WHAT’S NEW IN VENTILATION?

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Preamble

Anaesthesia equipment has always fascinated me. As a Registrar in the early 1980’s I was lucky enough to work with John Lawrence as he developed the Prince of Wales CPAP / SIMV ICU ventilator – Bird Mk 7a pneumatics driving a bag-in-a-bottle with a CPAP system with two 5 litre reservoir bags! This stimulated what became a life-long interest in ventilation.

By the early 1990’s, international standardisation, medico-legal concerns and the global marketplace ended the use of ‘home-made’ anaesthetic equipment, and my equipment development days were over. Or so I thought!

To my surprise, Ohmeda USA asked my advice with the design and software of a very advanced electronic anaesthetic machine, way ahead of anything else at the time. I spent a week in Madison evaluating how to best implement a full feedback control machine, from user interface considerations through to control algorithms. This was fascinating work. The end result, many years later, was the 7900 ventilator, still the basis for many current GE products.

Since then I’ve helped develop Dräger’s advanced anaesthesia products, including later revisions of the Julian software, the Primus, Zeus and their future products.

With every manufacturer I’ve emphasised the need to keep the user interface simple, intuitive, quick and easy to use and – most importantly – reliable. I’ve encouraged uncluttered graphically-rich screens that utilise familiar icons and display algorithms, such as ‘virtual rotameters’ and the like, rather than a mass of numbers.

At the same time I’ve used the latest machines on a day to day basis, and as a result have had first-hand experience of new and innovative technologies such as electronic gas mixing, Pressure Support ventilation, feedback control of gases and volatile agents, breathing sound simulation, etc.

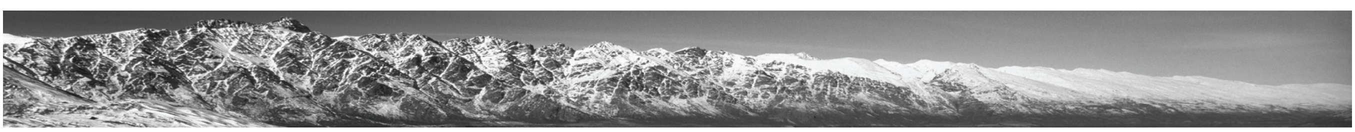
The focus of this talk is how to get the most out of the new ventilators on modern anaesthetic machines, how to compare one machine to another in performance terms, and what kind of user interface elements are most valuable and why.

Development of Anaesthetic Ventilators

Over the last 30 years, anaesthetic machines and ventilators have barely changed, despite significant advances in monitoring and IV therapy. In contrast, ICU ventilation has been through a kind of electronic renaissance over the same period.

Until recently, very few of these ICU features have been made available to the anaesthetist – mostly because anaesthetists told the manufacturers –

- We don’t need any of these ‘advances’ to give a good GA
- Most of my patients are healthy anyway
- If they can’t breathe on the bag, they need intubation
- Rotameters and bellows are essential
- Electronics and computers are unreliable and crash often



- It's safer for me to stick with something I know and understand

As a counter-argument to the above, those who have used ICU ventilation modes on anaesthetic machines might reply –

- Advanced ventilation modes really do make life easier, even with healthy patients
- LMAs and Pressure Support go very well together
- Quite a lot of our patients have worse lung function than we think – and we can now do something about it
- We don't actually need rotameters or bellows anymore
- Electronic machines are very reliable indeed – and far more precise and capable than anything we've used before
- Re-discovering the art of ventilation is possible only if we have the right tools for the job

Advanced Ventilation Capabilities

The following ventilation functionalities should – I think – be present on an advanced anaesthesia machine –

1. High-fidelity, clinically helpful displays
   - On-screen flow and pressure waveforms (+/- loops)
   - Intuitive indication of spontaneous vs controlled breaths
   - Clear indication of current 'mode' of ventilation
   - Clear and obvious indication of leak
   - Sensible and effective alarms
2. An effective Pressure Support / CPAP mode, requiring –
   - Reliable, sensitive detection of inspiration (triggering)
   - High flow capability once triggered (>120 L/min)
   - Rapid, controllable pressure rise to desired set point
   - Rapid drop to CPAP / PEEP pressure on termination
   - Low resistance to expiration
   - Sensible management of apnoea during Pressure Support
3. Integrated flow sensors for tidal volume waveforms, loops and Minute Volume monitoring
4. Real time breathing sound simulation based on actual gas flows –
   - Just like an oesophageal stethoscope
   - Think of it like a pulse oximeter for ventilation!
5. Time-synchronisation of control breaths to spontaneous efforts
   - An effective SIMV algorithm
6. Support for spontaneous efforts in-between control breaths
7. Volume-preset Pressure Control mode
   - Where the anaesthetist sets tidal volume, but machine delivers constant pressure
8. Circuit compliance compensation
   - So that the set tidal volume will actually be delivered
9. Fresh gas flow compensation or fresh gas decoupling
   - So that tidal volume is not affected by changes in fresh gas flow
10. ETT and / or breathing circuit resistance compensation
    - Reduces work of breathing for a given ETT / circuit to near-zero
    - Flow-proportional pressure increase on inspiration and
    - Flow-proportional PEEP / CPAP decrease in expiration
11. PEEP / CPAP optimisation
12. Lung recruitment
13. Completely automatic self-checking and calibration
    - With sensible, easily-understood error messages

Note –
1. A 'feature' that works really well on one machine can be almost useless on another – just because a machine says it has the feature doesn't mean it will work well in practice!
2. That the only way to reliably assess work of breathing is to breathe through a machine yourself, in a variety of modes, ideally in a direct A to B comparison

Pressure Support

Pressure Support is a patient-triggered ventilation mode intended to assist spontaneous respiration and reduce work of breathing. The machine must have sensitive flow sensors and the ability to rapidly start and stop high inspired gas flows of at least 120 L/min. Well-designed pressure support modes make it much easier for a patient to breathe through an anaesthetic circuit and provide a precise (and easily adjusted) amount of respiratory support.

Pressure Support means increasing airway pressure by a set amount as soon as the patient breathes in, and dropping airway pressure back to zero (or PEEP / CPAP pressure) as soon as they breathe out.

Any delay in bumping the pressure up and delivering gas flow quickly to the patient on inspiration is unhelpful, especially for tachypnoeic patients. Hence the machine must be able to sensitively and reliably detect the very start of an inspiratory effort (the 'inspiratory trigger'), and respond immediately with lots of gas flow in reserve to avoid 'flow starving' the patient. Not all machines are equal in this regard.

In general the most sensitive inspiratory triggers use inspiratory flow sensors, the sensitivity of which can be adjusted to avoid false triggering on the heartbeat. A good machine can trigger a 5 kg child on an adult circuit and do a better job in supporting their respiration at 40 breaths/min than you or I could with a T-piece!

The effectiveness of this mode also depends on prompt identification of the end of inspiration, a rapid fall in circuit pressure at that time, and minimal expiratory resistance. Again, these parameters vary significantly from machine to machine.

Effective Pressure Support can reduce the work of breathing in a circle circuit to zero or better than zero. It can almost completely eliminate inadequate ventilation, expiratory effort and see / saw respiration on LMA's, even in quite obese patients, and can be fast enough to support gasping or inadequate respiration even in near-moribund patients or small children. $EtCO_2$ values are invariably lower and work of breathing is reduced.

Pressure Support can be used for induction, maintenance and emergence. It is no longer necessary to squeeze the bag at any stage of the anaesthetic, keeping both hands free for other things. This is especially useful when both hands are needed to get a seal around the mask or when you need to support the patient's respiration at the end of the case, send for the next patient and write up the notes at the same time!

Most Pressure Support modes have some fall-back mode in case of apnoea. They will either revert to a control mode like Pressure Control – and stay there – or stay in Pressure Support and self-trigger at the fall-back rate, switching back to patient-triggering as soon as the patient starts to breathe again. The latter is preferable.

To provide the trigger sensitivity, high peak flows and low expiratory resistance required for optimal Pressure Support, 'hybrid' ICU / anaesthesia breathing systems have been developed. These incorporate ICU-type ventilator components within the circle system. Typically the inspiratory flow delivery device (bellows, piston, or blower) is located just proximal to the inspiratory valve of the circuit, and an ICU-type PEEP / CPAP valve is located just after the expiratory valve – just like an ICU ventilator. Circuits like these can provide much better Pressure Support than the traditional circle system layout.

Typical disadvantages of Pressure Support include –
- A significant learning curve. It takes a while to figure out which patients benefit most, how to assess the benefit in a given patient, how to determine the best settings to use, etc. It took me over two years before I became completely comfortable with using Pressure Support on induction of anaesthesia
- Traditional hand-bagging gives us visual feedback by watching the chest move and tactile feedback from squeezing the bag. In Pressure Support, the bag is not held, so that useful tactile information is no longer available. Instead, information about how stiff the lungs are and / or whether or not there is airway obstruction must be deduced from observation of the flow and pressure curves on a screen. If these

waveforms are available, there are very characteristic flow and pressure appearances for obstruction, ‘stiff lungs,’ etc. However it takes time to become really familiar with these. The utility of the Pressure Support mode in a given ventilator therefore depends not just on performance of the ventilator but also if the user interface provides simultaneous high-fidelity non-auto-scaling flow and pressure curves and whether or not breathing sounds are provided

- The machine be subject to false triggering (if the trigger threshold is too low)
- The machine may fail to trigger (if the threshold is set too high or if the patient becomes obstructed), or be so efficient as to induce cyclical episodes of hyperventilation-induced apnoea
- When the mask is taken off during Pressure Support the ventilator will immediately think that the patient has breathed in, and will dump anaesthetic gas into the room until it empties the bag. It’s best to put the ventilator into a ‘standby’ mode (ie zero gas flow and no support) before adjusting the mask or taking it off the patient to intubate. The ventilator should be able to quickly and easily return from standby back to Pressure Support mode, and to restore all gas flows at the same time. When choosing a new anaesthetic machine, make sure that you can go in and out of standby quickly and easily, otherwise Pressure Support is not going to be much help on induction of anaesthesia

Well implemented Pressure Support provides an incredibly useful addition to our ventilation capabilities. Compared to un-assisted spontaneous respiration you should see obvious improvements in tidal volume, reduced respiratory effort, and improved monitoring. Additionally you should find it much more effective than hand bagging, better at generating CPAP, and very helpful when you want two hands to hold the mask. As an alternative to simple spontaneous respiration it should manage apnoea much better and provide useful alarms for disconnection, hypoventilation, etc.

Poorly implemented Pressure Support is of little benefit to the patient or the anaesthetist and the disadvantages start to outweigh the advantages. If you meet someone who says, “I tried Pressure Support, but it didn’t seem much good!”, ask what type of machine they were using, and how long they have been using it for.

Work of Breathing

Work = Force × Distance. Power / energy consumption is work done per unit time. For spontaneous respiratory effort, energy consumption translates to pressure exerted by the inspiratory muscles × flow generated per unit time.

Greater respiratory effort is needed to breathe through the circuit of an anaesthetic machine.

Inspiratory work can be completely overcome by Pressure Support. Resistance to gas flow through tubes is proportional to flow rate. ‘Proportional assist’ is a new ICU mode in which the amount of pressure support is increased dynamically according to inspiratory flow rate. Combined with pressure support this can make the breathing circuit appear more ‘transparent’ to the conscious patient, especially if they try to take a deeper breath than usual, however simple pressure support is sufficient for almost all anaesthetised patients.

Expiratory resistance adds to work of breathing because greater inspiratory effort is required to get a big enough breath to overcome that resistance. Pressure Support does not reduce expiratory work. Negative PEEP during expiration might seem helpful but isn’t. A kind of reverse proportional assist in which PEEP / CPAP is dynamically reduced in proportion to exhaled flow would completely eliminate expiratory resistance but this is not available on any ventilator that I know of.

With good Pressure Support modes, the improvements in ventilation are obvious (just switch it on and off and compare tidal volumes and patient effort clinically, in good machines its chalk and cheese).

Comparing One Machine to Another

Jaber et al have verified that triggering in the latest anaesthesia machines is comparable to that of modern ICU ventilators.

There are no studies that compare overall work of breathing in Pressure Support mode from one anaesthetic machine to the next.

Pressure Control and Volume Preset Pressure Control (Autoflow) Modes

Control modes of ventilation (IPPV) can be implemented around either fixed inspired volumes (classic IPPV / Volume Control) or fixed inspiratory airway pressure (Pressure Control).

Volume control modes of ventilation are popular with anaesthetists because –

- Tidal volumes are maintained even if lung compliance varies during the case (and it does)
- Circuit integrity can be monitored using simple pressure alarms
- Barotrauma and very abnormal lung compliance are uncommon on routine lists
- 10 ml/kg x 10 is easy to remember

Yet the same classic volume control modes are rarely used in ICU. When using a control mode, intensivists almost always choose Pressure Control because –

- Airway pressures are higher even for breaths of the same volume
- Barotrauma and ventilator associated lung injury are reduced when pressure control is compared to volume control
- Analysis of the inspired flow curve in Pressure Support is helpful in fine-tuning inspiratory time
- Patient comfort is greater with synchronised pressure modes
- Inspired and expired flow monitoring can be used to generate equivalent alarms
- The square pressure wave gives maximal time for long time constant lung units to open (ie is more efficient)

Older anaesthetic machines with Ulco type ventilators had effective alarms in Volume Control modes, but there were no useful tidal volume alarms if the machine was set to pressure cycling. So, historically, a whole generation of anaesthetists were trained to use Volume Control mode for IPPV ventilation.

Now that modern anaesthesia ventilators include integrated flow sensors, they can provide effective minute volume based alarms in Pressure Control modes, making Pressure Control as safe to use as Volume Control.

However basic Pressure Control modes do not guarantee a predetermined tidal volume.

To address this and provide the best of both worlds, some newer ventilators can operate fundamentally in pressure mode but also dynamically adjust the driving pressure on a breath by breath basis to maintain a preset tidal volume. These "volume preset, pressure controlled" modes of ventilation go by several acronyms – PRVC, Autoflow, VC+, etc. Typically the first breath is a standard Volume Control breath, and the plateau pressure from this breath is used for the next Pressure Control breath. The machine then dynamically adjusts the pressure used for each subsequent breath to maintain, on average, the desired tidal volume.

In this mode an abrupt reduction in compliance will cause a fall in tidal volume, followed by an algorithmically-generated increase in driving pressure (as for classical Volume Control IPPV).

Pressure Control and Volume Preset Pressure Control (Autoflow) modes of ventilation are gradually being introduced on newer anaesthesia ventilators and provide a small but incremental improvement in ventilation efficiency. The lower peak airway pressures and improved ventilation efficiency of Volume Preset Pressure Control (Autoflow) modes are particularly helpful during laparoscopies.

Optimising Inspiratory and Expiratory Times

Few anaesthetists give much thought to what the best settings are for inspiratory and expiratory time. In most cases, the manufacturer default of an I:E ratio of 1:2 is used, or an arbitrary adjustment is made.

An I:E ratio of 1:2 approximates the normal value found in spontaneously breathing people. It is not necessarily the best value for ventilated anaesthetised patients.

Normal people unconsciously minimise respiratory work and are not concerned about atelectasis. It would be more work – and usually it would be unhelpful – for a conscious person to hold inspiration for any longer than say two seconds, and at the same time, a long time in relaxed expiration has no particular adverse effects.

On the other hand, anaesthetised supine patients are prone to atelectasis and collapse, and once ventilated by machine they do no work – the machine does it all for them. This means that the 'best' settings for the patient can now be those which optimise lung mechanics even if they require more effort to do so.

In a theoretically 'ideal' lung, all lung units have the same time constant. For such a lung, short inspiratory times would not result in regional V/Q inequalities, because all the alveoli would expand to an equal extent. But in a real lung, especially a middle aged anaesthetised patient, some lung units have longer time constants than others. If a number of slow lung units are not fully equilibrated at the end of inspiration, the distribution of ventilation will be unequal. The resulting V/Q inequalities will lead to an A-a gradient and potentially lung collapse and hypoxaemia.

In most cases the anaesthetised patient can be better ventilated by careful fine-tuning of inspiratory and expiratory times (and obviously the respiratory rate, all three being interconnected). This can only be done with a machine that has a Pressure Control mode and can show inspiratory and expiratory flow curves on-screen.

For most anaesthetised patients an I:E ratio of 1:1 at a rate of 12-14 is probably a much better starting point than the traditional values of 1:2 at a rate of 10.

Using Pressure Control mode, one can be sure that the inspiratory time is long enough when the inspiratory flow curve falls to nearly zero by the end of a inspiration. At this point in time, all lung units, regardless of time constant, will have reached equilibration. Holding the inspiratory time any longer provides no additional benefit in terms of ventilation and may have a negative impact on cardiac output. Any shorter and one risks atelectasis, A-a gradients and potential hypoxaemia.

The same considerations apply to expiratory time. Expiratory time should be long enough for expiration to finish, but no longer. Leaving the patient 'stalled' in expiration without further expiratory gas flow will encourage collapse. On the other hand, if expiration is not complete when the next breath starts, gas trapping and 'auto-peep' will occur, leading to hyperinflation and typically a negative impact on cardiac output.

Consider an obese patient in lithotomy with the following ventilator settings –

- Inspiratory time - 2s
- Expiratory time - 4s
- Rate – 10 breaths/minute
- I:E ratio – 1:2

If that patient fully exhales in one second (a typical value in this situation, because their weight helps push it out faster than normal), what happens to their lungs for the remaining three seconds of that expiratory time? Certainly it doesn't help their ventilation, because no more gas is leaving the lung. All that happens is that their lungs are progressively compressed under the weight of their abdomen. A shorter expiratory time – so that inspiration starts at the exact moment expiration has just finished – will permit a higher respiratory rate, lower tidal volumes, lower airway pressures while retaining overall minute ventilation and FRC.

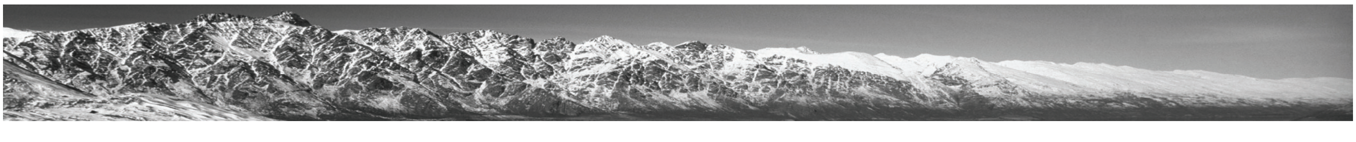
Managing Lung Collapse – Recruitment Manoeuvres

Lung collapse occurs rapidly following induction of anaesthesia, especially when the following are present –

- No N_2 splinting (ie pre-oxygenation, use of nitrous)
- Periods of apnoea at zero PEEP (eg during intubation, induction apnoea)
- Obese or elderly patients
- Head down position
- Absence of appropriate levels of PEEP / CPAP
- Short inspiratory times
- Long expiratory times
- Underlying respiratory disease

It is not uncommon for as much as ½ to ⅓ of a patient's lung volume to become collapsed during induction where muscle relaxants are used to facilitate intubation. This usually goes unrecognised.

Until I started inducing patients with Pressure Support and CPAP I was completely unaware of just how much collapse occurs on induction – and how quickly it happens. What I saw was that the patient's lung compliance would fall abruptly after intubation – due to collapse. In fact, if I just took the mask off and did nothing for 30-40



seconds, lung compliance would fall a great deal. When I did the maths on how much stiffer the lung was, it became apparent that many patients 'lose' nearly a third of their functional lung volume on intubation!

One way to quantify collapse – with a modern ventilator – is to assess lung compliance before and after a recruitment manoeuvre. When I say lung compliance I mean lung plus chest wall or total compliance. The normal units are ml/cmH_2O. Healthy non-anaesthetised patients typically have lung compliance of about 100ml/cmH_2O, but typically under anaesthesia we are accustomed to values more like 50ml/cmH_2O.

Recruitment manoeuvres re-expand collapsed lung. Classically they involve holding airway pressure at between 30 and 45 cmH_2O for say thirty seconds. The magnitude of the improvement in lung compliance after recruitment quantifies the extent of any pre-existing lung collapse. Pressure Control mode can be used for both measurement of compliance and performing recruitment manoeuvres.

The approach I use is to turn the ventilator into Pressure Control mode and then –

- Optimise inspiratory and expiratory times as above
- Set / guess an initial PEEP value
- Select a differential pressure that gives a modest (say 50ml/kg) initial tidal volume
- Increase PEEP in 5 cmH_2O steps, holding each step for say 3-4 breaths
- Keep going up to a PEEP of 20-30, holding there for say 30 seconds
- Stepping the PEEP back down again to the PEEP value that gives the best tidal volume
- Noting the improvement in tidal volume, if any, at each step

This technique not only quantifies the improvement in compliance after recruitment – we can measure the increase in tidal volume for the same differential airway pressure – but it also determines the optimal mechanical PEEP value to use thereafter.

Strategies for maintaining open lungs (aka preventing or treating lung collapse) include regular recruitment manoeuvres, using and optimising PEEP, avoiding apnoea at all times, using Pressure Control mode for ventilation, optimising inspiratory and expiratory times as described above, and maximising circuit nitrogen levels. Should the patient be extubated supine in 100% oxygen they are likely to quickly re-collapse, so consideration should be given to extubating them sitting up, with PEEP on and not in 100% oxygen.

Optimising Ventilator Settings in Different Clinical Situations

Optimising means fine-tuning settings to best achieve a defined outcome.

For instance, to reduce physical trauma to the lung through shear stress, the lung should be recruited, PEEP optimised, a constant-pressure mode of ventilation used, and the ventilation pattern should tend to low-volume higher-frequency settings. Mild hypercapnoea may be acceptable.

If CO_2 elimination is important, rapid respiration with good tidal volumes, even if inspiration or expiration are incomplete or airway pressures are high, will easily solve the problem except if the patient has significant airflow resistance (eg severe asthma).

When airway resistance is a major issue, longer inspiratory and expiratory times and permissive hypercapnoea may be required. If oxygenation is an issue, it's important to clear atelectasis with recruitment, find an optimal PEEP (taking care not to negatively impact cardiac output too much), use a constant-pressure mode of ventilation, and try to ensure that all alveoli, including long-time constant (hypoxic) alveoli, are ventilated effectively. This means that both inspiration and expiration should be long enough in time so that the flow curves fall to zero before the next phase commences.

Phasic – in and out – gas flow during the respiratory cycle will have a net effect on the movement of pulmonary secretions in and out of the lungs. The drag of airflow on secretions is much less at low flows than high flows. Keeping flows low (ie constant) on inspiration while allowing high expiratory peak flows on expiration will cause elimination of sputum; doing the opposite just blows the spit back in.

From the above it can be seen that there really is an 'art' to ventilation. This has largely been lost on anaesthetists because our equipment has not given us the tools to 'see' what we are doing. With the newer machines, we can regain that sense of enthusiasm and control when dealing with patients with sick lungs.

A Short Note About Gas Consumption

In any gas-driven bellows-type ventilator gas consumption must at least equal the patient's minute volume. If a venturi is used (eg Ulco Campbell) at least 50% more is required. Ten litres/minute of drive gas for five hours a day, five days a week, 50 weeks a year equals 750,000 litres of oxygen per machine – in addition to fresh gas flow. In contrast, zero gas consumption for an electrically driven piston or turbine. This is partly why Dräger have moved away from bag and bottle type gas driven ventilators.

References

1. Jaber S, Tassaux D, Sebbane M, Pouzeratte Y, Battisti A, Capdevila X, Eledjam JJ, Jolliet P. Performance characteristics of five new anesthesia ventilators and four intensive care ventilators in pressure-support mode: a comparative bench study. Anesthesiology 2006; 105(5): 944-52
2. Bourgain JL, Billard V, Cros AM. Pressure support ventilation during fibreoptic intubation under propofol anaesthesia. British Journal of Anaesthesia 2007; 98(1): 136-40
3. Brimacombe J, Keller C, Hormann C. Pressure support ventilation versus continuous positive airway pressure with the laryngeal mask airway: a randomized crossover study of anesthetized adult patients. Anesthesiology 2000; 92(6): 1621-3
4. von Goedecke A, Brimacombe J, Hormann C, Jeske HC, Kleinsasser A, Keller C. Pressure support ventilation versus continuous positive airway pressure ventilation with the ProSeal laryngeal mask airway: a randomized crossover study of anesthetized pediatric patients. Anesthesia & Analgesia 2005; 100(2): 357-60
5. Banchereau F, Herve Y, Quinart A, Cros AM. Pressure support ventilation during inhalational induction with sevoflurane and remifentanil in adults. European Journal of Anaesthesiology 2005; 22(11): 826-30
6. Bosek V, Roy L, Smith RA. Pressure support improves efficiency of spontaneous breathing during inhalation anesthesia. Journal of Clinical Anesthesia 1996; 8(1): 9-12