Mechanical ventilation. Part II: Basic principles and function of ventilators.

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■ Mechanical ventilation.
Part II: Basic principles and function of ventilators.

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■ Μηχανικός αερισμός των πνευμόνων.
Μέρος ΙΙ: Βασικές αρχές και λειτουργία των αναπνευστήρων.

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ABSTRACT. Mechanical ventilation is the process of supporting respiration by manual or mechanical means. When normal breathing is inefficient or has stopped, mechanical ventilation is life-saving and should be applied at once. The ventilator increases the patient's ventilation by inflating the lungs with oxygen or a mixture of air and oxygen. Ventilators play an important role in the anaesthetic management of patients, as well as in the treatment of patients in the ICU. However, there are differences between the anaesthetic ventilators and the ventilators in ICU. The main indication for mechanical ventilation is difficulty in ventilation and/or oxygenation of the patient because of any respiratory or other disease. The aims of mechanical ventilation are to supply adequate oxygen to patients with a limited vital capacity, to treat ventilatory failure, to reduce dyspnoea and to facilitate rest of fatigued breathing muscles. Depression of the central nervous system function is a pre-requirement for mechanical ventilation. Some times, opioids or muscle relaxants can be used in order to depress patient's breathing. Mechanical ventilation can be applied using many different modes: assisted ventilation, controlled ventilation, continuous positive pressure ventilation, intermittent positive pressure ventilation and jet ventilation. Furthermore, there are different types of automatic ventilators built to provide positive pressure ventilation in anaesthetized or heavily sedated or comatose patients: manual ventilators (Ambu-bag), volume-controlled ventilators with pressure cycling, volume-controlled ventilators with time cycling and pressure-controlled ventilators. In veterinary practice, the ventilator should be portable, compact and easy to operate. The controls on most anaesthetic ventilators include settings for tidal volume, inspiratory time, inspiratory pressure, respiratory rate and inspiration: expiration (I:E) ratio. The initial settings should be between 10-20 ml/kg for tidal volume, 12-30 cmH$_2$O for the inspiratory pressure and 8-15 breaths/min for the respiratory rate. Mechanical ventilation is a very important part of treatment in the ICU, but many problems may arise during application of mechanical ventilation in critically ill patients. All connections should be checked in advance and periodically for mechanical problems like leaks. Moreover, complications like lung injury, pneumonia, pneumothorax, myopathy and respiratory failure can occur during the course of mechanical ventilation causing difficulty in weaning.

Keywords: function, principles, ventilators

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ΠΕΡΙΛΗΨΗ. Ο μηχανικός αερισμός είναι η διαδικασία με την οποία υποστηρίζεται η αναπνοή χειροκίνητα ή μηχανικά. Όταν η αυθόρμητη αναπνοή είναι ανεπαρκής ή έχει σταματήσει, ο μηχανικός αερισμός αποτελεί τη θεραπεία που θα σώσει τη ζωή του ζώου και πρέπει να εφαρμόζεται αμέσως. Ο αναπνευστήρας αυξάνει τον αερισμό του ασθενούς με τη διοχέτευση οξυγόνου ή μείγματος αέρα και οξυγόνου στους πνεύμονες. Οι αναπνευστήρες διαδραματίζουν σημαντικό ρόλο στο πλαίσιο της αναισθητικής διαχείρισης των ασθενών, αλλά και στη θεραπεία τους στη Μονάδα Εντατικής Θεραπείας (ΜΕΘ). Ωστόσο, υπάρχουν διαφορές ανάμεσα στους αναισθητικούς αναπνευστήρες και στους αναπνευστήρες που χρησιμοποιούνται στη ΜΕΘ. Η κύρια ένδειξη για την εφαρμογή μηχανικού αερισμού είναι η δυσχέρεια στον αερισμό ή/και την οξυγόνωση του ασθενούς, λόγω παθήσεων του αναπνευστικού συστήματος ή λόγω άλλων παθήσεων. Οι στόχοι του μηχανικού αερισμού είναι η παροχή επαρκούς οξυγόνου στους ασθενείς με μειωμένη ζωτική χωρητικότητα, η αντιμετώπιση της αναπνευστικής ανεπάρκειας, η μείωση της δύσπνοιας και η ανακούφιση των αναπνευστικών μυών που βρίσκονται σε κόπωση. Η καταστολή της λειτουργίας του κεντρικού νευρικού συστήματος αποτελεί προϋπόθεση για το μηχανικό αερισμό. Οπιοειδή ή μυοχαλαρωτικά μπορεί να χρησιμοποιηθούν για την καταστολή της αναπνοής του ασθενούς. Ο μηχανικός αερισμός μπορεί να εφαρμοστεί με διάφορους τρόπους: ως υποβοηθούμενος αερισμός, ελεγχόμενος αερισμός, συνεχής αερισμός θετικής πίεσης, διαλείπων αερισμός θετικής πίεσης και υψίσυχνος αερισμός. Επιπλέον, υπάρχουν διαφορετικοί τύποι αυτόματων αναπνευστήρων που παρέχουν αερισμό με θετική πίεση σε αναισθητοποιημένους ασθενείς ή σε ασθενείς που βρίσκονται σε καταστολή ή σε κωματώδη κατάσταση, όπως οι χειροκίνητοι αναπνευστήρες (αυτο-αναπληρούμενος ασκός), οι αναπνευστήρες ελεγχόμενης πίεσης, των οποίων η λειτουργία βασίζεται στην πίεση (ο τερματισμός της εφαρμογής θετικής πίεσης γίνεται με βάση την πίεση), οι αναπνευστήρες ελεγχόμενου όγκου, των οποίων η λειτουργία βασίζεται στο χρόνο (ο τερματισμός της εφαρμογής θετικής πίεσης γίνεται με βάση το χρόνο), και οι αναπνευστήρες ελεγχόμενης πίεσης. Στην κτηνιατρική πράξη, ο αναπνευστήρας κατά προτίμηση είναι φορητός, συμπαγής και ο χειρισμός του πρέπει να είναι εύκολος. Οι ρυθμίσεις στους περισσότερους αναισθητικούς αναπνευστήρες αφορούν τον όγκο αναπνοής, το χρόνο εισπνοής, την εισπνευστική πίεση, την αναπνευστική συχνότητα και την αναλογία εισπνευστικής προς εκπνευστική φάση (I:E). Οι αρχικές ρυθμίσεις συνήθως είναι: για τον όγκο αναπνοής 10-20 ml/kg, για την εισπνευστική πίεση 12-30 cmH$_2$O και για την αναπνευστική συχνότητα 8-15 αναπνοές/min. Ο μηχανικός αερισμός είναι ένα πολύ σημαντικό μέρος της θεραπείας στη ΜΕΘ, αλλά κατά τη διάρκεια της εφαρμογής του σε βαρέως πάσχοντες ασθενείς είναι πιθανόν να εμφανιστούν πολλά προβλήματα. Μηχανικά προβλήματα, όπως διαρροές, μπορεί να προκύψουν και για αυτό οι αναπνευστήρες πρέπει να ελέγχονται εκ των προτέρων και περιοδικά. Επιπλέον, παθολογικές καταστάσεις όπως τραυματισμός του πνεύμονα, πνευμονία, πνευμοθώρακας, μυοπάθεια και αναπνευστική ανεπάρκεια μπορεί να εμφανιστούν κατά τη διάρκεια του μηχανικού αερισμού και να καταστήσουν προβληματική την αποσύνδεση από τον αναπνευστήρα.

Λέξεις ευρετηρίασης: αναπνευστήρες, αρχές, λειτουργία

INTRODUCTION

Mechanical ventilation is the act of assisting or controlling the patient's breathing by the use of a machine driven or hand-operated device (Battaglia and Shawver 2007). Mechanical ventilation supports respiration by manual or mechanical means when normal breathing is inefficient or has stopped (Tol and Palmer 2010). The main aim of mechanical ventilation is to generate flow and volume and, as a result, to provide adequate alveolar ventilation with the minimal work of breathing (Grasso 2011). The application of positive pressure to patient's airway opening during inspiration is the main method to assist breathing and restore adequate ventilation. Moreover, the ventilator should have some means by which it "decides" when to stop the process of the inflation of the lungs (inspiration), thus allowing expiration, and when to re-initiate inflation (Mushin et al. 1980). Ventilators apply such sequential respiratory cycles and, as a result, they provide efficient breathing. Furthermore, the venti-

lators are able to overcome the effects of breathing system compliance and gas compression on tidal volume (Dorsch and Dorsch 2008).

Ventilators play an important role in the anaesthetic management of patients, as well as in the treatment of patients in the Intensive Care Unit (ICU), as they provide artificial support of respiratory function (Richard et al. 2002, Hopper et al. 2007, Richard and Kacmarek 2009, Thille et al. 2009). There are differences between the ventilators used in anaesthesia and those used in the ICU. The main difference between the two types of ventilators is that the ICU ventilators can deliver higher inspiratory pressures and flows than the anaesthesia ventilators (Mushin et al. 1980, Gravenstein et al. 1987, Tung et al. 2005). Moreover, the ICU ventilators are usually capable of administering a mixture of air and oxygen, while anaesthetic ventilators do not usually provide this option. On the other hand ICU ventilators do not facilitate administration of inhalant anaesthetic drugs.

One of the main principles of ICU ventilators is to maintain adequate gas exchange, while avoiding re-opening of damaged alveoli and distension of healthy alveoli (Stewart et al. 2011). Depression of the central nervous system function (comatose or heavily sedated/anaesthetized animal) is a prerequisite for mechanical ventilation. Some times, muscle relaxants and/or opioids may be used in order to depress patient's breathing and thus avoid spontaneous breathing against the ventilator (Drellich 2002).

Indications for mechanical ventilation

Critically ill patients with or without pulmonary compromise may require mechanical ventilation. The main indication for mechanical ventilation is difficulty in ventilation and/or in oxygenation of the patient. Trauma in thoracic wall or any other respiratory disease (e.g. lung injury, pneumonia, pulmonary oedema, pulmonary haemorrhage) can affect the normal breathing pattern (Battaglia and Shawver 2007, Hopper et al. 2007, Haskins 2011b). The objectives of mechanical ventilation are to minimize the work of breathing and to reverse the hypoxaemia or acute respiratory acidosis. In particular, the aims of mechanical ventilation are to supply adequate ventilation and oxygenation in patients with a limited vital capacity, to treat ventilatory failure, to reduce dyspnoea and to facilitate rest of fatigued breathing muscles (Sykes et al. 1976, MacIntyre 1986, Hopper et al. 2007).

Hypoxaemic patients ($PaO_2 < 60$ mmHg) need ventilatory support. The efficiency of gas exchange can be further assessed by the calculation of two different indexes: the alveolar-arterial gradient (A-a) and the PaO_2/FiO_2 ratio. The (A-a) gradient is calculated by the following equation: $P(A-a) = PAO_2 - PaO_2 = [(PB - PH_2O) FiO_2 - PaCO_2/R] - PaO_2$, where PB is the barometric pressure (usually 760 mmHg), PH_2O is the partial pressure of water vapor at the patient's body temperature (49-50 mmHg), FiO_2 is the fractional inspired concentration of oxygen and R is the respiratory quotient (the ratio of oxygen consumption to CO_2 production, 0.78-0.92 in dogs, usually 0.8). When FiO_2 is 0.21 (the patient is breathing room air), the (A-a) gradient should normally be less than 10 mmHg, whereas when FiO_2 is 1 (the patient is breathing pure oxygen), it should be less than 100 mmHg. The PaO_2/FiO_2 ratio should normally be more than 400 mmHg. Values less than 300 mmHg indicate inef-ficient gas exchange and less than 200 indicate acute respiratory distress syndrome and necessitate mechanical ventilation (Sorrell-Raschi 2009).

In some patients, hypercapnia occurs without hypoxemia ($PaCO_2 > 60$ mmHg) because of hypoventilation. Hypoventilation is inadequate minute ventilation and it causes not only hypercapnia but, also, acidosis (pH < 7.2) (Drellich 2002). Hypoventilation occurs when spontaneous breathing becomes depressed because of 1) drugs administered therapeutically (anaesthetic agents), 2) disease of the central or peripheral nervous system, 3) obstructive upper or lower airway disease and 4) pleural space problems. Persistent hypoventilation can lead to hypoxaemia. This happens because the volume of fresh gas delivered to the alveoli is not adequate to provide the necessary oxygen to maintain the PaO_2 (Sykes et al. 1976, Mushin et al. 1980, Battaglia and Shawver 2007, Drellich 2002, Hopper et al. 2007). In critically ill patients, compensatory hyperventilation frequently occurs in an attempt to avoid hypoxemia and this may result to hypocapnia. Mechanical ventilation may be beneficial for those patients. Additionally, neurological issues or damage of peripheral nerves due to structural or metabolic factors can cause mechanical hypoventilation (MacIntyre et al. 2001). Hormones, nutrition and electrolytes can, also, influence ventilatory muscle function. For example, inadequate nutrition may lead to protein catabolism and a loss of muscle performance. Finally, in humans, there are physiological non-respiratory factors, like stress of the staff, the patient or the family, which can lead to ventilator dependence (MacIntyre et al. 2001).

The components of a ventilator

The ventilator consists of the driving gas supply, the controls, the alarms, the bellows, the housing, the two valves (the spill and the exhaust), the ventilator hose connection and the positive end-expiratory pressure valve (Ward 1975, Dorsch and Dorsch 2008). Firstly, the driving gas can be air, oxygen or a mixture of oxygen and air. A sufficient amount of pressurized driving gas is required to activate the bellows (Szpisjak et al. 2005). Moreover, the controls regulate the volume, the flow, the pressure and the timing of the bellows compression.

An important component of the ventilator is the bellows. Most of the bellows are made of rubber and

there are two types of them: ascending and descending. The ascending bellows is compressed downwards during inspiration and it expands upwards during expiration. At the end of expiration, the pressure in the bellows rises up to 2-4 cmH$_2$O and the spill valve opens (Mushin et al. 1980, Hammond 2007, Dorsch and Dorsch 2008). On the other hand, a ventilator with descending bellows is compressed upwards during inspiration and it re-expands downwards during expiration. Whatever the type of bellows, it is contained in a clear plastic cylinder (canister), where there is a volume scale in order to estimate the delivered tidal volume. This is called housing. Moreover, the clear plastic canister allows the bellows' movement to be observed (Ward 1975, Dorsch and Dorsch 2008). It is important to note that if there is a disconnection or leak in the breathing system, then the bellows will eventually collapse. However, the ventilator may continue functioning for some period of time, but delivering inadequate tidal volumes (Gravenstein and Nederstigt 1990).

As already mentioned, there are two valves on a ventilator, the spill and the exhaust valve. The spill is used to drive the excess respired gases into the scavenging system. It is closed during inspiration and it remains closed until the bellows is completely extended and then the valve opens to vent excess breathing system gases. The exhaust valve is closed during inspiration and it opens during expiration in order to allow the driving gas inside the housing to be exhausted to the atmosphere. Exhaust valves are used in pneumatically powered ventilators, whereas in piston ventilators, there is no exhaust valve. There is a connector between the ventilator and the breathing system. In the newest models of ventilators, the connections are internal so as to minimize the possibility of misconnections or disconnections (Ward 1975, Sykes et al. 1976, Hammond 2007, Dorsch and Dorsch 2008).

Finally, ventilators incorporate a positive end-expiratory pressure (PEEP) valve, so as to allow improvement of oxygenation by prevention of alveolar collapse; it can be used either in spontaneous or controlled ventilation. A manually controlled valve was used in older anaesthesia machines or ventilators. The newer ones have electronically controlled PEEP valves. The PEEP valve should be set up in the proper pressure so as to avoid complications like barotrauma (Ward 1975, Sykes et al. 1976, Hammond 2007, Dorsch

and Dorsch 2008).

The connection between the breathing system and the ventilator

The ventilator has the role of the reservoir bag in a breathing system (Hartsfield 1999). Most anaesthesia ventilators have a bellows, which is kept in a pressure chamber and is connected to the breathing system. The bellows connects the breathing system with the ventilator driving gas. The bellows plays a major role during inspiration and expiration. The bellows is compressed at a specified rate and volume by the driving gas. The driving gas is delivered into the space between the bellows and its container and it triggers the compression of the bellows and the administration of the fresh gas into the breathing system. Simultaneously, the spill and the exhaust valves are closed (McKelvey and Hollingshead 2003, Dorsch and Dorsch 2008).

Guidelines for mechanical ventilation

In most ventilators, the delivered tidal volume and the respiratory frequency are the two main determinants of the patient's ventilation (Mushin et al. 1980). The principal factors affecting the delivered to the patient tidal volume are 1) the fresh gas flow, 2) the compliance and the compression volumes of the lungs and 3) the leaks of the circuit. First of all, alterations in the fresh gas flow in the inspiratory/expiratory (I:E) ratio or in the respiratory rate influence the delivered tidal and minute volumes. The I:E ratio should be 1:2 or less for mechanical ventilation (Hartsfield 1999, Singer and Corbridge 2009). The measurement of the expired fresh gas flow is a better method than the measurement of the inspired fresh gas flow as any leakage between the measurement point and the patient will be smaller and will result to an underestimate than an overestimate of the tidal volume (Mushin et al. 1980). Furthermore, any change in compliance affects the tidal volume. In particular, a decrease in compliance of the breathing system can result in an increase in tidal volume (Mushin et al. 1980). Finally, a leak in the endotracheal tube or in the device will, also, affect the tidal volume (Ward 1975, Mushin et al. 1980, Dorsch and Dorsch 2008). In mechanical ventilation, the tidal volume is greater than the tidal volume in spontaneous breathing and it is initially set to 10-20 ml/kg in small animals (Hartsfield 1999).

Automatic ventilators: their role

Automatic ventilators provide intermittent positive pressure ventilation (IPPV) in anaesthetized or heavily sedated or comatose patients. An anaesthetic ventilator is a reservoir bag in a closed container that can substitute for the reservoir bag of an anaesthetic breathing system. The anaesthetic ventilator performs the same task as an anaesthetist who periodically squeezes the reservoir bag of the circle system, so as to ventilate the patient. Some ventilators are separate units that can be attached to an anaesthetic unit and other ventilators are manufactured as a part of an anaesthetic machine (Ward 1975, Sykes et al. 1976, Hartsfield 2007, Dorsch and Dorsch 2008).

Classification of mechanical ventilation

There are different types of mechanical ventilation that can be used during ventilatory support. First of all, there is the *controlled ventilation* and the *assisted ventilation* (Marino 1998).

In controlled ventilation there is a complete control of all ventilatory activity. The ventilator initiates inspiration and a preset respiratory rate is maintained. Frequency, tidal and minute volumes are set by the user. This type of ventilation is important when the patient is unable to initiate an effective respiration. On the other hand, in assisted ventilation, the target of the anaesthetist is to synchronize the compression of the breathing bag with the animal's spontaneous breathing (Hartsfield 1999). Modern ventilators are capable of augmenting the ventilation produced by the animal's spontaneous breaths, as the ventilator assists each breath, which is initiated by the animal.

Moreover, ventilation could, also, be applied as *continuous positive-pressure ventilation*. This ventilation involves applying positive pressure for every breath as the animal cannot breath spontaneously (Hartsfield 1999, Battaglia and Shawver 2007, Stefanopoulou 2009). *Positive end-expiratory pressure (PEEP)* is maintained in the lungs during the expiratory phase of mechanical ventilation. In particular, this pressure is maintained slightly higher than the atmospheric pressure during expiration. The main effect of application of this pressure is the prevention of collapsing of the small airways and the alveoli. Moreover, PEEP causes an increase in functional residual capacity. However, the application of PEEP in mechanical ventilation is not devoid of negative

consequences, which pertain to the circulatory system; it can cause a decrease in venous return and cardiac output (Singer and Corbridge 2009). In contrast, *continuous positive airway pressure (CPAP)* is the maintenance of positive pressure above the ambient pressure during ventilator-assisted spontaneous breathing. In other words, CPAP is the application of a preset positive pressure during the entire breathing cycle. In this type of ventilation, the operator sets a predetermined pressure and all breaths are spontaneously triggered and ventilator supported (Tol and Palmer 2010). The main indications for CPAP, in humans, are chronic obstructive disease and asthma (Hartsfield 1999, Battaglia and Shawver 2007, Tol and Palmer 2010).

Intermittent positive-pressure ventilation (IPPV) is a type of ventilatory support in which mandatory positive pressure breaths are delivered at preset time intervals. It is used for animals that have a depressed respiratory pattern especially during an operation under general anaesthesia. The respiratory rate, the tidal volume, the maximum airway pressure and the I:E ratio are all set and, in this mode, a fixed minute ventilation is delivered, but animals need to be deeply sedated and sometimes paralyzed in order to avoid asynchrony with the ventilator (Hartsfield 1999, McKelvey and Hollingshead 2003, Battaglia and Shawver 2007, Tol and Palmer 2010).

Lastly, *jet ventilation* is a mode of ventilatory support, used for maintaining oxygenation when a definitive airway is absent. The oxygen supply is directed through a cannula attached to an endoscope via an intra-tracheal catheter or via a cannula inserted through the cricothyroid membrane. Jet ventilation provides oxygenation in emergency situations in which the animal cannot be intubated and should be considered as temporary management (Tol and Palmer 2010).

Common types of ventilators

The automatic ventilators can be classified in many different ways. The kind of power source, drive mechanism, cycling mechanism and the type of bellows are some of the criteria that have been used for the classification of the ventilators. Electricity, compressed gas or both can be used as the power source. Anaesthetic ventilators are described according to the way that the gas flow is delivered to the patient and are,

therefore, categorized in pressure-controlled and volume-controlled ventilators. In pressure-controlled ventilators, flow is supplied at a preset maximum pressure which will not be exceeded, but the tidal volume delivered may vary, while in volume-controlled ventilators, the preset tidal volume will be delivered and the pressure necessary to deliver this volume may vary (Ward 1975, Sykes et al. 1976, Mushin et al. 1980, Chatburn 1992, Dorsch and Dorsch 2008, Stefano-poulou 2009). Moreover, another characteristic of ventilators is cycling. Cycling describes the method of transition from inspiratory to expiratory phase. Most of the times, a timing mechanism plays a major role in the function of the ventilator (e.g. volume-controlled ventilators with time cycling) and volume or pressure limits (e.g. volume-controlled ventilators with pressure cycling) may affect the change in respiratory cycle from inspiration to expiration (Hartsfield 1999, Hartsfield 2007, Battaglia and Shawver 2007, Hammond 2007, Chatburn 2010).

Manual ventilators

Manual ventilators (ambu) are manual compression bags, which can be connected to an endotracheal tube. These ventilators can be used in short-term ventilation or in cardio-pulmonary resuscitation. Furthermore, because of the manual operation, the volume delivery and the fraction of inspired oxygen are not accurately controlled and, therefore, their use is limited (Battaglia and Shawver 2007).

Volume-controlled ventilators with pressure cycling

The main characteristic of these ventilators is that the delivered flow is constant during the inspiration and the inspiration is terminated when a pre-defined pressure is achieved (Chatburn 1992, Chatburn 2010). Any resistance in the system does not affect the delivered volume (Sykes et al. 1976, Battaglia and Shawver 2007). Moreover, there is a control in these ventilators, which regulates the amount of pressure delivered to the patient's lungs and ventilator system. The duration of inspiration is controlled by the peak inspiratory pressure. The pressure of the delivered gas is not stable and there is a relation with the compliance of the lungs. Gas flow, airway resistance, compliance of both the lungs and the chest wall and the nature of the delivered gases affect the airway pressure, which increases during inspiration and, therefore, a constant flow is maintained (Marino 1998, Battaglia and Shawver 2007,

Dorsch and Dorsch 2008). In these ventilators, only the cycling pressure and the inspiratory rate can be set, but not the tidal volume (Hammond 2007).

Advantages and disadvantages

First of all, the tidal volume is fixed. In animals with normal airways, when the cycling pressure is set to 15-20 cmH_2O, the correct tidal volume should be provided. Moreover, in patients with respiratory problems where the compliance of the lungs and the resistance of the airways are abnormal, a high airway pressure cycling can be set. As the tidal volume is stable, the ventilator's settings do not change and it still works at the same pressure in pathological situations (lung lobe removal, one lung ventilation). Thus, the lung can be protected from over-inflation. Finally, volutrauma is less likely to occur, as the tidal volume is stable and the airway pressure is the main setting (Sykes et al. 1976, Battaglia and Shawver 2007). On the other hand, the main disadvantage is that the tidal volume may not be adequate, especially in animals with abnormal airways (Battaglia and Shawver 2007).

Volume-controlled ventilators with time cycling

These ventilators are characterized by the constant delivered flow during inspiration, which terminates when the pre-determined tidal volume is reached (Sykes et al. 1976, Chatburn 1992, Chatburn 2010). Moreover, the anaesthetist sets the tidal and minute volumes and the ventilator drives them independent of animal's effort. In these ventilators, in contrast with the pressure-limited ventilators, the inspiratory pressure does not affect the duration of inspiration (Ward 1975, Sykes et al. 1976).

Advantages and disadvantages

This type of ventilators is very simple, as the anaesthetist sets the appropriate tidal volume, even if changes in resistance and compliance occur during anaesthesia (i.e. mucus in the endotracheal tube can reduce internal diameter and the resistance can be increased). In such cases, the airway pressure is increased in order to maintain the fixed flow (Ward 1975, Mushin et al. 1980, Marino 1998, Hartsfield 2007). However, this type of ventilator is not appropriate for animals weighing less than 5 kg, as it is difficult to set the proper tidal volume, which may be extremely harmful. Most of the volume-controlled ventilators have a high-pressure valve with a warning sound, which is fixed at pressures between 65 to 80 cm

H$_2$O. These pressures can be harmful in young animals as they can cause volutrauma (Hammond 2007).

Pressure-controlled ventilators

This type of ventilation is rare in veterinary anaesthesia. The delivered pressure remains constant over the period of inspiration. When inspiratory pressure is achieved, flow continues at a gradually reducing rate until the end of inspiratory phase (Stefanopoulou 2009). The termination of the inspiration is controlled by the modification of the inspiratory phase. In pressure-controlled ventilators, flow continues when the pressure is reached, in contrast to the volume-controlled ventilators in which flow stops irrespective of inspiratory phase time. In addition in this type of ventilator, tidal volume is the result of the flow of gas from the ventilator to the patient's lungs over a period of time (Sykes et al. 1976, Battaglia and Shawver 2007, Hammond 2007, Chatburn 2010).

Advantages and disadvantages

The main advantage of the above-mentioned ventilators is the improvement of the inspiratory flow pattern. In volume-controlled ventilators, the inspiratory flow rate is constant, while in pressure-controlled ventilators, the inspiratory flow rate is reduced during lung inflation. This mechanism can decrease peak airway pressures and improve gas exchange. In contrast, their disadvantage is that it is impossible to ensure that the ventilator is indeed delivering proper tidal volumes (Marino 1998, Battaglia and Shawver 2007).

Triggering

In mechanical ventilation, inspiration begins when a trigger reaches a preset value. The trigger variable can be time, pressure, volume or flow (Singer and Corbridge 2009). The two common types of triggering are time- and pressure-triggering. In controlled ventilation, the triggering is the time. In time triggering, the expiratory phase time is set by the user, either directly or indirectly, with a preset I:E ratio and respiratory rate. In particular, the ventilator delivers breaths according to the preset frequency independent of the patient's breathing (Branson 1994, Sassoon and Gruer 1995, Goulet et al. 1997, Hammond 2007, Chatburn 2010). With pressure-, volume- and flow-triggering, the patient initiates a breath and the ventilator delivers gas flow once the preset pressure, volume or flow are

reached (Branson 1994, Sassoon and Gruer 1995, Goulet et al. 1997). With certain modes of ventilation, like assist/control, if pressure- or volume- or flow-triggering do not occur within a pre-defined time period, then time becomes the trigger variable and the ventilator delivers a breath. The pressure-triggering is widely used in ICU, where respiratory muscle paresis, inadequate tidal volume or peripheral alveolar collapse may occur. It is, also, used in situations where hypoventilation should be treated (Hammond 2007).

The characteristics of a veterinary ventilator

The requirements of a ventilator for use in anaesthesia are more basic than those needed in ICU. A second-hand human ventilator or a veterinary ventilator is a good choice. A ventilator should be compact, portable and easy to operate. Moreover, the purchase and the service should be economical. The controls on most anaesthetic ventilators include settings for tidal volume, inspiratory time, inspiratory pressure, respiratory rate and I:E ratio.

Recommendations for the initial settings are: 10-20 ml/kg for tidal volume and 12-30 cm H$_2$O for inspiratory pressure. The respiratory rate should be set between 8-15 breaths/min. Moreover, the inspiratory time should be as short as possible compared to the expiratory time, so that positive intra-thoracic pressure will minimally affect venous return and cardiac output. Therefore, the I:E ratio should be 1:2 or less (i.e. 1:3), depending on the respiratory rate (Ward 1975, Hartsfield 1999, Battaglia and Shawver 2007, Singer and Corbridge 2009, Hess 2010). The ventilator can be used with non-rebreathing or rebreathing anaesthetic breathing systems. Air, oxygen and all anaesthetics can be used. The ventilator should, also, be capable of humidifying inspired gas. Furthermore, the continuous monitoring of airway pressure and of expired volume is particularly desirable (Ward 1975, Hammond 2007). The safety of the ventilator should, also, be considered. The ventilator should have the ability to maintain output even when leaks develop. Rapid disassembly of the ventilator for easy sterilization should be feasible and the ventilator should, also, contain bacterial filters. Alarms for low pressure, circuit disconnection and high pressure or pressure overload are very useful (Sykes et al. 1976, Mushin et al. 1980, Hartsfield 1999, Hammond 2007, Hartsfield 2007).

Weaning the patient from mechanical ventilation

Weaning from mechanical ventilation refers to

gradual disconnection of the patient from the ventilator. In particular, weaning describes the process by which artificial ventilation is gradually withdrawn and the patient returns to normal spontaneous respiration. In human literature, weaning, also, refers to "liberation" from a noxious and dangerous condition (Schmidt and Hall 2005, Singer and Corbridge 2009). Weaning from IPPV after short periods of intra-operative ventilation is less of a challenge than weaning after prolonged ventilation of the critically ill patient in the ICU, a situation in which the respiratory function may be suppressed (Hammond 2007). Weaning from the ventilator should not be delayed for more than the period that mechanical ventilation is necessary. Otherwise, the delayed discontinuation of mechanical ventilatory support exposes patients to unnecessary risks of infection, injury, airway trauma, prolonged sedation-anaesthesia, muscle failure and it, also, increases financial costs (MacIntyre et al. 2001, MacIntyre 2004, MacIntyre 2006, MacIntyre 2007). However, definite discontinuation of mechanical ventilation should be performed only after the airway has been secured and adequate gas exchange under conditions of spontaneous breathing has been ensured (MacIntyre 2004). In human medicine, it has been reported that 42% of the time that a patient spends on a mechanical ventilator is during the discontinuation process (MacIntyre et al. 2001, MacIntyre 2004, MacIntyre 2007). The patient may be disconnected from the ventilator and ventilated by squeezing the reservoir bag of a breathing system at a reduced rate, until spontaneous ventilation returns (Hammond 2007). In veterinary clinical practice, multiple ventilator modes, such as pressure support and synchronized intermittent mandatory ventilation, can be used in order to wean a patient off the ventilator support (Hopper et al. 2007, Haskins 2011a). The most common technique used for weaning is the cessation of artificial ventilation for periods of 2-3 minutes, with gradual prolongation of these periods depending on the patient's performance during the last period (Nunn 2000, MacIntyre 2004, Hopper et al. 2007, MacIntyre 2007, Haskins 2011a). Moreover, a reduction of the tidal volume may, also, diminish pulmonary stretch and increase respiratory drive. However, care should be taken in order to avoid alveolar collapse. It should be noted that attempts to wean the patient from the ventilator are not likely to succeed, unless the $PaCO_2$ is allowed to rise to normal or even mildly elevated levels. This aim is accomplished by a reduction in the minute ventilation (reduction in tidal volume or reduction in respiratory rate or reduction in both). In anaesthetic practice, the weaning from mechanical ventilation is performed at the end of a surgery, as the surgical stimulus and the depth of CNS depression are minimized (Schmidt and Hall 2005, Hammond 2007). In case of use of muscle relaxant drugs, reversal of their action is a pre-requirement in order for an attempt to wean the patient from mechanical ventilation to be successful. Potent opioids (e.g. fentanyl, remifentanyl) administered via constant rate infusions in high doses may undermine the process of weaning, and their dosage should be, thus, reduced. The animal's breathing pattern is observed and the blood gases are checked (Hopper et al. 2007, Haskins 2011a). Once the patient can breathe spontaneously without labour, extubation can be performed. Blood gases are evaluated after the extubation and oxygen therapy may be necessary in a mildly hypoxic patient. Monitoring of hemoglobin saturation via pulse oximetry during recovery can be very useful (Hartsfield 1999, Schmidt and Hall 2005, Battaglia and Shawver 2007). In conclusion, the best indicators for the probability to successfully wean a patient from the ventilator are proof that the underlying disease has been cured and the affirmation that minimal ventilator settings are required to maintain the "artificial lung" function (Haskins 2011a).

Problems and complications during ventilation

Understanding the function of the ventilator used helps the user to support the patient and solve problems. When machine cycling fails, the first action undertaken should be to check gas and electrical sources. Tanks should be filled and all electrical connections should be confirmed. Leaks (hose connections or cuff of endotracheal tube) are the most common causes of ventilator malfunction, as most of the devices are pressure or volume limited (Battaglia and Shawver 2007). Moreover, secretions, mucous plugs and an improper size of the endotracheal tube can affect the function of the ventilator (Ward 1975, Hartsfield 1999, Hammond 2007, Hartsfield 2007).

Complications can develop during mechanical ventilation. Ventilator-induced lung injury (VILI) is lung damage that can occur as a result of shearing forces stretching the alveoli during mechanical ventilation and is the most common complication of

mechanical ventilation (Ranieri et al. 1999, Gurkan et al. 2003, Singer and Corbridge 2009, Ranieri 2011). Studies in animal models have shown that mechanical ventilation can exacerbate or initiate an inflammatory response, which can lead to VILI. The mechanisms of this inflammatory response are 1) pathologic evidence of neutrophil infiltration, 2) increased cytokine level in lung lavage and 3) increased cytokine level in systemic circulation (Ranieri et al. 1999). Ventilator-induced lung injury can be distinguished into volutrauma (alveolar over-distension by excessive tidal volume), barotrauma (alveolar over-distension because of high pressure settings) and auto-PEEP (high alveolar pressures occur when there is insufficient time for the expiratory phase) (Tol and Palmer 2010). However, clinical trials in small animal medicine have shown that mechanical ventilation with lower tidal volumes, similar to those observed during spontaneous ventilation, may decrease the mortality of patients with VILI (Amato et al. 1998, Stewart et al. 1998, Gurkan et al. 2003). Ventilator associated pneumonia, pneumothorax, pulmonary edema, oral ulceration, corneal ulceration, sepsis and septic shock are complications of mechanical ventilation in dogs and cats (Lee et al. 2005, Hopper et al. 2007, Singer and Corbridge 2009, Haskins 2011b). In addition, the consequences of prolonged sedation/anaesthesia and muscle paralysis, which are necessary for the application of positive pressure ventilation, should be balanced over the benefits of mechanical ventilation in an attempt to avoid serious respiratory distress, myopathy and delayed weaning (Tol and Palmer 2010). Finally, one more severe devastating complication of mechanical ventilation is oxygen toxicity, which histologically resembles ARDS and is caused by reactive oxygen species generated in the lung. Prolonged exposure to high oxygen concentrations can cause oxygen toxicity. It is reported that patients should not be exposed in 100% oxygen for more than 12 hours. The same guideline is recommended in veterinary medicine. Thirty to thirty three percent concentration of inspired oxygen is generally considered safe even for prolonged administration.

CONCLUSION

Mechanical ventilation is an important part in veterinary anaesthesia and ICU. Clear goals for therapy should be established and complications should be taken into consideration and prevented. Weaning from the ventilator may be a difficult process, but it is, also, rewarding. According to a phrase, "if you give it a day, you should give it a week; if you give it a week, you should give it two" (Drellich 2002), it takes time for tissues to heal and regain function and mechanical ventilation provides a means to support life during this time. ▪

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