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Review

Respiratory management of inhalation injury

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ABSTRACT

Advances in the care of patients with major burns have led to a reduction in mortality and a change in the cause of their death. Burn shock, which accounted for almost 20 percent of burn deaths in the 1930s and 1940s, is now treated with early, vigorous fluid resuscitation and is only rarely a cause of death. Burn wound sepsis, which emerged as the primary cause of mortality once burn shock decreased in importance, has been brought under control with the use of topical antibiotics and aggressive surgical debridement.

Inhalation injury has now become the most frequent cause of death in burn patients. Although mortality from smoke inhalation alone is low (0–11 percent), smoke inhalation in combination with cutaneous burns is fatal in 30 to 90 percent of patients. It has been recently reported that the presence of inhalation injury increases burn mortality by 20 percent and that inhalation injury predisposes to pneumonia. Pneumonia has been shown to independently increase burn mortality by 40 percent, and the combination of inhalation injury and pneumonia leads to a 60 percent increase in deaths. Children and the elderly are especially prone to pneumonia due to a limited physiologic reserve.

It is imperative that a well organized, protocol driven approach to respiratory care of inhalation injury be utilized so that improvements can be made and the morbidity and mortality associated with inhalation injury be reduced.

Contents

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1. Introduction

Respiratory complications caused by smoke inhalation, burns, and their treatment epitomize the challenges which confront clinicians caring for burn patients. Smoke inhalation injury and its sequelae impose demands upon the respiratory therapists, nurses and doctors who play a central role in its clinical management. These demands may range from intubation and resuscitation of victims in the emergency room to assistance with diagnostic bronchoscopies, monitoring of arterial blood gases, airway maintenance, chest physiotherapy, and mechanical ventilator management [1]. Additional demands may be placed upon the clinical care team in the rehabilitation phase in determining disability or limitations diagnosed by pulmonary function studies or cardiopulmonary stress testing. In some countries outside the United States, the duties of the respiratory therapist are augmented by a combination of physicians, nurses, and physiotherapists. It is imperative that a well organized, protocol-driven approach to respiratory management of burn care be utilized so that improvements can be made, and the morbidity and mortality associated with inhalation injury can be reduced. This article provides an overview of the common hands-on approaches to the treatment of inhalation injury with emphasis on pathophysiology, diagnosis, management techniques to include bronchial hygeine therapy, pharmacologic adjuncts, mechanical ventilation, late complications and cardiopulmonary exercise rehabilitation.

2. Pathophysiology

Upper airway injury that results in obstruction during the first 12 h after-insult is caused by direct thermal injury as well as chemical irritation. The pathophysiologic changes in the parenchyma of the lungs that are associated with inhalation injury are not the result of direct thermal injury. Only steam, with a heat-carrying capacity many times that of dry air, is capable of overwhelming the extremely efficient heat-dissipatory capabilities of the upper airways [2]. Nor is the carbonaceous material present in smoke directly responsible for damage, although it can serve as a carrier for other agents [3].

Damage to the lung parenchyma is caused by the incomplete products of combustion. Many such substances present in burning cotton are injurious, but the most important products are the aldehydes and oxides of sulphur and nitrogen [4]. Burning polyvinylchloride (PVC's) yields at least 75 potentially toxic compounds, including hydrochloric acid and carbon monoxide [5].

An invisible, odorless gas, carbon monoxide has a much stronger affinity for hemoglobin than does oxygen, thus leading to a tremendous reduction in the oxygen-carrying capacity. The shortage of oxygen at the tissue level is made worse by a concomitant leftward shift of the oxyhemoglobin dissociation curve [6].

The pathology of the upper and lower respiratory tract lesions is due to the formation of edema. Bronchoscopic study of these lesions in the first 24 h after-injury showed a gradual

evolution of an edematous trachealbronchial mucosa [7]. Light microscopy demonstrated areas of almost complete de-epithelization in the tracheobronchial regions. Marked lesions are also present in the lower respiratory tract. Focal areas of congestion and edema are seen; alternating with the areas of collapse and pneumonia they are the results of compensatory emphysema. Large portions of the epitheal lining of the trachea and main bronchi may be shed. Progressive separation of the epithelium with formation of pseudomembranous cast causes complete or partial obstruction of the airways [8]. The lesions vary from a mild superficial desquamation of homogenous, swollen epithelia cells, to a complete disruption of the epitheal tracheobronchial lining, with focal necrosis and the formation of pseudomembranes composed of mucus, cellular debris, fibrinous exudate, polymorphonuclear leukocytes, and clumps of bacteria. The pulmonary parenchyma surrounding injured airways shows varying degrees of congestion, interstitial and alveolar edema, neutrophil infiltration, occasional hyaline membranes and dense atelectasis. Over time, these lesions progress, forming a castlike material composed primarily of fibrin [9]. Once formed, these cast can prove lethal by causing complete respiratory obstruction.

The second important factor in the pathophysiology of inhalation injury is the marked decrease in pulmonary compliance, which can be reduced by more than 50% [10]. In the first 24 h after-injury, this fall in the compliance corresponds with increases in the extravascular lung water and pulmonary lymph flow.

Inhalation injury results in the immediate inactivation of surfactant thus acute microatelectasis occurs with a resulting ventilation perfusion mismatch. In severe injuries, physiologic shunt leading to profound hypoxemia and acute microvascular injury with increased transvascular fluid flux produces a clinical picture of the adult respiratory distress syndrome (ARDS) [11].

3. Diagnosis

The clinical diagnosis of inhalation injuries has traditionally rested upon a group of indirect observations. These include facial burns, singed nasal vibrissae, and a history of injury in an enclosed space [12]. Taken individually, each of these signs has a high incidence of false positivity, but as a group they have been found to actually underestimate the true incidence of inhalation injury.

Carbonaceous secretions represent another classic sign of smoke inhalation that is a less exact predictor of the presence or severity of injury than is popularly believed. Carbonaceous secretions should be regarded as an indicator of exposure to smoke but should not establish either the diagnosis of inhalation injury or its sequela.

Hypoxia, rales, rhonchi and wheezes are seldom present on admission, occurring only in those with the most severe injury and implying an extremely poor prognosis [13]. The admission chest X-ray has also been shown to be a very poor indicator. Although two-thirds of patients develop changes of diffuse or focal infiltrates or pulmonary edema within 5–10 days of injury, the admission film is seldom diagnostic but is important for baseline evaluations [14].

The current standard for diagnosis of inhalation injury in most major burn centers is fiberoptic bronchoscopy [15]. Useful only in identifying upper airway injury, findings include the presence of soot, charring, mucosal necrosis, airway edema and inflammation [16]. Widespread use of this technique has led to an approximate two-fold increase in the diagnosis over that based in the traditional clinical signs and symptoms discussed earlier. Bronchoscopy without findings cannot rule out the possibility of parenchyma damage.

To evaluate true parenchyma damage, Xenon scanning has been utilized [17]. This is a safe, rapid test requiring a minimum of patient cooperation, it involves serial chest scintiphotograms after an initial intravenous injection of radioactive Xenon gas. It demonstrates areas of the decreased alveolar gas washout, which identifies sites of small airway obstruction caused by edema or fibrin cast formation. Although the possibilities of both false negatives and false positives exist, they occur chiefly in patients in whom scanning is delayed for 4 or more days or in patients who have pre-existing lung disease.

Another more recent method of evaluating inhalation injury is the estimation of extravascular lung water by simultaneous thermal and dye dilution measurements. This procedure has been unable to quantify the severity of injury but has been proven useful in separating parenchymal from upper airway injury [18].

A frequent concurrent form of injury, carbon monoxide poisioning, can be evaluated only by measurement of serum carboxyhemoglobin levels. Clinical findings of headache, nausea, and behavioral disturbances occur only at levels above 30%. The pathognmonic cherry-red skin discoloration occurring only at levels above 40% is less likely to be present than the cyanosis of respiratory depression [3]. The time from injury to measurement is very important, because it takes 4 h for levels to fall by one-half while patients breath room air and less than 1 h on 100% oxygen. Carbon monoxide levels are a poor indicator of injury since most burn victims are placed on 100% oxygen at the scene of the accident and upon transfer to an emergency facility.

4. Management techniques

4.1. *Airway issues*

Acute upper airway obstruction (UAO) occurs in approximately one-fifth to one-third of hospitalized burn victims with inhalation injury and is a major hazard because of the possibility of rapid progression from mild pharyngeal edema to complete upper airway obstruction with asphyxia [19]. The worsening of upper airway edema is most prominent in supraglottic structures. Serial nasopharyngoscopic evaluations demonstrate obliteration of the aryepiglotic folds, arytenoid eminences, and interaryteniod areas by edematous tissues that prolapse to occlude the airway [20]. For patients with large surface burns that require rapid fluid administration, these changes may be accentuated. Burns of the neck, especially in children, can cause unyielding eschars that externally compress and obstruct the airway. Escharotomies

to the neck may be helpful in reducing the tight eschar and therefore decrease the pressure exerted on the trachea. Whenever UAO is suspected the most experienced clinician in airway management should perform endotracheal intubation. Securing the endotracheal tube can be difficult due to the burn wound and the rapid swelling that occurs within the first 72 h. Mlcak and his co-workers reported on a technique of airway security that has been used effectively on burn children [21].

4.1.1. *Bronchial hygeine therapy*

Airway clearance techniques are an essential component of respiratory management of patients with smoke inhalation. Bronchial hygiene therapy is a term used to describe several of the modalities intended to accomplish this goal. Therapeutic coughing, chest physiotherapy, early ambulation, airway suctioning, therapeutic bronchoscopy and pharmacologic agents have been effective in the removal of retained secretions.

Therapeutic coughing functions to promote airway clearance of excess mucus and fibrin cast in the tracheal bronchial tree. The impairment of the cough mechanism will result in retained secretions, bronchial obstruction, atelectasis, and/or pneumonia. A cough may be either a reflex or a voluntary action. During a voluntary cough, alveolar, pleural, and subglottic pressures may rise as much as 200 cm H_2O. A failure of the cough mechanism may be due to pain, drugs or artificial airways. When this occurs, it is often necessary to perform the following techniques which may be used to improve the voluntary cough and aid in airway clearance. The patient is asked to start a small breath and small cough, then a bigger breath and harder cough, and finally a really deep breath and hard cough. This technique is especially effective for postoperative patients who tend to splint from pain.

Another technique involves the therapist placing the index and middle finger flat in the sternal notch and gently massaging inward in a circular fashion over the trachea. This is most effective in obtunded patients or in patients coming out of anesthesia. Patients with artificial airways cannot cough normally since a tube is either between the vocal cords (endotracheal) or below the cords (tracheostomy). Adequate pressure cannot be built up without approximation of the cords. These patients may have a cough stimulated by inflating the cuff on the tube, giving a large, rapid inspiration by a manual resuscitation bag, holding the breath for 1–2 s, and rapidly allowing the bag to release and exhalation to ensue. This technique is normally performed by two therapists and is made more effective by one therapist performing vibration and chest compressions from the time of the inspiratory hold, all during exhalation. Coughing and deep breathing is encouraged every 1–2 h to aid in removing retained secretions [22].

4.2. *Chest physiotherapy*

Chest physiotherapy has come to mean gravity-assisted bronchial drainage with chest percussion and vibrations. Studies have shown that a combination of techniques are effective in secretion removal [23–26].

Bronchial drainage/positioning is a therapeutic modality which uses gravity-assisted positioning designed to improve pulmonary hygiene in patients with inhalation injury or retained secretions. There are 12 basic positions in which patients can be placed for postural drainage. Due to skin grafts, donor sites, and the use of air fluid beds, clinical judgment dictates that most of these positions are not practical. In fact, positioning in the Trendelenburg and various other positions may acutely worsen hypoxemia. Evidence has shown that a patient's arterial oxygenation may fall during positioning[27]. To accomplish the same goal it is common practice, in intensive care units, to turn patients side to side every 2 h so as to aid in mobilizing secretions.

Percussion aids in the removal of secretions from the tracheal bronchial tree. Percussion is done by cupping the hand so as to allow a cushion of air to come between the percussor's hand and the patient's chest. If this is done properly, a popping sound will be heard when the patient is percussed. There should be a towel between the patient and the percussor's hand in order to prevent irritation of the skin. Percussion is applied over the surface landmarks of the bronchial segments which are being drained. The hands rhythmically and alternately strike the chest wall. Incisions, skin grafts, and bony prominences should be avoided during percussion [22].

Vibration/shaking is a shaking movement used to move loosened secretions to larger airways so that they can be coughed up or removed by suctioning. Vibration involves rapid shaking of the chest wall during exhalation. The percussor vibrates the thoracic cage by placing both hands over the percussed areas and vibrating into the patient, isometrically contracting or tensing the muscles of their arms and shoulders. Mechanical vibrations have been reported to produce good clinical results. Gentle mechanical vibration may be indicated for patients who cannot tolerate manual percussion. Chest physiotherapy techniques should be used every 2–4 h for patients with retained secretions. Therapy should continue until breath sounds improve [22].

4.3. *Early ambulation*

Early ambulation is another effective means of preventing respiratory complications. With appropriate use of analgesics, even patients on continuous ventilatory support can be taken out of bed and placed into a chair. The sitting position has several beneficial effects which include:

- the patient can breathe with regions of the lungs which are normally hyperventilated;
- muscular strength and tone are preserved;
- contractions are prevented and exercise tolerance is maintained.

4.4. *Airway suctioning*

Airway suctioning is another method of clearing an airway. Normal bronchial hygiene is usually accomplished by the mucociliary escalator process. When these methods are not effective in maintaining a clear airway, tracheobronchial suctioning is indicated [28–31]. Nasotracheal suctioning is intended to remove from the trachea accumulated secretions, and other foreign material which cannot be removed by the

patient's spontaneous cough or less invasive procedures. Nasotracheal suctioning has been used to avoid intubation which was solely intended for the removal of secretions. Nasotracheal suctioning refers to the insertion of a suction catheter through the nasal passages and pharynx into the trachea in order to aspirate secretions or foreign material. The first step in this process is to hyperoxygenate the patient with 100% oxygen. The patient should be positioned in an inclined position in which the head of the bed is raised at a 45° angle and the catheter slowly advanced through the nares to a point just above the larynx. The therapist or nurse then listens for air sounds at the proximal end of the catheter. When airflow is felt to be strongest and respiratory sounds are loudest, the tip of the catheter is immediately above the epiglottis. On inspiration, the catheter is advanced into the trachea. After the vocal cords have been passed, a few deep breaths are allowed and the patient is reoxygenated. Suction is begun while the catheter is slowly withdrawn from the trachea. The patient should not be suctioned for more than 15 s without being reoxygenated. Suctioning is not without potential hazards [32]. Complications include irritation of the nasotracheal mucosa with bleeding, abrupt drops in PO_2, vagal stimulation, and bradycardia. Preoxygenating and limiting suction time have been shown to decrease or eliminate the fall in the PO_2.

4.5. *Therapeutic bronchoscopy*

When all other techniques fail to remove secretions, the use of the fiberoptic bronchoscope has proven to be of benefit. In addition to its diagnostic functions, bronchoscopy retains important therapeutic applications. Copious secretions encountered in patients with inhalation injury may require repeated bronchoscopic procedures when more conservative methods are unsuccessful. The modern fiberoptic bronchoscope is small in diameter, flexible, and has a steerable tip which can be maneuvered into the fourth or fifth generation bronchi for examination or specimen removal [22].

4.6. *Pharmacological adjuncts*

Bronchodilators can be helpful in some cases. Inhalation injury to the lower airways results in a chemical tracheobronchitis which can produce wheezing and bronchospasms. This is especially true for patients with pre-existing reactive airway diseases. Most drugs which are used in the management of bronchospasms are believed to act on the biochemical mechanism which controls bronchial muscle tone. Aerosolized sympathomimetics are effective in two ways: they result in bronchial muscle relaxation and they stimulate mucociliary clearance. The newer bronchodilators are more effective and have fewer side effects than the older generation drugs [22].

Racemic epinephrine is used as an aerosolized topical vasoconstrictor, bronchodilator, and secretion bond breaker. The vasoconstrictive action of racemic epinephrine is useful in reducing mucosal and submucosal edema within the walls of the pulmonary airways. A secondary bronchodilator action serves to reduce potential spasm of the smooth muscles of the terminal bronchioles. Water, employed as a diluent for racemic epinephrine, serves to lower both adhesive and cohesive forces of the retained endobronchial secretions, thus serving as a bond-breaking vehicle. Racemic epinephrine has also been used for the treatment of post-extubation stridor. Its mode of action is thought to be related to the vasoconstrictive activity, with the resultant decrease in mucosal edema. Aerosolized treatments may be given every 2–4 h as long as the heart rate is not excessively increased [22].

Aerosolized *N*-acetylcysteine is a powerful mucolytic agent in use in respiratory care. *N*-Acetylcysteine contains a thiol group; the free sulfhydryl radical of this group is a strong reducing agent which ruptures the disulfide bonds which serve to give stability to the mucoprotein network of molecules in mucus. Agents which break down these disulfide bonds produce the most effective mucolysis [33]. *N*-Acetylcysteine is an irritant to the respiratory tract. It can cause mucosal changes, and it may induce bronchospasm. For this reason, patients are evaluated for signs of bronchospasm and a bronchodilator may be added if necessary. *N*-Acetylcysteine has proven to be effective in combination with aerosolized heparin for the treatment of inhalation injury in animal studies [34].

Heparin/*N*-acetylcysteine combinations have been used as scavengers for the oxygen free radicals produced when alveolar macrophages are activated either directly by chemicals in smoke or by one or more of the compounds in the arachidonic cascade. Animal studies have shown an increased *P*/*F* ratio, decreased peak inspiratory pressures, and a decreased amount of fibrin cast formation with heparin/acetylcystine combinations. In a retrospective review Desai et al. showed that the use of Heparin/*N*-acetylcysteine to be effective in pediatric patients with inhalation injury [35]. Results indicate a significant decrease in the reintubation rates, incidence of atelectasis and improved mortality for patients treated with Heparin/*N*-acetylcysteine therapy. Therefore, a standard treatment for patients with inhalation injury might include 5000–10,000 units of heparin and 3 ml normal saline nebulized every 4 h, alternating with 3–5 ml of 20% *N*-acetylcysteine for 7 days. This insures that the patient receives an aerosolized treatment every 2 h. Baseline and daily clotting studies are recommended for the entire length of the aerosolized Heparin/*N*-acetylcysteine treatments [22].

Table 1 shows the Inhalation Injury treatment protocol used at the Shriners Hospital for Children, Galveston Burn

Table 1 – Inhalation injury treatment protocol

Titrate humidified oxygen to maintain SaO_2s' > 90%
Cough, deep breath exercises every 2 h
Turn patient side to side every 2 h
Chest physiotherapy every 4 h
Aerosolize 3 cc's of 20% *N*-acetylcysteine every 4 h with a bronchodilator
Alternate aerosolizing 5000 units of Heparin with 3 cc's of normal saline every 4 h
Nasotracheal suctioning as needed
Early ambulation on post-operative day 5
Sputum cultures for intubated patients every Monday, Wednesday, Friday
Pulmonary function studies prior to discharge and at out-patient visits
Patient/family education regarding inhalation injury

The protocol is continued for 7 days.

Hospital. This protocol has been in place and used clinically since 1990 with over 560 patients treated.

4.6.1. *Mechanical ventilation*

Over the past 30 years, and especially over the past decade, there has been an increase in new ventilatory techniques which present alternatives for the treatment of patients with smoke inhalation. Unfortunately, although the number of options available to the clinician has appeared to increase exponentially, well controlled clinical trials defining the specific role for each of the modes of ventilation and comparing them to other modes of ventilation has not been forthcoming. Based upon current available data, the recommendations from the American College of Chest Physicians consensus conference on mechanical ventilation generally serve as guidelines[36]. The general consensus concludes:

- The clinician should choose a ventilator mode that has been shown to be capable of supporting oxygenation and ventilation and that the clinician has experience in using.
- An acceptable oxygen saturation should be targeted.
- Based primarily on animal data, a plateau pressure of greater than 35 cm H_2O is cause for concern. With clinical conditions that are associated with a decreased chest wall compliance, plateau pressures greater than 35 cm H_2O may be acceptable.
- To accomplish the goal of limiting plateau pressures, P_{CO_2} should be permitted to rise (permissive hypercapnia) unless other contraindications exist that demand a more normal P_{CO_2} or pH.
- Positive end-expiratory pressure (PEEP) is useful in supporting oxygenation. An appropriate level of PEEP may be helpful in preventing lung damage. The level of PEEP required should be established by empirical trials and reevaluated on a regular basis.
- Large tidal volumes (8–10 ml/kg) with PEEP may be needed to improve oxygenation if the use of protective ventilatory strategies become ineffective. Peak flow rates should be adjusted as needed to satisfy patient inspiratory needs.

A new multicenter study by the Acute Respiratory Distress Syndrome Network of the National Heart, Lung, and Blood Institute (NHLBI) is the first large randomized study comparing high versus low tidal volumes for patients with ARDS [37]. The trial compared traditional ventilation treatment, which involved an initial tidal volume of 12 ml/kg of predicted body weight and an airway pressure measured of 50 cm H_2O or less, to ventilation with a lower tidal volume, which involved an initial tidal volume of 6 ml/kg of predicted body weight and a plateau pressure of 30 cm H_2O or less. The volume-assist-control mode was used for the ventilation study. The trial was stopped after the enrollment of 861 patients because mortality was lower in the group treated with lower tidal volumes than in the group treated with traditional tidal volumes and the number of days without ventilator use during the first 28 days after randomization was greater in this group [37].

This study was the first large randomized investigation that documented a decrease in mortality with the use of lower tidal volumes for the treatment of patients with ARDS. In light of this new evidence, the tidal volumes used when initiating mechanical ventilation should be 6–8 ml/kg of predicted body weight. If the patient becomes obstructed with fibrin cast and presents with an acute increase in P_{CO_2} and decrease in PaO_2, the clinician should first provide aggressive pulmonary toilet, then consider changing over to volume ventilation with higher tidal volumes. If ventilation continues to worsen, tidal volumes of 8–10 ml/kg may be needed to provide adequate mechanical ventilation.

4.7. *Modes of ventilation*

4.7.1. *Control mode*

In the control mode of ventilation, the ventilator cycles automatically at a rate selected by the operator. The adjustment is usually made by a knob calibrated in breaths/min. The ventilator will cycle regardless of the patient need or desire for a breath, but guarantees a minimum level of minute ventilation in the apneic, sedated or paralysed patient. The control mode of ventilation is often utilized in patients with the adult respiratory distress syndrome due to the high peak pressures needed to achieve adequate chest expansion. The major disadvantage with this mode is that the patient cannot cycle the ventilator and thus the minute ventilation must be set appropriately.

4.7.2. *Assist-control mode*

In the assist-control mode of ventilation in which every breath is supported by the ventilator, a back-up control rate is set; however, the patient may choose any rate above the set rate. Using this mode of ventilation, the tidal volume, inspiratory flow rate, flow waveform, sensitivity and control rate are set [38–40].

Advantages are that assist-control ventilation combines the security of controlled ventilation with the possibility of synchronizing the breathing pattern of the patient and ventilator, and it ensures ventilatory support during each breath.

Disadvantages are as follows:

- Excessive patient work occurs in case of inadequate peak flow or sensitivity settings, especially if the ventilator drive of the patient is increased.
- It is sometimes poorly tolerated in awake, nonsedated subjects and can require sedation to insure synchrony of patient and machine.
- It can cause respiratory alkalosis.
- It may worsen air trapping with patients with chronic obstructed lung disease [36].

4.7.3. *Synchronized intermittent mandatory ventilation (SIMV)*

This mode of ventilation combines a preset number of ventilator-delivered mandatory breaths of preset tidal volume with the facility for intermittent patient-generated spontaneous breaths [41,42].

Advantages are as follows:

- The patient is able to perform a variable amount of respiratory work and yet there is the security of a preset mandatory level of ventilation.

- SIMV allows for a variation in level of partial ventilatory support from near total ventilatory support to spontaneous breathing.
- It can be used as a weaning tool.

Disadvantages are:

- Hyperventilation with respiratory alkalosis.
- Excessive work of breathing due to the presence of a poorly responsive demand valve, suboptimal ventilatory circuits or inappropriate flow delivery could occur.
- In each case, extra work is imposed on the patient during spontaneous breaths.

4.7.4. *Pressure control mode*

In pressure-controlled ventilation all breaths are time or patient triggered, pressure-limited, and time-cycled. The ventilator provides a constant pressure of air to the patient during inspiration. The length of inspiration, the pressure level, and the back-up rate of are set by the operator. Tidal volume is based upon the compliance and resistance of the patient's lungs, the ventilator system as well as on the preset pressure. Pressure control ventilation has become a frequently used mode of ventilation for the treatment of ARDS.

4.7.5. *Pressure support ventilation (PSV)*

Pressure support ventilation (PSV) is a pressure-targeted, flow-cycled, mode of ventilation in which each breath must be patient triggered. It is used both as a mode of ventilation during stable ventilatory support periods and as a weaning method [43–46]. It is primarily designed to assist spontaneous breathing and therefore the patient must have an intact respiratory drive.

Advantages are:

- It is generally regarded as a comfortable mode of ventilation for most patients.
- Pressure support reduces the work of breathing.
- It can be used to overcome the airway resistance caused by the endotracheal tube.
- Pressure support may be useful in patients who are difficult to wean.

Disadvantages are:

- The tidal volume is not controlled and is dependent on respiratory mechanics, cycling frequency, and synchrony between the patient and ventilator.
- Pressure support may be poorly tolerated in some patients with high airway resistances because of the preset high initial flow rates [22].

4.7.6. *Alternate modes of ventilation*

During the last decade, a new concept has emerged regarding acute lung injury. In severe cases of adult respiratory distress syndrome (ARDS), only a small part of the lung parenchyma remains accessible to gas delivered by mechanical ventilation [46,47]. As a consequence, tidal volumes of 10 ml/kg or more may overexpand and injure the remaining normally aerated lung parenchyma and could worsen the prognosis of severe acute respiratory failure by extending nonspecific alveolar damage. High airway pressures may result in overdistension and local hyperventilation of more compliant parts of the diseased lung. Overdistension of lungs in animals has produced diffuse alveolar damage [48–50]. This is the reason why alternative modes of ventilation, all based on a reduction of end-inspiratory airway pressures and/or tidal volumes delivered to the patient, have been developed and are used by many clinicians caring for patients with severe forms of acute or chronic respiratory failure. Three alternative modes of ventilation, high-frequency percussive ventilation (HFPV), inverse ratio ventilation (IRV), and airway pressure release ventilation (APRV) will be briefly discussed.

4.7.7. *High-frequency percussive ventilation (HFPV)*

High-frequency percussive ventilation (HFPV) is a term used to describe a high-frequency time-cycled pressure ventilator commonly known as the VDR ventilator. The use of HFPV facilitates a lung protective strategy by providing ventilation at lower mean airway pressures. With this mode of ventilation, subtidal volumes are delivered in a progressive stepwise fashion until a preset oscillatory equilibrium is reached and exhalation is passive.

High-frequency percussive ventilation is a new technique that has shown some promise in the ventilation of patients with inhalation injury [51–53] Clinical studies indicate that this mode of ventilation may aid in reducing pulmonary barotrauma [52,53]. In a retrospective study, Cortiella et al. has shown a decrease incidence of pneumonia, peak inspiratory pressure and a improved P/F ratio in children ventilated with the use of HFPV as compare to controls [54].

In the first prospective randomized study on HFPV, Mlcak have shown a significant decrease in the peak inspiratory pressures needed to ventilate pediatric patients with inhalation injury [55]. No significant differences were found for incidence of pneumonia, P/F ratio's or mortality.

Based upon clinical experience the following guidelines are given for initial set up of the HFPV in children. The pulsatile flow (PIP) rate should set at 20 cm H_2O. The pulse frequency (high rate) should be set between 500 and 600. The low respiratory rate should be set at about 15–20. Oscillatory PEEP levels should be initially set at about 5 cm H_2O and demand peep set on 3 cm H_2O. The *I*:*E* ratio should be set at 2:1. Ventilator settings are adjusted based upon the patients clinical condition and blood gas values. To improve oxygenation the ventilator can be set up in a more diffusive mode (increased pulse frequency) and to eliminate carbon dioxide the ventilator can be set up in a more convective mode (decreased pulse frequency) [22].

Clinicians must be familiar with the technique used and its possible limitations. There must be adequate humidification of the respiratory gases or severe necrotizing tracheobronchitis can occur. Special delivery devices for providing adequate humidification during HFPV are required.

4.7.8. *Inverse ratio ventilation (IRV)*

Inverse ratio ventilation (IRV) is the use of an inspiratory/expiratory (*I*:E) ratio greater than 1:1. The rationale behind this is to maintain a high mean airway pressure and to hold peak alveolar pressure within a safe range. The second theoretical

concept underlying inverse ratio ventilation is the prolongation of inspiration to allow for recruitment of lung units with a long time constant. Deep sedation and/or paralysis is nearly always required with this mode of ventilation. At this time there is no conclusive evidence based data comparing inverse ratio ventilation to conventional mechanical ventilation in patients with inhalation injury.

4.7.9. *Airway pressure release ventilation (APRV)*

Airway pressure release ventilation (APRV) is a pressure-regulated mode of ventilatory support that allows for time-cycled decreases in pressure to facilitate CO_2 elimination. This mode may permit spontaneous breathing while limiting airway pressures and may therefore limit the amount of sedative, analgesic, and neuromuscular blocking agents infused. Several studies suggested improved oxygenation compared with pressure-controlled ventilation [56]. Evidence-based recommendations to use this mode of ventilation in inhalation injury await outcome studies.

4.8. *Typical ventilator settings required for conventional mechanical ventilation*

A large multicentered study by the NHLBI evaluated the use of Volume Ventilation with low versus high tidal volume on ARDS. This study documented a decreased incidence of mortality in patients with ARDS who were ventilated with small tidal volumes [37]. Based upon this study, it has become clinically accepted practice to use small tidal volumes when initially setting up mechanical ventilation.

Table 2 describes the authors typical guidelines for initial ventilator settings in children [22]. The guidelines for adults are given in the text below.

4.8.1. *Tidal volumes*

In volume-cycled ventilation, a machine-delivered tidal volume is set to be consistent with adequate gas exchange and patient comfort. The tidal volume selected for burned patients normally varies between 6 and 8 ml/kg of predicted body weight. Numerous factors, such as lung/thorax compliance, system resistance, compressible volume loss, oxygenation, ventilation and barotrauma, are considered when volumes are selected [57]. Of critical importance is the avoidance of overdistension. This can generally be accomplished by insuring that peak airway and alveolar pressures do not exceed a maximum target. Many would agree that a peak alveolar pressure greater than 35 cm H_2O in adults raises concern regarding the development of barotrauma and ventilator-induced lung injury increases [58,59]. The clinician must always look at the patient to insure adequate chest expansion with the setting of the tidal volume. Expired tidal volumes should be measured for accuracy at the connection between the patient's ventilator circuit and the artificial airway. This insures that the volume selected reaches the patient and is not lost in the compressible volume of the ventilator tubing.

The range of tidal volumes will vary depending on the disease process, with some diseases requiring maximum tidal volumes and others needing less. Severe interstitial diseases such as pneumonia and ARDS may require a tidal volume of 8–10 ml/kg to adequately inflate the lungs and improve gas exchange if protective ventilatory strategies become inadequate. However, the acceptable range of 6–8 ml/kg allows the clinician to make more precise adjustments in volume, as needed by the patient.

Table 2 – Mechanical ventilation guidelines in children

Variable	Settings
Tidal volumes	6–8 ml/kg
Respiratory rates	12–45 breaths/min
Plateau pressures	<30 cm H_2O
I:E ratio's	1:1–1:3
Flow rates	40–100 l/min
PEEP	8 cm H_2O

Table 3 – Targeted arterial blood gas goals

Variable	Goal
pH	7.25–7.45
PaO_2	55–80 mmHg or SaO_2 of 88–95%
$PaCO_2$	35–55 mmHg (permissive hypercapnia can be used if pH $\geq$ 7.25)

4.8.2. *Respiratory rate*

Setting of the mandatory ventilator respiratory rate is dependent on the mode of ventilation selected, the delivered tidal volume, dead space to tidal volume ratio, metabolic rate, targeted P_{CO_2} levels, and level of spontaneous ventilation. With adults, set mandatory rate normally varies between 4 and 20 breaths/min, with most clinically stable patients requiring mandatory rates in the 8–12 range [57]. In patients with inhalation injury, mandatory rates exceeding 20 per min may be necessary, depending on the desired expired volume and targeted P_{CO_2}. It is important to have targeted arterial blood gas values set to aid the clinical team in proper management (Table 3) [22]. Along with the P_{CO_2}, pH, and patient comfort, the primary variable controlling the selection of the respiratory rate is the development of air trapping and auto PEEP [60]. Auto PEEP is gas trapped in alveoli at end expiration, due to inadequate time for exhalation, bronchoconstriction or mucus pulgging. It results in an increase in the work of breathing.

The respiratory rates of children and infants all need to be set substantially higher than those of adults. For pediatrics, the respiratory rate can be set at from 12 to 45 depending on the disease state and the level of targeted P_{CO_2} one wishes to achieve. Slower respiratory rates are useful in the patient with obstructed airways because slower rates allow more time for exhalation and emptying of hyperinflated areas [22].

Arterial blood gases should be assessed after the patient has been on the ventilator for approximately 20 min and the respiratory rate adjusted accordingly.

4.8.3. *Flow rates*

The selection of peak inspiratory flow rate during volume ventilation is primarily determined by the level of spontaneous inspiratory effort. In patients triggering volume breaths, patient effort, work of breathing, and patient ventilator synchrony depend on the selection of peak inspiratory flow.

Peak inspiratory flows should ideally match patient peak inspiratory demands. This normally requires peak flows to be set at 40–100 l/min, depending on expired volume and the inspiratory demand [36].

4.8.4. *Inspiratory/expiratory (I:E) ratio*

The time allowed for the inspiratory and expiratory phases of mechanical ventilation is commonly referred to as the inspiratory/expiratory (*I:E*) ratio. The inspiratory part of the ratio includes the time to deliver the tidal volume before the exhalation valve opens and exhalation begins. The expiratory part of the ratio includes the time necessary for the tidal volume to exit through the exhalation valve before the next inspiration begins. The inspiratory time should be long enough to deliver the tidal volume at flow rates that will not result in turbulence and high peak airway pressures. The usual *I:E* ratio is 1:1–1:3 [61].

In severe lung disease it is acceptable to prolong the inspiratory time to allow for better distribution of gas and enhance oxygen diffusion. When a longer inspiratory time is required, careful attention should be given to sufficient expiration to avoid stacking of breaths and impeding venous return. Prolonged inspiratory time creates a more laminar flow, which helps to keep the peak pressures lower. Rapid inspiratory times are tolerated in patients with severe airway obstruction. The rapid inspiratory time allows for a longer expiratory phase, which may help to decrease the amount of overinflation [22].

4.8.5. *Inspired oxygen concentration*

As a starting point and until the level of hypoxemia is determined, a patient placed on a ventilator should receive an oxygen concentration of 100%. The concentration should be systematically lowered as soon as arterial blood gases dictate. In general, as a result of the concerns regarding the effects of high oxygen concentration on lung injury, the lowest acceptable oxygen level should be selected as soon as possible. In patients who are difficult to oxygenate, oxygen concentrations can be minimized by optimizing PEEP and mean airway pressures and selecting a minimally acceptable oxygen saturation [62].

4.8.6. *Positive end-expiratory pressure (PEEP)*

PEEP is applied to recruit lung volumes, elevate mean airway pressure, and improve oxygenation [63]. The level of PEEP used varies with the disease process. PEEP levels should start at 8 cm H_2O and be increased in 2.5 cm increments. Increasing levels of PEEP in conjunction with a prolonged inspiratory time aids in oxygenation and allows for the safe level of oxygen to be used. The use of pressure volume curves to determine the best PEEP level has been recommended to aid in over stretching the alveoli. This technique has certain limitations and is dificult to perform in the clinical setting. The use of PEEP trials can determine the best PEEP without causing a decrease in cardiac output.

Optimal PEEP is the level of end-expiratory pressure that results in the lowering of intrapulmonary shunting, significant improvement in arterial oxygenation, and only a small change in cardiac output, arteriovenous oxygen content differences or mixed venous oxygen tension.

4.8.7. *Weaning and discontinuing ventilatory support*

As the conditions that warranted placing the patient on mechanical ventilation stabilizes and begins to resolve, attention must be placed on removing the ventilator as quickly as possible. Patients receiving mechanical ventilation for respiratory failure should undergo a formal assessment of discontinuation if the following criteria are met: [64]

1. Evidence for some reversal of the underlying cause of respiratory failure.
2. Adequate oxygenation ($PaO_2/FiO_2 > 200$–250; requiring positive end expiratory pressure [PEEP] $\leq$ 5–8 cm H_2O; $FiO_2 \leq 0.4$–0.5) and pH $\geq$ 7.25.
3. Hemodynamic stability-requiring no or low dose vasopressor.
4. The capacity to initiate an inspiratory effort.

If the patients meet the above criteria, they should undergo a spontaneous breathing trial. The spontaneous breathing trial includes either a t-tube trial for 30 min or pressure support/CPAP for 1 h. Respiratory mechanics considered adequate prior to or during a spontaneous breathing trial are as follows: [64]

1. Respiratory rate <38 in children, <24 in adults.
2. Spontaneous tidal volume ≥4 ml/kg.
3. Expired minute volume <15 l/min.
4. Negative inspiratory force >30 cm H_2O.
5. Audible leak around the endotracheal balloon cuff.

In general, use of respiratory mechanics evaluate a patient's ability to sustain spontaneous ventilation. They do not assess a patient's ability to protect the upper airway. For this reason, traditional indices often fail to reflect the true clinical picture of a patient with an inhalation injury. For a complete evaluation prior to extubation, bronchoscopic examination will aid in determining if the airway edema has decreased enough to attempt extubation.

Prior to a scheduled extubation it is recommended that reintubation equipment be set up and that the person doing the extubation be experienced in emergency intubations.

If the patient demonstrates signs of inspiratory stridor, the use of racemic epinephrine by aerosol has been effective in reducing the mucosal edema and may prevent the patient from being reintubated.

5. Late complications of inhalation injury

5.1. *Tracheal stenosis*

Tracheal complications are commonly seen and consist of tracheitis, tracheal ulcerations, and granuloma formation. The location of the stenosis is almost invariably subglottic and occurs at the site of the cuff of the endotracheal or tracheostomy tube [65].

Several problems arising after extubation represent sequelae of laryngeal or tracheal injury incurred during the period of intubation. While tracheal stenosis or tracheomalacia are usually mild and asymptomatic, in some patients they can

present as severe fixed or dynamic upper airway obstructions. These conditions can require surgical correction. In the management of intubated patients, such complications should be mostly preventable by meticulous attention to the tracheostomy or endotracheal tube cuff. Inflation of the cuff should be to the minimal pressure level consistent with preventing a leak in the ventilator at end inspiration.

5.2. *Obstructive/restrictive disease*

Chronic airway disease is a relatively rare reported complication of inhalation injury and its supportive treatment. Spirometry is a useful screening tool for airway obstruction. Reports in the literature for adults indicate that lung function returns to normal after inhalation injury [66,67]. However, Mlcak et al. reported pulmonary function changes following inhalation injury for up to 10 years after-injury in children [68]. Fortunately, most pulmonary function abnormalities will persist for only months following lung parenchymal injury. In the great majority of cases eventual resolution of both symptoms and physiological abnormalities will occur. During the resolution phase serial measurement of airflow obstruction should be obtained. Desai et al. demonstrated that physiologic insults that occur as a result of thermal injury may limit exercise endurance in children [69]. Data from exercise stress testing showed evidence of a respiratory limitation to exercise.

In cases of persistent severe respiratory symptoms, the severity of the impairment should be documented and the patient evaluated for a cardiopulmonary exercise rehabilitation program.

5.2.1. *Cardiopulmonary exercise testing and rehabilitation*

Cardiopulmonary exercise testing (CPET) is commonly used to identify patterns of cardiovascular and respiratory abnormalites and limitations during exercise [70–72]. The CPET provides the medical team with a overall and integrated assessment of responses during exercise of the pulmonary, cardiovascular and skeletal muscle systems. The CPET is relatively noninvasive and provides assessment of the degree of exercise tolerance or intolerance, exercise-related symptoms, the objective determination of functional capacity and impairment, as well as information to be used in designing an exercsie rehabilitation program in severely burned individuals. The literature citing the use of CPET in severely burned adults is extremely scarce or non-existent. However, in severely burned children, there are reports of respiratory abnormalities [70]. More recently, we reported in burned children, that a cardiac limitation during maximal exercise is most prevalent, and that this limitation is dependent on the presence or absence of smoke inhalation injury, and the severity of this injury (unpublished data). Nevertheless, the CPET for reasons listed above remains a useful tool in the management of burned patients and in aiding clinical decisions.

The current Standard of Care for rehabilitation of severely burned individuals is to discharge the patient from the hospital, with a written set of instructions for physical and occupational therapy activities at home, in an unsupervised environment. This rehabilitative practice has been suboptimal and has not significantly impacted the persistent and extensive skeletal muscle catabolism and weakness, which is characteristic of severe burns. As a result patients manifest low pulmonary function, low aerobic exercise capacity, reduced muscle strength and muscle mass at 9 months post burn [73,74]. To counteract extreme physical deconditioning, muscle weakness and catabolism, our group has designed a 12-week exercise rehabiliation program, which supplements the physical and occupational therapy exercises [74]. This program has been successful in severely burned children, and has resulted in improvements in exercise tolerance and pulmonary function (FEV1, FVC and MVV), which suggests an improvement in respiratory muscle function [73]. The exercise rehabiliation program also increased lean mass and muscle strength, power, and work, and also decreased the number of surgical interventions for major burn scar contractures involving large joints [74,75].

Though the majority of data on the effects of exercise rehabiliation comes from the severely burned, pediatric population, its applicability to severely burned adults is highly recommended.

A compromised pulmonary function, in addition to a low functional capacity, muscle mass and muscle strength, relative to nonburned individuals, indicate a need to find rehabilitative interventions that improve physical function and performance. Finally, we recommend that an exercise program should be a fundamental component of a multidisciplinary outpatient treatment program for victims of severe burns.

6. Conclusion

Inhalation injury and associated major burns provide a challenge for health care workers who provide direct hands-on care. The technical and physiologic problems which complicate the respiratory management of these patients require an orderly, systematic approach. Successful outcomes require careful attention to treatment priorities, protocols and meticulous attention to details.

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