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Mechanical Ventilator for Respiratory Impaired Persons: A Review

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Abstract-
Mechanical ventilator is one of the most important devices used in anesthesia and intensive care units for generating a regulated flow of gas into a patient's lungs. Oxygen is required by every human to stay alive and in cases where a patient is undergoing an acute respiratory distress, a mechanical ventilator is used to deliver external ventilation which could be generated from a hospital's built in supply system or from a portable oxygen generator. The ventilator is connected to the patient's lungs through an endotracheal tube (ETT) to deliver air by compressing a conventional bag-valve mask (BVM) with a pivoting cam arm, thereby eliminating the need for a human operator. The device also operates by setting some parameters which can be predetermined by clinicians as well as an assist control mode and an alarm to determine when the system is over pressured. The paper focuses on review of Mechanical ventilators, the different modes of ventilation, anatomy tract of the respiratory system, respiratory mechanics, and approaches of ventilation.

1. Introduction

Mechanical ventilators have been in existence for many decades to treat patients with chronic respiratory disorder. The device is a life sustaining modality basically used in intensive care units and in anesthesia to deliver gas into and out of the lungs. When the body could no longer supply oxygen into and expel carbondioxide out of the lungs sufficiently, a ventilator would be required to keep the patient alive [1][2]. This artificial respirator integrates volume, pressure, flow and time to supply a tidal breath under positive pressure. The system is connected to a built in supply system or an oxygen generator in hospitals to deliver pressurized gas to the patient at a controlled pressure or volume. To prevent damage to the lungs due to high pressure, a pressure-controlled mode is designed which corresponds to the precise operation mode required by the patient [3].

The demand for this machine has tremendously increased over the years as a result of increased health problem relating to acute respiratory distress syndrome such as Asthma, chronic obstructive pulmonary disease (COPD) and other acute respiratory problems which are prevalent. The pain which comes with respiratory disorder can be excruciating and thus, more rampant in most developing countries [4]. Some of the major causes of lung disease can be linked to human exposure to smoking, air pollution and so on. Patients who suffer lung disease problems or have an underlying ailment resulting in the damage of lungs would need a ventilator as a support system to stay alive.

The medical device industry has grown rapidly and progressively over the past century. The usefulness of Mechanical ventilators in hospitals cannot be overemphasized; however, due to the startling short demand of this device across the globe in most health care sector, there is need for the production of ventilators in large quantities to help patients with breathing difficulties stay alive [5]. The sophistication and complexity of the designed instrumentation is nowadays rising and, with it, has also increased the need to develop some better, more effective and efficient maintenance processes, as part of the safety and performance requirements

The goal of initiating a mechanical ventilator is to alleviate the work of breathing of the patient and to allow the ventilator muscle to recover. The decision to initiate mechanical ventilation should be based on clinical judgment that considers the entire clinical situation and not simple numeric criteria. However, mechanical ventilation should not be delayed until the patient is in extremis. The life supporting machine assumes all or some work of breathing for the patient [6]. A patient requires a ventilator when he cannot achieve adequate level of ventilation to maintain adequate gas exchange and acid-base balance and in cases when the human body cannot remove CO_2 from the body effectively. A patient who is not ventilating properly exhibit increased levels of $PaCO_2$, since they are not ventilating it out of the body [7]. They are prone to respiratory or ventilator failure. At times, the patient could also be ventilating adequately, but, if the oxygen delivered into the lungs is not properly distributed throughout the body, that is, when a patient is not oxygenating as a result of decreased level of PaO_2, there would be a need for mechanical ventilation [8]. The demand for a mechanical ventilator in patient with decreased level of PaO_2 is not as a result of improper ventilation but poor oxygenation.

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The outbreak of the novel virus, COVID-19, has already stretched critical medical supplies to their limits and more of this ventilator is required to defeat the impact of the disease. As the COVID-19 pandemic continues to ramp up at an alarming rate, the government has called for assistance in solving or mitigating the upcoming shortage of respiratory ventilators [9][10]. This review presents the anatomy tract of the respiratory system, respiratory mechanics, various modes of ventilation, approaches of ventilating a patient and patients with various respiratory disorder.

2. Literature Review

2.1 Anatomy of the Respiratory Tract

The respiratory system comprises of organs such as nose, larynx, pharynx, trachea, bronchi and lungs which aids breathing [11]. From a functional perspective, there are two major areas in which the respiratory system can be divided; the conducting zone, comprising of structures which provides entry for the movement of air in and out of the lungs; the nasal cavity, pharynx, trachea, bronchi, and most bronchioles and the respiratory zone, majorly responsible for the exchange of gas [12]. This zone involves the structures of the lung which consists of the terminal bronchioles and alveoli.

The respiratory system performs two major functions in our body system: provides adequate oxygen required by the body to help the cells function appropriately and expels carbon dioxide out of the body. The respiratory organs work together as one member to help channel air into the lungs [13]. Oxygen is delivered into the bloodstream and carbon dioxide is moved out of the blood into the air. Air enters into our body system through our nose or mouth when we inspire. The various respiratory organs help to channel fresh air from the environment into our body system [14].

The fresh air is moved through the throat down to the lungs through the larynx and then the trachea. The easiness in breathing is also as a result of the opening in the upper airway. The upper airway keeps the air warm and moistens before it gets to the lungs. At the end of the bronchioles (small branches of air tubes in the lungs) is located tiny air sacs called Alveoli which are solely responsible for the exchange of oxygen and carbondioxide in the bloodstream [15].

Capillaries on the other hand are tiny branches of the pulmonary arteries as well as a network of small blood vessels that covers each alveolus [16]. Air moves down the trachea into the alveoli through the bronchi when we breathe in. The capillaries containing blood alongside with the air in the alveoli must be close to each other in order to ensure a sufficient diffusion of oxygen and carbon dioxide between them. The air we breathe in has sufficient oxygen needed by the body and moves down into the bloodstream across the walls of the alveoli while the carbondioxide which is the waste product moves in the opposite direction and is conveyed across the walls of the bloodstream into the air in the alveoli and finally removed from the body system as we breathe out [17].

During inspiration, much work is required by the muscles in our body to fill the lungs with air. A dome shaped muscle which is one of the major muscles in the lungs known as the diaphragm does more of the work of getting air into the lungs when we breathe in. During inhalation, the diaphragm contracts and flattens out while expanding the chest cavity [18]. Upon exhalation, the muscle relaxes at the end of inspiration and due to the elasticity nature of the lungs, it returns back to its original/resting position and moves air out as they go.

When the respiratory system get infected or start facing some breathing distress such asthma, pneumonia and other acute obstructive pulmonary disorder (COPD), delivering oxygen and expelling carbondioxide out of the body system becomes difficult and it becomes imperative for such person get support from an artificial respirator such as the ventilator in order to stay alive[19].

2.2 Respiratory Mechanics

Ventilation allows the flow and movement of gas in humans by the expansion and contraction of the chest wall to generate a pressure gradient which can be achieved by the respiratory muscles, positive or negative ventilation. It also helps understand how the lung functions by measuring pressure and flow. An adequate pressure must be applied to overcome two forces that restrict the movement of the respiratory system for ventilation to occur. The interaction of the applied and opposing forces is referred to as Respiratory Mechanics [20]. In hospitals, change in the respiratory mechanics of a patient under a close monitor could change suddenly, or show slow variation in respiratory conditions. This change get clinicians on their toes to make decisions based on the measured parameters by taking quick and immediate actions.

2.2.1 Opposing Forces

Elastic Recoil

During the course of a lung transplant or an autopsy, it is perceived that the lungs deflate after it has been removed from the thoracic cavity. After the removal of the lungs, the chest wall also increases in volume. As a result of this separation, the lungs recoils inward while the chest wall expands outward to attain their respective equilibrium volumes. If any changes occur in their volumes, an increasing pressure would also be applied. In order words, the more the lungs and the chest wall are elongated and compressed, the higher the amount of pressure needed to overcome the intrinsic elastic recoil [21].

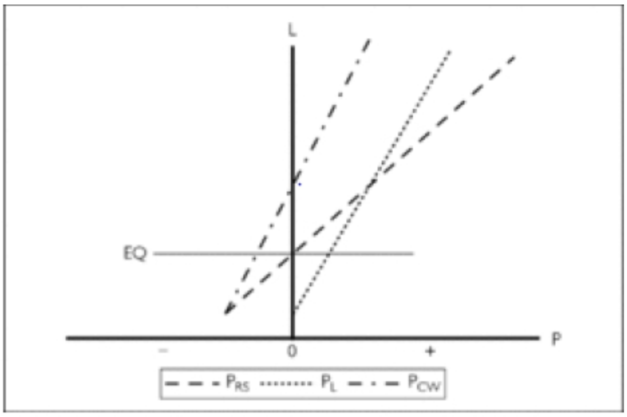

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Fig 1.0: Relationship between pressure (P) and length (L) of the lung spring (P_L), the chest wall spring (P_{CW}), and the "respiratory system" (P_{RS}).

The graph below depicts the elastic recoil of the lungs, chest wall, and intact respiratory system that show the pressure required to maintain a specific volume. In the figure below, as the spring elongates, more applied pressure is required to balance out its elastic coil. Increase in outward (+) or inward pressure (-) is also needed to lengthen or shorten the chest wall spring in order to balance the elastic coil and are elongated above or compressed their equilibrium length

2.2.2 Viscous forces

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During, inhalation, work is done to overcome the elastic coil of the respiratory system and also allow the delivery of gas in and out of the tracheobronchial tree. To overcome this, an additional pressure is needed to overcome the gas molecules generating friction as they come in contact with the surface of the airways and the cohesive forces between the molecules. This is known as the viscous forces.

The concept of viscous forces is similar to blowing or sucking air through a tube. Difference in intramural pressure (ΔP) between its two ends will allow air to flow through the tube. Just how much of a pressure gradient is needed depends on several factors, which are shown in this simplification of Poiseuille's equation [21]:

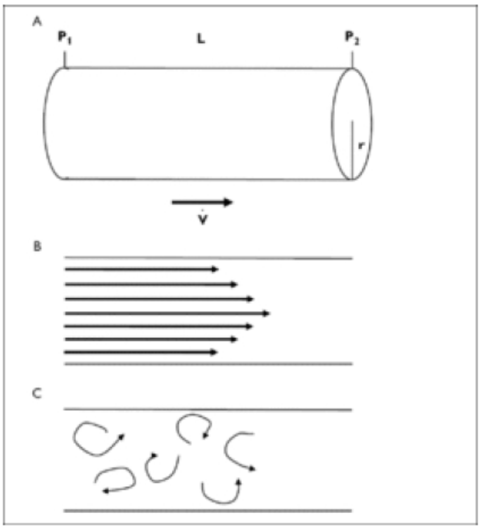

Fig 2:

(A) The pressure gradient between the ends of a tube (P – P) is determined by the rate of gas flow ($\dot{V}$) and the radius (r) and length (L) of the tube.

(B) During laminar flow, gas moves in concentric sheets, and velocity increases toward the center of the airway.

(C) Chaotic or turbulent flow requires a much higher pressure gradient

Compliance

Lung compliance in respiratory physiology is defined as the ability of the lung to expand while elastance is the inverse of compliance that is, ability to return to the resting position. Compliance is determined by the following equation: C = ΔV/ΔP, where C is compliance, ΔV is change in volume, and ΔP is change in pressure [22]. The inverse of compliance is elastance

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(E ~ 1/C). In mechanics of ventilation, elastic recoil and viscous forces are very crucial since elastic recoil is most often expressed in terms of compliance (C), expressed as the ratio of the volume change (ΔV) produced by a change in transmural pressure (ΔP_{TM}). When elastic recoil is high, a given pressure change produces a relatively small change in volume, and compliance is low and vice versa. Compliance which is a static measurement can only be calculated in the absence of flow.

C_{RS} is calculated as the V_T divided by the pressure required: $C_{RS} = \Delta V/\Delta P$. Acceptable C_{RS} is 50–100 ml/cmH_2O in mechanically ventilated patients. It is determined by the compliance of the lungs and chest wall. C_{RS} has been used to determine the optimal level of PEEP in patients with ARDS and the highest level of CRS corresponds to best PEEP [20].

Normal CL is 200 ml/cmH2O. CL is decreased with ARDS, cardiogenic pulmonary edema, pneumothorax, consolidation, atelectasis pulmonary fibrosis, pneumonectomy, bronchial intubation, and over-distention. CL is increased with emphysema.

2.2.3 Resistance

Viscous forces are measured by *resistance* (R), expressed as the ratio of the *intramural* pressure gradient (ΔP_{IM}) and the resulting flow (V). Unlike compliance, resistance is a dynamic measurement can only be calculated in the presence of flow. A small pressure gradient is needed to cause a flow when resistance is low, while a larger pressure gradient is needed to cause a flow when the resistance is high. In order to eliminate resistance to flow, compliance must be measured accurately [23].

2.2.4 Applied Forces

Adequate pressure is applied to overcome the elastic recoil and viscous forces of the lungs and chest wall during inhalation and exhalation. P is the transmural pressure of the respiratory system in the absence of gas flow, while P is the intramural pressure gradient driving flow. P is equal to the change in volume (ΔV) divided by respiratory system compliance (C), and from above, we know that P equals the product of resistance (R) and flow (V). So, we can rewrite Equation below as:

$$P_{APP} = (R \times V) + (\Delta V/C_{RS})$$

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This is called the *equation of motion* of the respiratory system. This illustrates that the applied pressure varies directly with resistance, flow rate, and volume and inversely with respiratory system compliance at any time during the respiratory cycle [21]. During the inhalation stage, the diaphragm and other inspiratory muscles deliver the pressure needed and in a case where these organs are no longer functioning, a mechanical ventilator provides the required pressure.

2.2.5 Time Constant

The time constant is an important concept in respiratory mechanics that evaluates the rate of change in the volume of a lung unit that is passively inflated or deflated. It is expressed by the relationship: $V_t = V_i \times e^{-t/\tau}$, where Vt is the volume of a lung unit at time t, V_i is the initial volume of the lung unit, e is the base of the natural logarithm, and is the time constant. For respiratory mechanics, τ is the product of resistance and compliance. Lung units with a higher resistance and/or compliance will have a longer time constant and require more time to fill and to empty. In contrast, lung units with a lower resistance and/or compliance will have a lower time constant and thus require less time to fill and to empty.

2.2.6 Inspiratory flow

All current-generation critical care ventilators monitor flow. Although some monitor flw with a pneumotachometer directly at the proximal airway, most monitor $\dot{V}_I$ at the inspiratory valve and $\dot{V}_E$ at the expiratory valve. During volume control ventilation, the $\dot{V}_I$ is that which is set on the ventilator. During passive pressure control ventilation, flow is the pressure applied to the airway, R_{aw}, and :$\dot{V}_I$=$(\Delta P/R_{aw})\times e^{-t/\tau}$, where ΔP is the pressure applied to the airway above PEEP, t is the elapsed time after initiation of the inspiratory phase, and e is the base of the natural logarithm [24].

2.2.7 Expiratory flow

Expiratory flow is normally passive and is determined by P_{alv}, R_{aw}, the elapsed time since initiation of exhalation, and τ: $\dot{V}= -(P_{alv}/R_{aw})\times e^{-t/\tau}$, Note that, by convention, expiratory flow is negative, and inspiratory flow is positive. End-expiratory flow is present if Raw is high and T_E is not sufficient, indicating the presence of air trapping (auto- PEEP) [25].

2.2.8 Tidal Volume

Critical care ventilators do not measure volume directly, but derive this from integration of flow. Because flow is usually not measured directly at the proximal airway, volume output from the ventilator is less than the volume delivered to the patient. Modern critical care ventilators correct volume for circuit compression, so the volume displayed by the ventilator closely approximates the volume delivered to the patient. The volume waveform may be useful to detect the presence of a leak (e.g, bronchopleural fistula, leak around the cuff, leak around the mask), which results in a difference between the inspiratory and expiratory V_T [26].

3. Modes of Ventilation

Mode of ventilation provides an infinite number of ways in which the patient interacts with the ventilator [27]. There are various modes of ventilation enabling the proper exchange of gas at a constant tidal volume and peak inspiratory flow as well as to help the patient breathe without putting much work on the patient. In assist control, the major determining factor involved in the interaction between the patient and the ventilator are the tidal volume and peak inspiratory flow (set by the physician) [25]. Some of the modes of ventilation are discussed below[28]:

1. Volume-Controlled Ventilation (VCV): In this mode, all breaths are delivered by the ventilator. The ventilator delivers a preselected ventilatory rate, tidal volume, and inspiratory flow rate, independent of spontaneous effort on the part of the patient [29].
2. Assist control volume ventilation: This is the most common ventilator mode used globally as the primary initial mode of ventilatory support. In this mode, the patient does not need to work so hard to get a particular tidal volume, all they need to do is to initiate a breathe and the ventilator perform the rest of the work. ACV may not be suitable for patients whose breathing pattern could be very rapid [30].
3. Synchronized Intermittent Mandatory Ventilation (SIMV): In this mode, the ventilator delivers its breaths to the patient at a particular set rate, pressure or volume which is in synchrony with the inspiratory effort of the patient. This is possible through an assist window that opens and closes at intervals depending on the setting by the SIMV rate. When the window is opened and the patient put in effort to generate breath, a mandatory breath would be delivered, however, if the patient does not make any effort, the ventilator helps with the delivery of mandatory breath[30].
4. Pressure-Controlled Ventilation (PCV): This mode of ventilation does not require the patient to initiate breaths. A ventilator set in this mode supplies the required breath in a pressure limited and time-cycled pattern. Each breath is characterized by a fixed level

of pressure at the airway (P_{aw}), in order for the inspiratory flow and the tidal volume to correspond to the patient's ventilator requirement[29]. Patient set on this mode are less vulnerable to barotrauma and delivers comfort and aligns with the ventilator by assisting the patient with its own ventilatory effort, thereby preventing diaphragmatic fatigue in respiratory impaired patients. However, one of the shortcomings of this mode is that it is more efficient in patients with stable respiratory condition.

5. Pressure Support Ventilation: This mode augments spontaneous breathing and also determines inflation volume and respiratory frequency by the patient. The delivery of PSV is via a specialized face mask [30].

4. Different Respiratory Disorders

Acute respiratory Distress Syndrome is a life threatening form of respiratory failure [31]. Acute respiratory distress syndrome (ARDS) continues to be a major healthcare problem, affecting 190,000 people in the USA annually, with a mortality of 27–45%, depending on the severity of the illness and comorbidities [30]. Despite advances in clinical care, particularly lung protective strategies of mechanical ventilation, most survivors experience impaired health-related quality of life for years after the acute illness. While most patients survive the acute illness, a subset of ARDS survivors develops a fibroproliferative response characterised by fibroblast accumulation and deposition of collagen and other extracellular matrix components in the lung.

Various studies have shown patients who are predisposed to various acute respiratory diseases require the need for Mechanical ventilator to stay alive. carried out a research on immunocompromised patients with deterred immune system. Patients with this condition are subjected to a less active or normal immune response to a foreign antigen and causes of this state could either be Congenital or Acquired [32]. It could be acquired as a result of malignancy, aging, malnutrition and could be congenital resulting from gene mutations. The mortality rate in immunocompromised patients has tremendously increased over the years to about 30 to 90%. Major complication associated with such patients is Infection. Patients diagnosed of HIV (with or without AIDS), transplantation patients, individuals on immunosuppressive therapy have immunocompromised conditions and it research shown that patients with this condition suffer greatly from acute respiratory failure.

Another research was conducted on Idiopathic Pulmonary Fibrosis (IPF) patients who suffer a dysfunctional impairment in their respiratory system. IPF is a lung disease characterized by a continuous declination in the functioning of the lungs and poor prognosis. As the condition becomes exacerbated, it becomes more and more difficult to take in adequate oxygen into the lungs [33]. In such case, the need for a mechanical ventilator in intensive care units becomes imperative especially for patients with an acute exacerbation of IPF called Hypoxemia.

Globally, the world is faced with a novel respiratory disease known as Coronavirus (or COVID19). The life threatening disease attacks the lower respiratory system when it gets into the human body resulting in the form of pneumonia and acute respiratory distress syndrome (ARDS). Patients with this virus may experience symptoms like fever, dry and persistent cough, shortness of breath [34]. Individuals who are obese are much more vulnerable to suffer a severe respiratory distress.

4.1 Approaches of Ventilation

Over the years, different approaches have been established in order to provide an optimal approach for ventilating patients with acute respiratory disorder. The use of any of these approaches should be carefully selected as different patients response to treatment can vary depending on the severity of the distress as well as possible contraindications of these approaches should also be assessed before recommending it to the patient. The two most common approaches delivering supplemental oxygen for patients with acute respiratory disorder are: Non invasive and Invasive ventilation [35]. However, Non invasive ventilation has gained more recognition and popularity in ICU modality than invasive ventilation since its application in 1980s. In this review, much attention would be paid to Non Invasive ventilation.

Invasive ventilator is a life saving therapy for severely ill patients. It involves an endotracheal tube and a mechanical ventilator to deliver artificial breaths. The delivery of air is via a tube which is inserted into the windpipe via the mouth or nose [36]. This approach aids in stabilizing patients with hypoxemic and hypercapnic respiratory distress, reduces inspiratory work of breathing, implement lung protective strategy to ventilate patients with ARDs [37]. Patients with chest wall disorder and neuromuscular disease suffering from acute respiratory disorder are placed on invasive mechanical ventilators.

Non invasive ventilator (NIV) has been described as one of the approaches which have been devised for the treatment of acute respiratory disorder in patients with Chronic Obstructive Pulmonary Disease (COPD), hypercapnia and cardiogenic pulmonary edema [38][39]. This approach is used as a first-line therapy in emergency departments such as ICU. Non invasive mechanical ventilation is defined as the delivery of positive pressure (continuous and/or intermittent) via a nasal or full face mask with various levels of pressure support set for inspiration and expiration (frequently 10–15 and 5–8 cm H2O) rather than an endotracheal tube or tracheostomy [40]. This technique has proven to greatly improve and provide comfort to patient with acute respiratory distress as well as eliminate the excruciating pain that comes with endotracheal tube and invasive approach of ventilation [41]. In a study concluded in USA, NIV has been used in the treatment of severe cases of COPD and its use as greatly increased to more than 400% in a decade (from 1% in 1998 to 4.5% in 2008) and led to a 42% reduction in IMV. It is considered a first-line treatment with COPD exacerbation, immunosuppressed patients with acute respiratory failure, chronic obstructive, acute hypoxemic respiratory failure pulmonary disease and so on [42]. The success of NIV can be achieved by close monitoring of some parameters such as the respiratory rate (patient's effort), oxygen saturation (to adjust F_iO_2), and pH and $PaCO_2$ (to assess efficacy).
NIV has a great potential at providing ventilatory assistance for the treatment of patients with mild acute respiratory failure and as an initial mode of ventilation in children with low respiratory tract infection (mainly in bronchiolitis and pneumonia). However, noninvasive ventilation should not be administered to patients who are unable to protect their airway, resulting from altered mental status [43]. In the presence of hypercarbia, patients may be subjected to a high risk and fail when placed on NIV. Patients are remove from NIV when they a desirable recovery has been attained

The two modes of NIV are Continuous Positive Airway Pressure (CPAP) and Noninvasive Intermittent Pressure Support ventilation (NIPSV). CPAP is generated with a simple oxygen source via a hermetical mask with a PEEP valve or a Boussignac mask. It does not aid inspiratory support and hold a quantity of air in the lungs on expiration. This mode of respiratory assistance was mostly used in younger children with the helmet as the commonly used interface [44].

NIPSV requires a ventilator, programmed with expiratory pressure (expiratory positive airway pressure [EPAP] or PEEP) and IPAP. NIPSV used in conjunction with a ventilator delivers ventilator assiatance during and after initiation of inspiratory effort by the patient.

5.Conclusion

Acute respiratory distress syndrome (ARDS) is a common condition in the intensive care unit and is characterized by low compliance. Typically, the start of inspiration occurs at low volumes (near the residual volume) and requires high pressure to overcome surface tension and inflate the alveoli.

During assisted mechanical ventilation there is an important interaction between the patient and ventilator. During mechanical ventilation the respiratory system is affected by two pumps, the ventilator (i.e. Paw), controlled by the physician, and the patient's own respiratory muscle pump (Pmus), controlled by the patient. Patient–ventilator interaction is mainly an expression of the function of these two controllers, which should be in harmony if the result is to be appropriate for the patient. Harmony depends on the physician, who should realize that the respiratory system is not passive but reacts, sometimes vigorously, to pressure from the ventilator, depending on factors related both to the ventilator and the patient.

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