continued if possible and caution should be applied to accidental overdistension of the lungs.[12,13]

The other variable influencing MV is respiratory rate (RR). Setting RR is far less critically discussed than setting VT. From a pragmatic point of view, once VT is adjusted to patient individual characteristics, RR is set to multiple VT until a desired MV is reached. Modern AWS allow for setting an inspiratory time as low as 0.2 s. This corresponds to the physiological inspiratory time of a healthy neonate, which is about 0.2–0.4 s.[11] However, higher RR increases cumulative dead space ventilation, which counteracts the goal of sufficient alveolar ventilation. Given the relatively liberal range for weight-adjusted VT, the clinician may be encouraged to adjust RR toward a lower limit. Consideration of the time constant of the respiratory system (Tau = $C_{RS} \cdot R_{RS}$) may be of help in this regard. In children presenting with a rather long time constant (high airway resistance), a low RR will be preferable. On the contrary, in children presenting with a rather short time constant (low compliance, eg, in the respiratory distress syndrome), the lungs empty more quickly (compare Part I, Figures 3 and 4); thus, high RR can be applied to achieve sufficient MV.

The setting of an appropriate inspiratory to expiratory ratio can be based on the expiratory flow profile. Complete inspiration and complete expiration can be assumed if the decelerating flow approximates zero at the end of each phase of the breath (Figure 2). Adjusting the expiratory time just to ensure complete exhalation limits the time the respiratory systems rest at the lowest pressure during the breathing cycle (ie, positive end-expiratory pressure) to a minimum, thus preventing derecruitment of the lungs by alveolar collapse. Moreover, during PCV, setting the expiratory interval in favor of the inspiratory time warrants development of the best tidal volume as the equilibration time is prolonged. This is particularly true at high RR and long Tau.

Recent research questions RR as an independent factor contributing to VILI.[14] In this comprehensive approach, the energy which is transferred from the ventilator to the patient's respiratory system is calculated. To date, however, the impact of the RR on pulmonary complications is not clear.

4 | ACHIEVING AN APPROPRIATE RECRUITMENT STATUS OF THE LUNGS

When considering opening of the lung, one has to distinguish between two phenomena, intratidal recruitment/derecruitment, and atelectasis. While the first describes the repetitive opening and closing of alveolar tissue, the second refers to more or less consolidated alveolar collapse and thus shunt region, not contributing to gas exchange.

By far, most children develop atelectasis during induction of anesthesia. Lung recruitment maneuvers are supposed to reverse the alveolar collapse. However, due to the usually high intrathoracic pressure recruitment, maneuvers may impair hemodynamics. In adults, peak inspiratory pressure about 40 cmH_2O (and about 50 cmH_2O in obese) is considered effective, whereas the inspiratory airway pressures applied in children can be lower. Reasoned by the high elasticity of the pediatric thorax, intrapulmonary pressure is distributed in a higher fraction to transpulmonary pressure and a smaller one to transthoracic pressure, compared with adults.

In children aged 6 months to 7 years, increasing PEEP to reach an inspiratory pressure of 30 cmH_2O during PCV (Figure 3) effectively prevented atelectasis in the majority of patients during laparoscopic surgery. In the 47 patients enrolled, no relevant hemodynamic events were observed.[15] Even a peak inspiratory pressure of 22 cmH_2O (10 cmH_2O PEEP + 12 cmH_2O driving pressure) was effective, when applied in opposing lateral body positions (90 seconds each side).[16]

Successful lung recruitment may be detected from imaging, analysis of respiratory system mechanics, or from reduction in anatomical

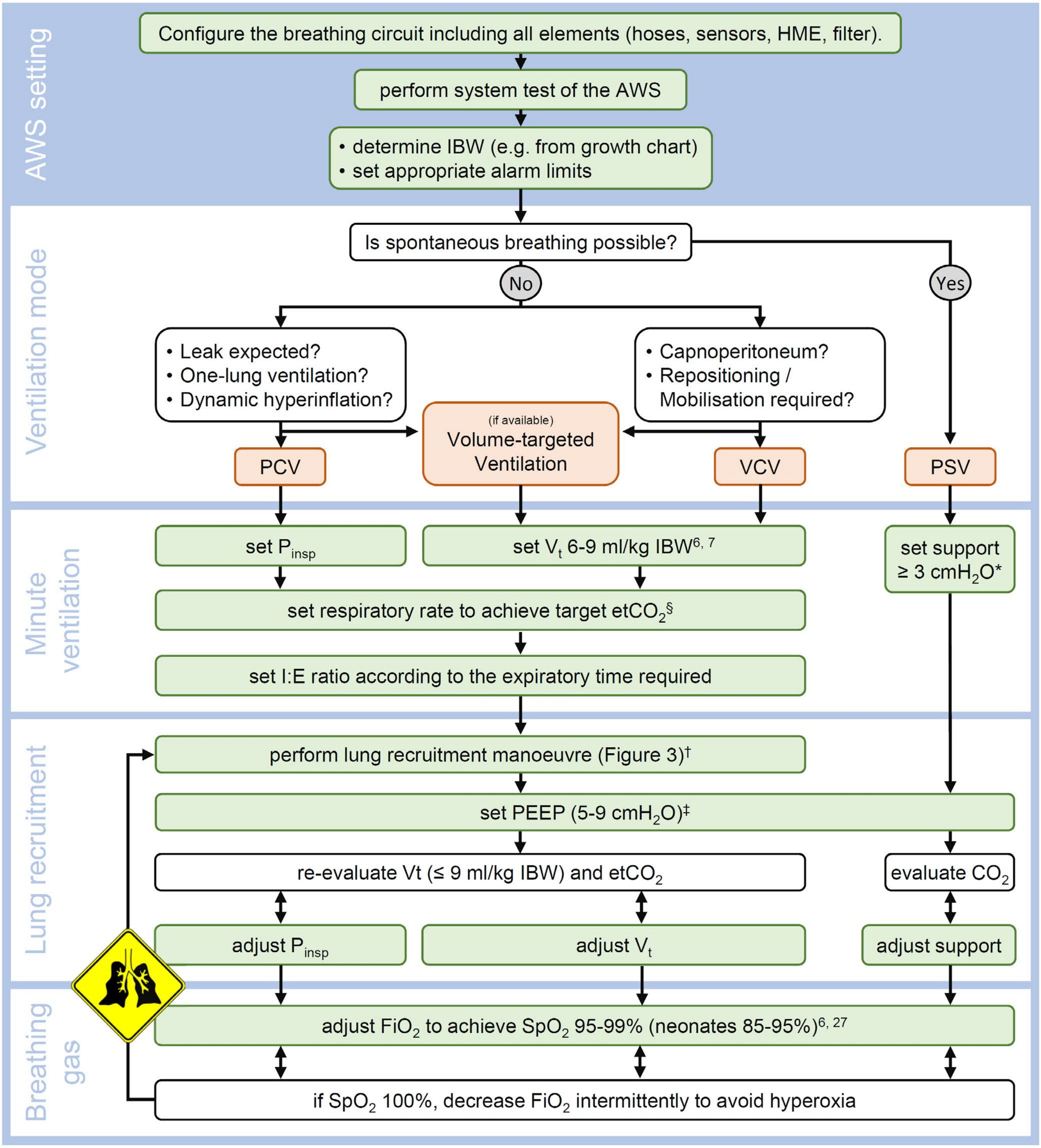

FIGURE 4 Flowchart to setting up the ventilator for pediatric ventilation in the operative setting. Please consider that the suggested task sequence depends on the clinical circumstances and may have to be adapted. Particularly during controlled ventilation, derecruitment of the lungs will take place time-dependently and after loss of positive airway pressure in the breathing circuit (eg, disconnection). Therefore, lung recruitment maneuvers need to be repeated and ventilator settings should be adjusted thereafter. *During pressure support ventilation (PSV), inspiratory pressure support should be adjusted to compensate for the resistance of the artificial airways; §Optimal end-tidal CO_2 may be within physiological ranges (35–45 mmHg),[29] with permissive hypercapnia being accepted in preterms and neonates (45–55 mmHg)[13]; †caution is required in regard to hemodynamic stability during lung recruitment maneuvers; ‡Positive end-expiratory pressure (PEEP) can be set empirically or guided on respiratory mechanics as described; IBW: ideal body weight; PCV: pressure-controlled ventilation; VCV: volume-controlled ventilation; P_{insp}: inspiratory airway pressure; V_t: tidal volume; I:E: inspiratory to expiratory ratio; FiO_2: fraction of inspired oxygen; SpO_2: oxygen saturation

dead space. C_{RS} increases, and with a volumetric capnography in place, the Bohr equation allows an approximation of the dead space reduction, correlating to an improved lung aeration (Equation 1).

$$VD = VT \times \frac{PaCO_2 - PexpCO_2}{PaCO_2} \quad (1)$$

Lung recruitment maneuvers appear to be effective for resolving acute atelectasis, for example, due to anesthesia induction or after disconnection of the breathing system. However, during ongoing mechanical ventilation, a study from our group found no persistent effects of recruitment maneuvers on compliance or the recruitment status of the lung.[17] In order to make the effects of a recruitment maneuver more sustainable, an appropriate level of PEEP should be applied thereafter.

While the use of low tidal volumes is widely accepted, the problem of setting optimal PEEP is still unsolved, particularly in pediatric patients. PEEP is supposed to splint the airways and thus to prevent collapse and reopening of the alveoli. When considering the physiological basis of PEEP setting, it has to be considered that closing volume in infants is higher than functional residual capacity.

In our studies, we found that intratidal recruitment/derecruitment was more often present in younger compared with older children and that recruitment maneuvers did not show any persisting effects in one of our studies.[17,18] Particularly, moderately increased levels of PEEP up to 7 cmH_2O did not significantly resolve intratidal recruitment/derecruitment, in contrast to adult patients. This points to a physiological nonrecruitability as a characteristic of the developing lung and may therefore not necessarily be detrimental. This is supported by an early study which suggests that occurrence of terminal airway closure occurs during normal breathing in younger children.[19]

In the absence of outcome-related evidence for PEEP strategies, it appears reasonable to make the adjustment of PEEP based on physiological considerations. Since imaging techniques and complex analyses of respiratory system mechanics are not available in a regular clinical setting, PEEP variation maneuvers may be used to find optimal PEEP. Minimizing driving pressure is currently discussed as target for guiding ventilation setting,[20] though this measure itself is not accessible as control variable of mechanical ventilation. Driving pressure results from the division of tidal volume by compliance.[21] It remains to aim at low driving pressure indirectly: C_{RS} may change with PEEP, particularly if PEEP is associated with recruitment of lung tissue. Consequently, PEEP may be set with the intention to improve compliance. A method proved valid in this regard is setting PEEP following a decremental PEEP trial.[22] For this, a maximum PEEP is set and reduced stepwise. If compliance decreases significantly with a certain PEEP step, PEEP is set back to the preceding value. This way, the highest compliance is achieved. As a consequence, during VCV, the lowest driving pressure would result in a certain tidal volume, and during PCV, the highest tidal volume would result in a certain pressure amplitude, which may then allow for reducing peak inspiratory pressure.

5 | COMPOSING THE BREATHING GAS TO THE ACTUAL NEED

Setting situation appropriate fraction of inspired oxygen (FiO_2) is a challenging task. It requires careful consideration of the patient's actual need, a safety reserve for what is to come, and possible side effects of oxygen. The oxygen consumption of spontaneously breathing children under the age of 3 years depends on body surface area and heart rate, thereby increasing from about 130 to 190 ml/(min · m^2) with age. In children aged 3 years and older, the oxygen consumption again slightly decreases to about 160 ml/(min · m^2) with gender being a significant factor as well.[23] It is well known that due to the high demand but relatively low FRC, the pulmonary oxygen reservoir lasts only a few seconds at sufficient pulmonary perfusion. However, high oxygen concentrations are potentially harmful in patients of all ages, causing negative effects such as lung capillary damage, myocardial infarction, and oxidative stress. Above that, it should be remembered that oxygen tension in the lungs directly affects pulmonary vascular resistance, which may be of relevance in patients with congenital heart disease. Particularly in preterm and term neonates, high oxygen concentrations can worsen retinopathy (due to its potential for neovascularization) and bronchopulmonary dysplasia.[24]

During induction of anesthesia, high oxygen concentrations are generally considered in order to gain time in case of difficult airway management. The optimal FiO_2 is not known; however, high oxygen concentration ($FiO_2 > 0.8$) during induction and maintenance of anesthesia can decrease postoperative lung volume and promote ventilation inhomogeneity.[25] If a child tolerates preoxygenation via spontaneous breathing through the breathing circuit, oxygenation can be considered sufficient if the end-expiratory fraction of oxygen is above 0.7 (with FiO_2 set at 0.8) or 0.9 (with FiO_2 set at 1.0),[25] with the regular presentation of the capnography indicating reliable gas measurement. At oxygen concentration in that range, it is likely that resorption atelectasis will take place,[26] which can, however, be effectively reversed by applying a lung recruitment maneuver and ventilation with PEEP thereafter.[15]

As soon as the airway is secured, FiO_2 should be lowered to the minimal level required. Rather than recommending a global value, which is universally applicable, oxygen delivery should be monitored to guide titration of FiO_2. If available, arterial oxygen concentration (PaO_2) <60 mmHg constitutes a landmark to increase oxygen concentration in the inspired gas (among other measures).[24] More routinely, oxygen saturation (SpO_2) is available as a noninvasively measured surrogate parameter for oxygen concentration in the blood. SpO_2 values as low as 95% (approximately corresponding to a PaO_2 of 60–80 mmHg at normal pH, temperature, and carbon dioxide) can be accepted in the absence of lung disease.[6] In the healthy neonate, preductal values for SpO_2 are generally accepted in the range of 85%–95%.[27] In regard to the monitoring of high oxygen levels, however, SpO_2 measurement has its limitations as it cannot mirror alveolar oxygen delivery exceeding the need of fully saturated hemoglobin. It is therefore recommended to periodically reduce FiO_2 to evaluate the inspired oxygen concentration which is required to just reach sufficient oxygen saturation.[12]

In order to maximize the benefits of the rebreathing system of the AWS, the fresh gas flow should be as low as possible. Minimal-flow anesthesia (<0.5 L/min) mainly bears the advantages of an economic and ecological use of volatile agents.[28] The meaning in regard to climatization (heating (>28°C) and humidification (17 and 30 mg H_2O/L)) of the circulating air has declined with the introduction of heat and moisture exchangers. At minimal-flow anesthesia with a FiO_2 titrated to the minimal oxygen delivery required, caution is advised if the demand on oxygen increases suddenly. As discussed in Part I of this article, increasing oxygen concentration in the breathing system can be time consuming, depending on the volume of the breathing system of the AWS and the patient's minute ventilation.

6 | SUMMARY

To date, none of the dimensions that determine the setting of ventilation in pediatric patients can be defined with sufficient precision. Changing characteristics of the growing respiratory system and circumstances of the surgical setting and individual comorbidities all influence the right decision at a particular time. Figure 4 provides a quick guide for routine clinical practice to approach the individual best ventilator settings.

It should be kept in mind that the ventilator settings have to address the high airway resistance, that minute ventilation can be based on a slightly higher tidal volume compared with that in adults, and that PEEP is a must due to the high closing capacity. Caution is advised when setting high inspiratory pressure, since this loads transpulmonary pressure in particular. Adjusting inspiratory to expiratory ratio in order to achieve maximum volume exchanges at a certain airway pressure and applying recruitment maneuvers where required frame a thoughtful (sophisticated) ventilator setting.

7 | REFLECTIVE QUESTIONS

1. In which clinical circumstances, volume-controlled ventilation can be considered advantageous?
2. Can the calculation of optimal tidal volume be based on ideal body in all ages?
3. What are the advantages of increasing inspiratory time?
4. What is an appropriate inspiratory pressure for a lung recruitment maneuver in lung healthy children?

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Johannes Spaeth https://orcid.org/0000-0003-3931-6400
Stefan Schumann https://orcid.org/0000-0003-0773-7489
Susan Humphreys https://orcid.org/0000-0003-0286-2088

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How to cite this article: Spaeth J, Schumann S, Humphreys S. Understanding pediatric ventilation in the operative setting. Part II: Setting perioperative ventilation. *Pediatr Anesth*. 2022;32:247–254. doi:10.1111/pan.14366