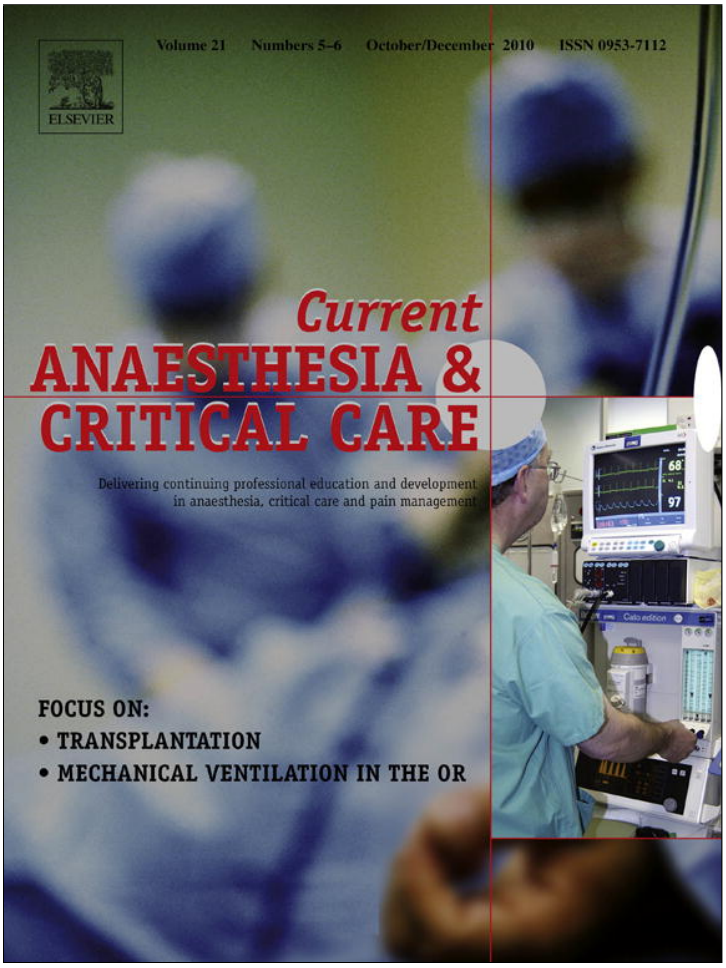
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FOCUS ON: MECHANICAL VENTILATION IN THE OR

Ventilating the newborn and child

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SUMMARY

The mechanical ventilation of neonates and children in operating theatres has always posed a challenge for anaesthesiologists. Firstly, the extreme physiological features of neonatal lungs make them very difficult to ventilate with an anaesthesia ventilator. Gattinoni's "baby lung" concept to describe ARDS lungs in adults comes from the physiological features of neonatal lungs (low dynamic compliance, low pulmonary time constant, low FRC, high closing volume, proneness to atelectasis, high inspiratory airway resistance). Secondly, the performance and technology (peak flow, insufflation power, trigger sensitivity, ventilation modes, etc.) of anaesthesia ventilators is still less advanced than those of critical care ventilators. It is possible to ventilate a normal healthy adult lung with an anaesthesia ventilator, but even today, using circle circuits, ventilating a premature baby, newborn or child in the operating theatre can be a real challenge. Over the last 5 years, great changes have been made to anaesthesia workstations, which now boast better mechanical ventilation performance for children as well as new ventilation modes. However, there is a lack of background knowledge regarding mechanical ventilation in operating theatres, and this limits the advantages that can be derived from this new technology, and thus any potential safety improvements in paediatric surgery.

1. Introduction

Over the last decade, many new developments have been incorporated into anaesthesia ventilators and it is becoming an increasingly important to have ICU ventilator performance in the operating theatre. Precision in terms of tidal volumes and pressure delivery and optimisation of ventilation settings and assisted spontaneous breathing are all important considerations, especially in children, obese patients, patients with ARDS and other patients at risk of pulmonary complications.[1,2]

The healthy lungs of neonates are good physiological models for altered pulmonary states in adults. Neonates have a low functional residual capacity so they are prone to atelectasis during anaesthesia. They are therefore perfect models for recruitment manoeuvres, the prevention of atelectasis and how to set PEEP. The low lung compliance of neonates is a good model for how to ventilate patients with ALI/ARDS, and their high airway resistance provides a good model for the study of bronchospasm. Neonatal lungs are the hardest, most critical test for any anaesthesia ventilator if you wish to know how the ventilator is going to behave when faced with altered pulmonary states in adults. That is why even an adult anaesthetist who is never going to anaesthetise children must know which key points to take into account when using mechanical ventilation with circle circuits in paediatric anaesthesia, because this will give him advance knowledge of how the ventilator will perform with adults.[1–4]

In this paper, we will provide a short review of all the aspects involved in perioperative ventilation in paediatric patients, highlighting only those aspects that are specific to paediatric patients.

2. Applied respiratory physiology

The differences between the respiratory systems of paediatric and adult patients are inversely proportional to the age of the child, with the greatest differences seen in premature babies and newborns. From six years of age, the respiratory system becomes more and more similar to that of adults, both physiologically and physiopathologically. The main differences in the respiratory physiology of adults and children are summarised in Table 1.[1,2,5]

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Table 1
Respiratory physiology: main differences between neonates and adults: All of these features are crucial to increased patient safety during neonatal anaesthesia.

Applied physiology of newborn and child
1. Glottis – cephalad and anterior: most neonates present a difficult intubation.
2. High bronchial hyperreactivity during the first-two years: bronchospasm is more frequent.
3. Less functional residual capacity (FRC): proneness to atelectasis and less apneic oxygenation time.
4. High airway respiratory resistances: anaesthesia ventilators have problems ventilating the newborn.
5. Easier barotrauma: because pulmonary compliance is much less than thoracic compliance.
6. More sensitive to volutrauma: always use Vt 6 ml/kg.
7. Respiratory incident more frequent: apnea of prematurity, laryngospasm, etc.

2.1. Anatomical differences in the respiratory system

The main anatomical differences in the respiratory systems of newborns are: relative macrocephaly, macroglossia, anterior glottis, large curled epiglottis, problems with nasal ventilation and subglottic stenosis. These anatomical characteristics make newborns difficult to ventilate and intubate, and we must always be prepared for such difficulties.[1,5,6] Cormack-Lehane laryngoscopy grades of III and IV are to be expected, so we need to use the little finger of the left hand to move the glottis back so that the planes are aligned and we can see the chords.[1,7]

2.2. Mechanics of the respiratory system

Upon birth, neonates have to generate an exceedingly high negative pressure of up to (−) 80 cmH_2O to expand their lungs for the first time.[1,5–7] The main characteristic of neonatal lungs is their low functional residual capacity (FRC), which makes them more prone to lung collapse and atelectasis, as well as shorter periods of apneic oxygenation. This decreased FRC is due to the force of pulmonary elasticity that makes the lung collapse during expiration. The cartilaginous rib cage in newborns cannot impede lung collapse as effectively as the bony rib cage of the adult. Newborn FRC is very close to the critical alveolar closing volume; so neonatal lungs will collapse more and faster than adult lungs. Newborns use a physiological mechanism to prevent their lungs from collapsing, closing their vocal cords before the end of expiration, stopping the expiration process using the glottic closure and Hering-Breuer reflex. Furthermore, their high respiratory frequency (twice or thrice that of adults) means that expiratory time is much shorter than in adults.[1,5–8]

The end-expiratory lung volume (EELV) of newborns is higher than their FRC and closing volume, and this leads to auto-PEEP (2–3 cmH_2O) that keeps their lungs open during expiration, avoiding atelectasis (Table 2).[1,5–8]

Table 2
Pulmonary volumes: differences between neonates and adults: All values are expressed per kilo except anatomical deadspace because we want to emphasise how important it is to take into account the artificial deadspace that we add in newborn and small children.

Volumes (ml/kg)	Newborn	Adult	Difference
Functional residual capacity (FRC) (anaesthetized)	20–25	45	+80%
Tidal volume	6–7	7–9	+15%
Minute volume (ml/kg/min.)	200–250	100	−65%
Anatomical deadspace (total volume not per kilo)	(6–8 ml)	(120–180 ml)	

2.3. Respiratory time constants

The time that a neonatal lung takes to fill up and empty is determined by the inspiratory and expiratory time constants, which are much shorter in newborns than in adults. Neonatal lungs fill up and empty much more quickly than adult lungs (newborn Ti 0.4 s vs. adult Ti 1.5–1.8 s). Newborns usually have an I:E ratio of 1:1, while adults usually have an I:E ratio of 1:2.[1,6,8]

2.4. Oxygen consumption

Metabolic oxygen consumption in newborns is 2 or 3 times higher than in adults (5–6 ml/kg/min vs. 2–3 ml/kg/min). To cope with this higher demand for oxygen, newborns increase their respiratory minute volume by doubling or tripling respiratory frequency, but maintaining tidal volume constant at 6–7 ml/kg. The increased oxygen consumption results in a much shorter apneic oxygenation time in newborns than in adults (30 s vs. 3–4 min).[1,7]

2.5. Lung and thorax compliance

There are three types of lung compliance or distensibility: specific, static and dynamic. Specific lung compliance measures alveolar distension capacity due to the structure of their wall. This way, refers to the Compliance per unit of lung volume (ratio C/Total lung volume); this way Specific lung compliance remains constant throughout a person's lifetime, and in all mammals. However, during the first few hours of life, newborns have a diminished specific lung compliance, which normalizes when the pulmonary surfactant is properly distributed and all amniotic fluid is cleared from the alveoli.[6]

Static compliance, measured when the inspiratory flow has been interrupted for a certain period of time, describes alveolar distension in the absence of any influence from flow resistance. Static compliance is also diminished in newborns during the first few days of life, until the pulmonary surfactant is well distributed.[7,8]

Dynamic lung compliance (C_{dyn}) is an overall measurement of lung distension. C_{dyn} is very low in newborns (<4 ml/cmH_2O) in comparison to adults (50–80 ml/cmH_2O). C_{dyn} continues to be very low (1 ml/cmH_2O per kg of ideal body weight) until between 10 and 12 years of age (Fig. 1).[9]

Chest wall compliance (C_W) is very high in newborns (100 ml/cmH_2O), and is always higher than C_{dyn}. This difference between C_{dyn} and C_W means that newborns are very susceptible to direct barotrauma, as the chest wall will never stop lung distension. Another key difference in newborns is that their cartilaginous chest wall will never prevent the lungs from collapsing during the expiratory phase.[1,5]

2.6. Airway resistance

Airway resistance basically depends on the production of turbulent flows and the diameter of the airways through which the air flows. Although the required airflow for paediatric patients is always lower than that for adult patients, neonatal airways are very narrow, leading to turbulent airflow at various points (first three bronchial branches), causing an exponential increase in resistance.[10]

Inspiratory airway resistance is 7–10 times higher in newborns than in adults (>75 $cmH_2O/l/s$ vs. 10–15 $cmH_2O/l/s$). In premature babies, inspiratory airway resistance can even exceed 150 $cmH_2O/l/s$.[6,9,10]

In a study we carried out on 60 children between 2 months and 14 years of age, inspiratory airway resistance was found to have an inversely exponential relationship with the weight and age of the child. Thus, the children under 2 years of age had an airway resistance of more than 40 $cmH_2O/l/s$ in all cases, and the smallest patient in the sample group (2 months, 4 kg) had an airway resistance of 64 $cmH_2O/l/s$. Meanwhile, the children between 2 and 4

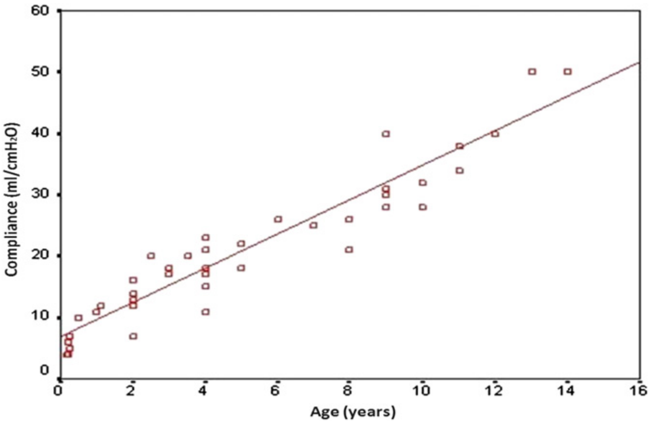

Fig. 1. Dynamic respiratory compliance (ml/cmH_2O) versus age (years) in paediatrics: data obtained from our study published in A&A. 2007 (9). A direct proportional correlation is observed between age and dynamic compliance in children ($p < 0.001$).

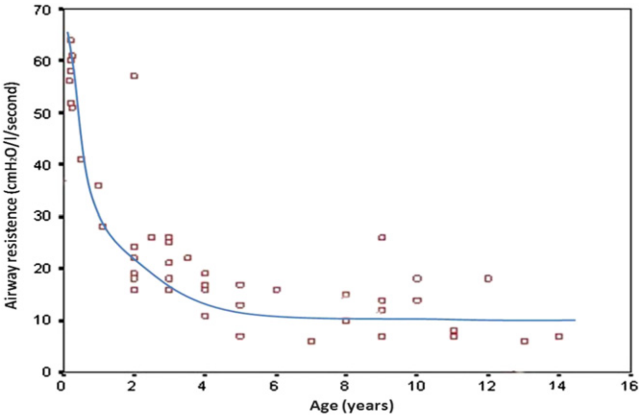

Fig. 3. Airway resistance (cmH_2O/l/s) versus age (years) in paediatrics: data obtained from our study published in A&A. 2007(9). An exponential inversely proportional correlation is observed between airway resistance and age ($p < 0.001$).

years of age had resistances of between 15 and 25 cmH_2O/l/s, slightly higher to normal adult resistance. From 4 years of age and above, the resistance decreases, becoming the same as the average adult resistance (8–15 cmH_2O/l/s) (Fig. 2).[9]

3. Respiratory monitoring in paediatrics

Respiratory monitoring is one of the most important aspects of mechanical ventilation in paediatric patients for two key reasons: firstly, because the most serious anaesthetic incidents in children are caused by problems with ventilation and airway management; and secondly, because the anatomical and physiological characteristics of children are very different to those of adults, and matters of very little clinical importance in adults, such as circuit compliance, increased artificial deadspace caused by gas monitoring or humidification devices, or minor leaks, can lead to critical incidents during paediatric anaesthesia. Beside the specific effect of the inhalatory anaesthesia in the respiratory system of the newborn.[1,11]

3.1. Flow-time curves

Inspiratory times in paediatric patients vary a great deal with age, ranging from 0.4 s in newborns to 1.6 s in older children and adolescents. However, expiratory times can vary even more with age and as a result of changes in the elasticity of the lungs, from 0.4 s in newborns to more than 2.4 s in older children. As a result of this high variability in respiratory time constants, it is particularly important that we know how to set inspiratory and expiratory times or the respiratory frequency and an I:E ratio correctly by studying the flow-time curve and setting times according to the specific characteristics of each lung. When dealing with paediatric patients, we must not set inspiratory and expiratory times based on pre-established rules with fixed I:E ratios.[1,5,7]

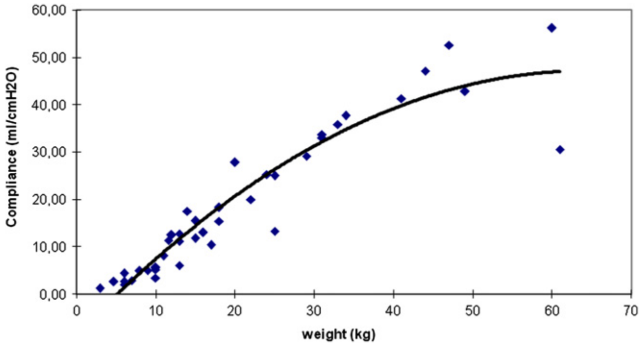

Fig. 2. Dynamic respiratory compliance (C_{dyn}) (ml/cmH_2O) versus weight (kg) in paediatrics: Data obtained from our study published in A&A. 2007 (9). A directly proportional correlation is observed between dynamic respiratory compliance and weight ($p < 0.001$). C_{dyn} is equal to 1 ml/cmH_2O per kg of ideal weight.

In paediatrics, the optimum inspiratory time should be guided by the flow-time curve in pressure-controlled ventilation, and it would be the shortest time in which there is flow towards the patient, with inspiratory time not being prolonged when flow has reached zero. In pressure support modes, the general rule is to prolong inspiratory time for a little longer in children than in adults. For adult patients, the cut-off point is usually at 30–25% of peak inspiratory flow, while the recommended cut-off point for children is 20% of peak flow. In volume-controlled mandatory modes, the flow curve is of no help when it comes to setting inspiratory time (Fig. 3).[5–8,12]

When setting the expiratory time for paediatric patients, special care must be taken to avoid dynamic over-distension or auto-PEEP (or intrinsic PEEP) by not leaving enough expiratory time to evacuate all the air that entered the lungs during inspiration. We must therefore always ensure that the expiratory flow curve reaches zero before starting the next inspiration.[1,2]

3.2. Gas monitoring

In the paediatric context, capnography and gas analysers are very important, as there are more factors that can lead to hypoventilation in children than in adults (compressible volume of the circuit, artificial deadspace, leaks, etc…). However, in paediatric patients, the monitoring itself can lead to significant clinical problems in patients weighing less than 5 kg.[1,8]

If we use the mainstream analyser, we do not reduce the volume within the circuit, but we increase the artificial deadspace by 3–4 ml. This means that we have to increase the newborn's tidal volume in order to maintain a constant alveolar tidal volume, even though this leads to an increased risk of volutrauma.[1]

However, if we decide to use the sidestream analyser, we are faced with two potential problems: an increase in artificial deadspace from the tube connecting the system to the patient circuit, and the resulting negative aspiratory flow (150–200 ml/min). To resolve the issue of deadspace, it is necessary to remove the connecting tube and connect the sampling line directly to the neonatal humidifying filter. To resolve the problem of the continuous 150–200 ml/min flow, it is necessary to increase tidal volume by

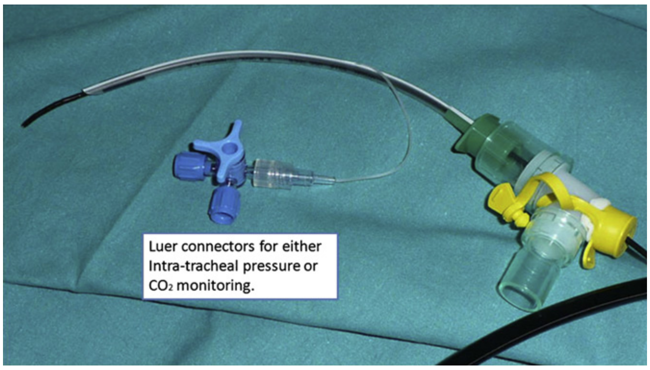

Fig. 4. Endotracheal tube with secondary lumen for either intratracheal pressure or $EtCO_2$ monitoring: this is a 3.5 mm Vigon endotracheal tube with secondary lumen that is usually used to delivery pulmonary surfactant. It can be connected to a three-way key and measure $EtCO_2$ at the end of the tube, avoiding all artificial deadspace. This second lumen can be used to measure intratracheal pressures. Such monitoring is especially important in instrumental airway procedures (fibrobronchoscopy, tracheal surgery).

2 ml/kg, knowing in this case that newborns are not at risk of volutrauma, as they are aspirated via the sampling line.[1]

3.3. *Intratracheal pressure and CO_2 monitoring*

Measuring intratracheal pressure is not new, and studies on the subject were carried out as far back as 1979.[13] The ability to monitor intratracheal pressure and CO_2 in the child's trachea is very useful in complex situations like surgery involving the trachea or fibrobroncoscopy procedures. To monitor these variables in smaller children, endotracheal tubes can be used with a channel specifically designed to monitor CO_2 or to administer surfactant (Fig. 4). The great advantage of these tubes is that they make it possible to monitor tracheal pressure and CO_2 without increasing airway resistance. Another option is to insert a catheter into the tube and exteriorise it with an airtight peice.[13,14]

4. Ventilation modes in paediatrics

4.1. *Pressure-controlled modes versus volume-controlled modes*

When ventilating newborns and small children, we need to choose between using pressure-controlled or volume-controlled modes. Traditionally, pressure-controlled modes have been recommended as they were thought to generate lower pressure than volume-controlled modes. However, this belief goes against the basic mathematical principle by which lung compliance is equal to the volume differential obtained by increasing pressure. Mathematically speaking, for any given lung compliance, increasing pressure by applying a determined volume is the same as increasing volume by applying a determined pressure. As such, in mathematical terms at least, it does not matter whether a pressure-controlled or a volume-controlled ventilation method is used for a set of lungs with a given compliance.[15,16]

However, differences do exist between volume-controlled and pressure-controlled ventilation. With pressure-controlled ventilation methods, the flow the machine uses during the inspiratory time decelerates, it starts very fast and slows down over the course of the inspiratory time. However, with volume-controlled methods, the machine uses a high, constant flow throughout the whole inspiratory time. As resistance is proportional to flow (laminar flow is linearly proportional and turbulent flow is exponentially proportional), if we have to ventilate patients with high airway resistance (newborns), the constant high flow used in volume-controlled modes will result in higher resistance than the decelerated flow used in pressure-controlled modes.[15–17]

In volume-controlled modes, the peak pressure and even the plateau pressure (if the inspiratory pause time is very short, less than 0.2 s) are higher than the maximum pressure obtained in pressure-controlled modes delivering the same volume. However, if we observe the intratracheal pressure in the same newborn we will see quite the opposite: in volume-controlled modes the area underneath the pressure curve inside the lung is smaller than in pressure-controlled modes, as the turbulent flow generated by volume-controlled modes means that it takes a little longer for the pre-tube pressure to become the same as the pressure inside the lung. In contrast, the decelerated flow in pressure-controlled modes makes it possible to overcome high resistance in less time, generating a larger area underneath the pressure curve inside the lungs for the same maximum pressure set at the ventilator. This is only clinically significant when ventilating very small patients (tubes <4.5 mm) and patients with bronchospasm.[15–17]

The other major difference between volume-controlled and pressure-controlled ventilation is found in situations with variable patient leak rates. This can occur quite frequently in paediatric anaesthesia when using uncuffed tubes or supraglottic devices such as laryngeal masks. With variable patient leak rates, pressure-controlled modes are always more useful for ensuring good ventilation because, by definition, pressure will always compensate for leaks no matter how high the leakage rates are, provided the flow generator is powerful enough and, in the case of anaesthesia machines, provided the fresh gas flow supply is higher than the total leak rate.[16,17]

The main drawback of pressure-controlled modes in surgery is that it is impossible to guarantee the tidal volume supplied. This is particularly dangerous in the operating theatre as the child is constantly being manipulated by the surgeon. Any pressure exerted on the child's chest or abdomen will result in a sharp decrease in the tidal volume delivered.[17]

4.2. *Pressure support ventilation (PSV)*

Anaesthesia machines now have a pressure support mode (PSV). This ventilation mode offers operating theatres all the benefits of mechanical ventilation while maintaining the advantages of spontaneous ventilation, which is particularly important in paediatrics (Figs. 5 and 6).

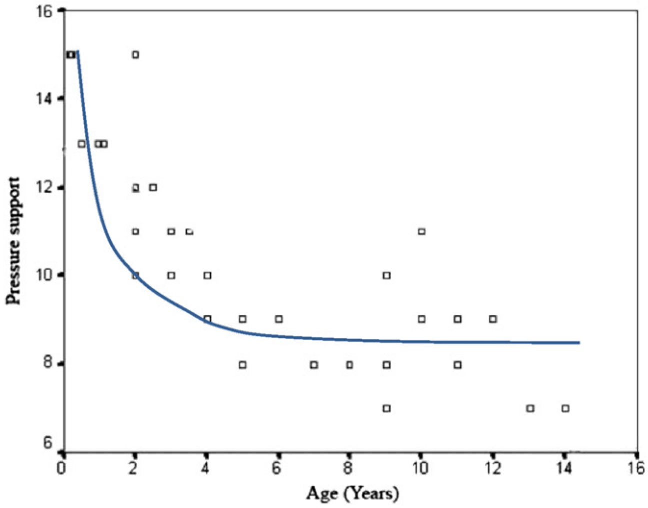

Fig. 5. Pressure support required (cmH_2O) versus age (years): Data obtained from our study published in A&A. 2007 (9). An exponential inversely proportional correlation is observed between pressure support and age ($p < 0.001$).

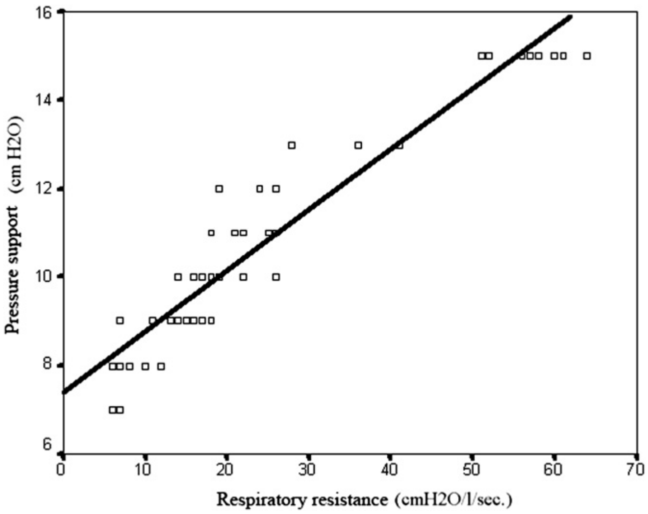

Fig. 6. Programmed support pressure (cmH_2O) versus airway respiratory resistance ($cmH_2O/l/s$) in paediatrics: Data obtained from our study published in A&A. 2007 (9). An inversely proportional correlation is observed between the programmed pressure support and the measured airway resistance, which is statistically significant ($p < 0.001$). At less than 40 $cmH_2O/l/s$ of airway respiratory resistance, the pressure support required is around 10 cmH_2O. Above 40 $cmH_2O/l/s$ of airway respiratory resistance, the pressure support required is around 14 cmH_2O.

We studied 60 patients, scheduled for general outpatient surgery under general anaesthetic combined with a laryngeal mask. Our results showed that the flow trigger is a very safe and effective way to detect respiratory effort, even in the smallest children. One significant finding of our research is that despite the fact that most machines and ventilators offer a range of flow trigger sensitivity settings (from 0.1 to 15 l/min), the most frequently used sensitivity setting in our study was 0.4 l/min, and most importantly, the sensitivity varied very little amongst the patient group (0.2–0.6 l/min). We found no correlation between the flow trigger setting used and the patient's age, weight, compliance, resistance, or respiratory frequency. A good correlation was found between the pressure support used (Group A = 15 cmH_2O, Group B = 10 cmH_2O and Group C = 9 cmH_2O) and the patient's age, weight, dynamic compliance, and particularly with their airway resistance.[9]

We believe that pressure support in outpatient paediatric anaesthesia could easily be set (trigger 1 l/min and pressure support 10 cmH_2O for patients weighing more than 10 kg and trigger 0.5 l/min and pressure support 15 cmH_2O for patients weighing less than 10 kg) based on the age and/or weight of the patient, and that this is the ventilation mode of choice when the surgery type does not exclude the patient from maintaining good spontaneous ventilation.[9]

5. The anaesthetic machine: the circle circuit in children

The key difference between a circle circuit and an open circuit lies in their design and construction. The circle circuit has the following components, which are not included in the open circuit:

- An internal circuit volume of between 4.5 and 8 l, depending on the machine.
- A gas reservoir (bag, below, etc.).
- An overflow valve or pop-off valve.
- A CO_2 canister or absorber.
- A flow generator, separate from the gas inlets (below, piston, turbine, injectors).

These components mean that the circle circuit has a series of features and parameters that must also be taken into account when using this type of anaesthetic workstation:

- Time constant.
- They so-colled "compliance" of the machine, i.e. "compressible volume" of the machine.
- "Compliance" or "compressible volume" compensation systems.
- Fresh gas flow usage rate.
- Leaks.

The internal volume of the anaesthesia machine generates what is known as the "machine compliance", a term used incorrectly to refer to the compressible volume left compressed inside the machine for every cmH_2O of positive pressure generated through mechanical ventilation. This volume is held inside the machine and if it is not compensated for, it reduces the tidal volume that reaches the patient. According to Boyle's Law on the compressibility of gases, 1 ml of tidal volume is lost for every litre of the machine's internal volume and every cmH_2O of pressure reached inside the machine. This can be very dangerous in small children. If, for example, we have to ventilate a child weighing 10 kg with an anaesthetic machine with a "compliance" of 5 ml/cmH_2O, when we set a tidal volume of 100 ml in volume control mode, if the pressure reaches 20 cmH_2O, the volume compressed and trapped inside the machine would be 100 ml, i.e. 100% of the volume set. This would be highly unlikely to occur with adult patients, and of course never happens with open circuit ventilators.[17,18]

To avoid situations like the one outlined above, "anaesthesia machine compliance compensation systems" have been designed. These systems are designed to administer more than the set volume to compensate for the compressed volume trapped inside the machine and to minimise the effect described above. The amount of tidal volume lost in each ventilation depends on how efficient the compensation system is. This is the main reason why anaesthetic machines with inefficient compensation systems in volume control mode hypoventilate patients with low dynamic compliance (children <5 kg).[17,18]

Every time we use a volume-controlled mode with a circle circuit to ventilate a child with a C_{dyn} that is lower than the machine's "compliance" or compressible volume, we run the risk of hypoventilating the patient, causing hypoxemia. In situations like this, if we use a pressure-controlled mode rather than volume-controlled mode and increase the maximum pressure until we reach the correct tidal volume for the child's weight, we can ventilate more safely even if the compensation system does not work properly.[17,18]

6. Lung-protective ventilation in paediatrics

6.1. Open lung approach (OLA)

OLA strategies are based on the physiological principle that opening up the highest possible number of alveoli means that the overall respiratory work is spread out more uniformly between all of them. As a result, mechanical ventilation will cause the least possible lung damage. As such, OLA is split into two essential stages, and it makes absolutely no sense to carry out one without the other. The first stage is to open up the lungs using recruitment manoeuvres (RM), followed by a second stage of manoeuvres to prevent the lungs from collapsing again, basically by setting the right PEEP so that the alveoli are kept open.[19,20]

6.2. Recruitment manoeuvres in children

The key rule of alveolar recruitment is that the higher the maximum pressure reached, and the longer that pressure is left to exert itself, the more alveoli will be recruited. However, there are drawbacks in that the higher the pressure, the higher the risk of direct barotrauma, and the longer that pressure is maintained, the greater the haemodynamic repercussions of the recruitment manoeuvre, and this is particularly problematic in paediatric patients. Given these four basic principles of lung recruitment manoeuvres, we must be flexible, adapting the maximum pressures reached and the length of time they are maintained to the characteristics of each patient.[19,20]

Another important point to take into account with RM is that the pressure that opens the lungs is not the PEEP, but the maximum pressure reached. The PEEP can only prevent re-collapse once the alveoli have been opened using RM. This is because there is always a minimum pressure required to open the alveoli. This pressure is known as the critical opening pressure, and depends on the physical condition of the alveoli.[21]

Generally speaking, although we need to adapt to the specific conditions of each lung, in most RM the recommended maximum pressure is 30 cmH_2O for healthy lungs, and up to 40–45 cmH_2O for distressed lungs.[22]

Although there are many possible RM, the most prudent method, and the one with the best risk-benefit ratio in paediatric patients, would be the pressure-controlled ventilation manoeuvre, setting the driving pressure (maximum pressure − PEEP) to 15 cmH_2O, and the PEEP to 5, then increasing it stepwise in 5 cmH_2O increments. With each PEEP increment, we would check the arterial pressure. In this way, we can check the effect it is having and even stop the manoeuvre in time if the arterial pressure drops by more than 20%.[22]

6.3. Manoeuvres to prevent lung re-collapse

The key to keeping the lung open is knowing how to set the lowest possible PEEP that is still high enough to keep the recruited alveoli open. This PEEP is known by various different names (open-lung PEEP, optimal PEEP, etc…). Different methods have been used to calculate this target PEEP. The first of these calculates the PO_2/FiO_2 ratio. Using this method, the target PEEP would be the lowest PEEP capable of maintaining the highest PO_2/FiO_2 ratio after the RM has taken place.[21,22] The most practical and simple method used in operating theatres and critical care units today is to calculate the open-lung PEEP based on dynamic compliance. The open-lung PEEP is the lowest PEEP able to maintain the highest dynamic compliance over time. Today we know that this lung stabilisation point is 4 cmH_2O higher than the collapsed lung PEEP, or the PEEP that leads to a decrease in dynamic compliance after it has reached its peak.[21,22]

6.4. Lung protection strategies

Lung protection strategies are based on the principle of leaving the lung to rest as much as possible to prevent it from being damaged even further by mechanical ventilation. For some years, open-lung strategies and lung protection strategies have been seen as completely opposing, conflicting strategies. Today, we know not only that they are not conflicting strategies, but also that they are complementary.[22]

The two key factors on which lung protection depends are: the driving pressure (<15 cmH_2O) and the use of physiological tidal volumes (6 ml/kg).[22]

The driving pressure is the difference between the plateau or maximum pressure and the PEEP. If it is more than 15 cmH_2O, the patient will be at serious risk of injury caused by mechanical ventilation. Thus, the truly damaging factor is not the maximum plateau pressure reached itself, but the pressure variation to which the alveoli are subjected between each inspiration and expiration, as this causes alveolar over-distension and atelectrauma.[22]

It is clear that in order to protect the lungs we must never exceed the physiological tidal volume of 6 ml/kg when using open circuit ventilators for critical care. When using circle circuit machines that do not compensate for the compressible volume of the patient's circuit and the artificial deadspace of filters, it is important to remember to add (3–4 ml/kg) to the tidal volume to ensure that 6 ml/kg is effectively administered to the patient.[22]

7. Conclusion

The key point that anaesthesiologists, neonatologists, paediatricians and intensivist should remember is that they are all ventilating the same patients, and that the lives of the youngest and most critical patients depend on careful ventilation, whether in the operating theatre or the intensive care unit.

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References

1. Motoyama E. Respiratory physiology. In: Bissonnette B, Dalens B, editors. *Pediatric anesthesia: principles and practice*. New York: McGraw Hill; 2002. p. 45–75.
2. Garcia-Fernandez J. Optimal PEEP – What we can learn from neonates. *Clin Window J*, http://www.clinicalwindow.net/cw_issue_22_art3.htm, 2006;**22**.
3. Flick RP, Sprung J, Harrison TE, Gleich SJ, Schroeder DR, Hanson AC, Buenvenida SL, Warner DO. Perioperative cardiac arrests in children between 1988 and 2005 at a tertiary referral center: a study of 92,881 patients. *Anesthesiology* 2007;**106**:226–37.
4. Gobbo Braz L, Braz JR, Modolo NS, do Nascimento P, Brushi BA, Raquel de Carvalho L. Perioperative cardiac arrest and its mortality in children. A 9-year survey in a Brazilian tertiary teaching hospital. *Paediatr Anaesth* 2006;**16**:860–6.
5. Frerichs I, Schiffmann H, Oehler R, Dudykevych T, Hahn G, Hinz J, Hellige G. Distribution of lung ventilation in spontaneously breathing neonates lying in different body positions. *Intensive Care Med* 2003;**29**:787–94.
6. Pandit PB, Pyon KH, Courtney SE, England SE, Habib RH. Lung resistance and elastance in spontaneously breathing preterm infants: effects of breathing pattern and demographics. *J Appl Physiol* 2000;**88**:997–1005.
7. Kianicka I, Diaz V, Renolleau S, Canet E, Praud JP. Laryngeal and abdominal muscle electrical activity during periodic breathing in nonsedated lambs. *J Appl Physiol* 1998;**84**:669–75.
8. Mellen NM, Roham M, Feldman JL. Afferent modulation of neonatal rat respiratory rhythm in vitro: cellular and synaptic mechanisms. *J Physiol* 2004;**556**:859–74.
9. Garcia-Fernandez J, Tusman G, Suarez F, Soro M, Llorens J, Belda J. Programming pressure support ventilation in pediatric patients in ambulatory surgery with laryngeal mask. *Anesth Analg* 2007;**105**:1585–91.
10. Manczur T, Greenough A, Nicholson GP, Rafferty GF. Resistance of pediatric and neonatal endotracheal tubes: influence of flow rate, size, and shape. *Crit Care Med* 2000;**28**:1595–8.
11. García-Fernández J, Parodi E, García P, Matute E, Álvarez I, Cediel R, Gilsanz F. Clinical actions of subarachnoid sevoflurane administration *in vivo*: a study in dogs. *Br J Anaesth* 2005;**94**:530–4.
12. Barberis L, Manno E, Guerin C. Effect of end-inspiratory pause duration on plateau pressure in mechanically ventilated patients. *Intensive Care Med* 2003;**29**:130–4.
13. Stenqvist O, Sonander H, Nilsson K. Small endotracheal tubes: ventilator and intratracheal pressures during controlled ventilation. *Br J Anaesth* 1979;**51**:375–81.
14. Stenqvist O. Practical assessment of respiratory mechanics. *Br J Anaesth* 2003;**91**:92–105.
15. Gander S, Frascarolo P, Suter M, Spahn DR, Magnusson L. Positive end-expiratory pressure during induction of general anesthesia increases duration of nonhypoxic apnea in morbidly obese patients. *Anesth Analg* 2005;**100**:580–4.
16. Llorens J, Ballester M, Tusman G, Blasco L, García-Fernandez J, Jover J, Belda J. Adaptive support ventilation for gynaecological laparoscopic surgery in trendelenburg position: bringing ICU modes of mechanical ventilation to the operating room. *Eur J Anaesthesiol* 2009;**26**:135–9.
17. Marks JD, Schapera A, Kraemer RW, Katz JA. Pressure and flow limitations of anesthesia ventilators. *Anesthesiology* 1989;**71**:403–8.
18. Reske A, García-Fernandez J, Jaber S. Ventilation performance and mechanics in anesthesia. *Anesth Internat* (in press).

19. Halbertsma FJ, van der Hoeven JG. Lung recruitment during mechanical positive pressure ventilation in the PICU: what can be learned from the literature? *Anaesthesia* 2005;**60**:779–90.
20. Suarez Sipmann F, Böhm SH, Tusman G, Pesch T, Thamm O, Reissmann H, et al. Use of dynamic compliance for open lung positive end-expiratory pressure titration in an experimental study. *Crit Care Med* 2007;**35**:214–21.
21. Barbas CS, de Matos GF, Pincelli MP, da Rosa Borges E, Antunes T, de Barros JM, et al. Mechanical ventilation in acute respiratory failure: recruitment and high positive end-expiratory pressure are necessary. *Curr Opin Crit Care* 2005;**11**:18–28.
22. Tusman G, Böhm S. Prevention and reversal of lung collapse during the intraoperative period. *Best Pract Res Clin Anaesthesiol* 2010;**24**:183–97.