SCIENTIFIC SECTION

Review Article

Inhalation injury caused by the products of combustion

WALTER J. PETERS, MD, PH D, FRCS[C]

Inhalation injury results from a type of chemical burn (tracheobronchitis) of the respiratory tract. When this injury occurs in patients with serious cutaneous burns the mortality is exceedingly high — 48% to 86%. The injury can be divided into three types according to the level at which the damage occurs: upper airway, major airway and terminal airway. The early signs and symptoms may be complicated by carbon monoxide poisoning. The patient's condition usually follows a staged progression that is proportional to the extent and severity of the tracheobronchitis. Indirect laryngoscopy, bronchoscopy, scintiscanning of the lung with xenon 133 and serial analysis of arterial blood gases are useful diagnostic techniques. Treatment must be expeditious, and it depends on the severity of the injury. The prophylactic use of antibiotics and steroids is contraindicated.

Les blessures par inhalation résultent d'un type de brûlure chimique (trachéobronchite) des voies respiratoires. Quand ces lésions surviennent chez des patients ayant des brûlures cutanées sérieuses, la mortalité est excessivement élevée — 48% à 86%. Les blessures peuvent être divisées en trois types selon le niveau touché: voies respiratoires supérieures, voies respiratoires principales et voies respiratoires terminales. Les signes et symptômes précoces peuvent être compliqués par un empoisonnement au monoxyde de carbone. L'état du patient suit habituellement une progression graduelle qui est proportionnelle à l'étendue et à la gravité de la trachéobronchite. Une laryngoscopie indirecte, la bronchoscopie, la scintigraphie pulmonaire au xénon 133 et les analyses sériées des gaz du sang artériel sont des techniques diagnostiques utiles. Le traitement doit être entrepris rapidement et il dépend de la gravité de la brûlure. L'emploi prophylactique des antibiotiques et des stéroïdes est contre-indiqué.

The seriousness of inhalation injuries in which the respiratory tract is damaged by the inhalation of products of combustion has been recognized for many years. Pliny the Elder[1] (AD 23–79) reported that in the second Punic War prisoners were executed by being placed in cages above greenwood fires. Since then there have been numerous instances of inhalation injury causing death, including several disasters involving many people. Two of the most famous were the cellulose fire in Cleveland in the early 1930s and the Cocoanut Grove fire in Boston in 1942. The risks of complications following inhalation injury were first appreciated after the Cocoanut Grove fire.[2] Many victims initially appeared to have only minimal cutaneous or other injuries and were managed accordingly. Subsequently their condition rapidly deteriorated and many died from respiratory problems.

Inhalation injury remains one of the most serious consequences of injury by fire.[3] When a patient with an inhalation injury has also suffered serious cutaneous burns the mortality is much higher than with either of these injuries alone,[4,5] ranging from 48% to 86%.[6]

Classification

Thermal injury

Direct heat has been shown to cause edema and obstruction above the trachea.[7,8] Below this level, however, it is an extremely uncommon cause of injury.[9-11] A blast of hot air causes a reflex closure of the vocal cords, preventing damage to the airway. When the intake of hot air is steady and sustained, it is very effectively cooled by the moist air already within the respiratory tract. Air at 270°C blown into the larynx of a group of dogs was cooled to 50°C by the time it reached the trachea.[11] In two studies[9,10] involving 697 burn casualties, only one patient showed evidence of necrosis of the respiratory tract as a result of direct heat. This injury, caused by a fire in a chamber containing 100% oxygen, extended only a few centimetres below the glottis. Steam, with a heat-carrying capacity 4000 times that of hot air, can produce direct heat injury, but this specific cause is uncommon.

Chemical injury

It is currently recognized that inhaled products of combustion can cause a type of chemical burn (tracheobronchitis) that may involve various levels of the respiratory tree.[4] Smoke inhalation injuries can

From the division of plastic surgery, Toronto General Hospital, and the department of surgery, University of Toronto

Reprint requests to: Dr. Walter J. Peters, Ste. 240, 10th floor, Eaton Building, Toronto General Hospital, 101 College St., Toronto, Ont. M5G 1L7

NFB Photothèque ONF, Ottawa, supplied the cover illustration for this issue of the Journal.

← For prescribing information see page 281

thus be divided into three types according to the level at which the damage occurs:[4,12,13]

- Upper airway — larynx and vocal cords.
- Major airway — tracheobronchial tree.
- Terminal airway (parenchymal) — bronchioles and alveoli.

Generally the type of injury is upper airway in 60%, major airway in 30% and parenchymal in 10% of cases,[4] although damage may occur simultaneously in two or all three of these areas.

In their study of the victims of the Cocoanut Grove fire Aub and associates[2] described a group of smoke inhalation syndromes related to the time of onset of respiratory symptoms. Stone and colleagues[14,15] also divided patients into categories according to the interval between the accident and the appearance of symptoms and attempted to define the injury by its clinical phases. The patients studied by the Stone group had suffered a specific respiratory injury as well as facial flame burns and singed nasal vibrissae; the fire had been in a closed space.[14]

Carbon monoxide poisoning

Carbon monoxide poisoning is frequently associated with inhalation injury.[16] Although carbon monoxide is the gas most commonly produced in all types of fire, most burn patients survive exposure to it. Those who succumb to asphyxia usually die at the scene of the fire or very shortly after they arrive at a hospital. The affinity of hemoglobin for carbon monoxide is 250 times greater than that for oxygen. In addition, carbon monoxide causes hemoglobin to bind to oxygen with abnormal tenacity, so that the oxygen–hemoglobin dissociation curve progressively shifts to the left. Thus, the oxygen tension in the tissues must decrease to very low levels before appreciable amounts of oxygen are released from hemoglobin.[16]

Pathogenesis

There is some degree of mucosal erythema, edema, ulceration and hemorrhage immediately after smoke is inhaled.[4] Subsequently these features progress in stages in proportion to the extent and severity of the chemical burn (Table I).[4,16,17]

Acute stage

Respiratory distress may develop within a few hours in the patient who has suffered a severe inhalation injury involving the proximal and distal airways. The rapid deterioration in the condition of such patients results from bronchospasm or extensive alveolar damage or both, and is usually lethal.[4] However, at this stage most patients, in whom the inhalation injury is usually much less severe, have no abnormal findings or minimal signs and symptoms of damage. For these patients this stage is a "lucid interval" before the onset of the second stage.

Second stage

This stage generally occurs 8 to 48 hours after the patient is injured, but it can also develop more quickly, without differentiation from the acute stage. It is characterized by edema of the upper airway, where it may result in obstruction (primarily of the false vocal cords), or the lower airway, where pulmonary edema may develop, or both.

In the first 24 hours symptoms are more likely to be due to upper airway obstruction.[4,14] In the following 24 to 48 hours they are more likely to be due to pulmonary edema, which tends to be more severe in patients with limited cardiopulmonary reserve and in those whose fluid replacement is overly vigorous. As the lung parenchyma becomes edematous its compliance decreases, as does the arterial–alveolar difference in oxygen tension, owing to shunting hypoxia (caused by the shunting of blood from damaged areas) and increased pulmonary vascular resistance.[17]

Recently experiments with dogs have demonstrated a virtually instantaneous deficit of surfactant in the dogs' lungs after smoke inhalation.[18] This may explain the early development of atelectasis and alveolar wall instability with this injury.[18] Because the half-life of surfactant may be 43 to 45 hours,[19] the rapid depression in the amount of this substance in these experiments suggests that the surfactant that was already present was inactivated.[18] The development of pulmonary edema following this reduction in the amount of surfactant might help explain why victims of smoke inhalation who also have cutaneous burns and therefore require large volumes of fluid are so vulnerable to complications of fluid administration.[18]

Third stage

In this last stage, which usually occurs after the third day, the patient has pneumonia that usually is bronchial, caused by gram-negative bacteria and associated with profuse bronchorrhea. It occurs most commonly in patients with major airway damage who have lost ciliary and mucosal protection. These patients clear their lung secretions poorly, and their capacity for both systemic and local immunity is reduced.[4]

Although the cause of the exceedingly high mortality after the combination of inhalation injury and serious cutaneous burns and the exact interrelation between these injuries remain unknown,[6] an adult form of respiratory distress syndrome may develop in these patients because of the combination of injuries and the pneumonia.[20,21]

Uncommonly, rapidly progressive pulmonary insufficiency may occur in patients with inhalation injuries who do not seem to have edema. The condition of these patients tends to deteriorate, and they suffer severe

Table I—Stages of inhalation injury

Stage	Time after inhalation	Features
Acute	3 to 8 hours	Minimal to respiratory distress from bronchospasm or alveolar damage or both
Second	8 to 48 hours	Edema of upper airway (obstruction) or lower airway (pulmonary edema) or both
Third	After third day	Pneumonia, usually due to gram-negative organisms

hypoxia and hypercarbia in spite of intubation and ventilatory support. Although the mechanism is unclear, this condition may be a result of direct damage to the capillary–alveolar membrane.[4]

Diagnosis

The early diagnosis of a smoke inhalation injury, whether the upper, major or terminal airways are involved, is often difficult because the characteristic clinical and radiologic signs may not yet be apparent 24 to 48 hours after inhalation. Certain clinical features should lead physicians to suspect an inhalation injury, including a facial burn, singed nasal vibrissae, hoarseness, carbonaceous sputum and wheezing. Patients whose burns are the result of a fire in a closed space may have inhalation injury as well.

A diagnosis of carbon monoxide poisoning may have to be made without biochemical confirmation. Exposure to significant amounts of carbon monoxide results in hypoxemia, the signs of which vary from irritability to depression. Any suspicion of alterations in consciousness or mental clarity necessitates administration of high concentrations of oxygen as soon as possible.

Chest roentgenograms and blood gas values are often normal in the period immediately after the injury is suffered but become abnormal before the onset of respiratory insufficiency.[8,22] The radiologic findings include the appearance of patchy or diffuse peribronchial infiltrates that may persist for several weeks.[23] As well, a significant depression of the partial pressure of oxygen in arterial blood (Pa_{O_2}) — particularly below 250 mm Hg when the fractional intake of oxygen ($F_{I}O_2$) is 100% — has been shown to be associated with early respiratory insufficiency.[8]

Other tests that can be diagnostic include indirect laryngoscopy, fibreoptic bronchoscopy,[24,25] xenon 133 lung scanning[5] and pulmonary function testing.[4] At our unit all patients suspected of having inhalation injury undergo bronchoscopy on admission to hospital to ascertain the level of the injury and to obtain some indication of its severity. If this procedure, which allows the clinician to observe the upper and major airways, is not readily available, indirect laryngoscopy (with a flashlight and laryngeal mirror) provides similar information to the level of the vocal cords. The endoscopic criteria for an inhalation injury include mucosal erythema, edema, ulceration, hemorrhage and the presence of carbonaceous material, although patients who are in hypovolemic shock may not demonstrate mucosal changes until adequate amounts of fluid have been administered.[24] These conditions are present immediately after the injury and become progressively worse, depending on the severity of the injury.[24] With severe injuries edema may be massive, producing anatomic distortion, with airway narrowing and obstruction. Further hemorrhage and ulceration may develop and lead first to ischemia and then to necrosis.[24] The patient may also suffer from pulmonary sepsis.[24]

Scintiscanning with ^{133}Xe, which permits the assessment of parenchymal injuries by measuring the delay in clearance from the lungs of injected or inhaled xenon gas, is a more useful tool for evaluating problems of the terminal airways,[6] although it is usually not until 3 to 4 hours after an injury that there is sufficient edema for the scintiscan to yield abnormal findings. This delay may well extend beyond the optimal time for starting therapy.

False-negative results may be obtained with both scintiscanning and bronchoscopy.[5] In such cases in particular pulmonary function tests can be of value, indicating decreases in lung volume and in flow rates in those with a serious inhalation injury. However, although these tests indicate that an inhalation injury is present, they frequently fail to define the extent of the injury.

Treatment

Treatment of patients with an inhalation injury depends on the severity of the injury and on the types of complications they have. The treatment for exposure to carbon monoxide is rapid administration of oxygen, usually as an emergency measure at the scene of the fire. A nomogram, based on the blood level of carboxyhemoglobin at the time of admission, can be used to calculate the level of carbon monoxide in the patient's blood at the time of exposure.[16] This estimate may help the physician to judge the prognosis of a severe injury. Although mechanical ventilation may be required if the carbon monoxide level approaches the lethal limit, hyperbaric oxygen is rarely required.

Treatment of all patients with a diagnosis of inhalation injury includes the administration of humidified oxygen, intermittent positive-pressure ventilation every 2 to 4 hours,[23] and frequent pulmonary toilet by careful, gentle suctioning.[26] Patients are given vigorous chest physiotherapy, and coughing and deep breathing exercises are emphasized early. Those with bronchospasm and wheezing are treated with bronchodilators such as aminophylline given systemically or in aerosol form.

If bronchoscopy or indirect laryngoscopy reveals severe edema of the vocal cords an endotracheal tube is immediately inserted, although in some cases the swelling is so severe as to make this very difficult or even impossible.[27,28] Hoarseness and stridor often indicate occlusion of the upper airway. Early intubation may also be indicated after severe burns of the face, nose or mouth.[7] Tracheostomy is rarely required early, as it could be a further source of infection. It may be required later in patients with a combination of inhalation injury and severe cutaneous burns.[27] A nasotracheal tube will often serve as a splint for the upper airway obstruction until the edema subsides, generally by the fourth or fifth day after the injury.

Patients are observed very carefully over the first 24 to 48 hours after the injury for signs of airway obstruction requiring mechanical ventilation. Positive-pressure ventilation is generally instituted when the Pa_{O_2} falls below 60 mm Hg at an $F_{I}O_2$ of 50% or when the vital capacity is below 15 ml of air per kilogram of body weight.[29] Since the most serious abnormality is a reduction in effective lung volume due to airway and alveolar closure, the ventilator must reopen collapsed alveoli with a sufficiently high inflation pressure and volume to keep them open at the end of expiration

and thus allow adequate gas exchange. This frequently requires the addition of positive end-expiratory pressure (PEEP), generally in 5-cm increments, when the Pa_{O_2} fails to improve with positive pressure alone at an F_{IO_2} of 50%. To avoid a reduction in cardiac output a Swan–Ganz catheter is generally inserted if PEEP levels of 10 cm saline or greater are required to keep the Pa_{O_2} at 70 to 90 mm Hg.[29,30]

In our unit, patients requiring intubation and ventilation are usually managed in the respiratory care unit, which provides the facilities and the expertise necessary for precise minute-to-minute monitoring.[23] The inspired oxygen content, rate of ventilation and tidal volume are regulated so as to keep the arterial blood gases and the pH at required levels (e.g., P_{O_2} greater than 75 mm Hg). The hourly input and output of fluids and the daily body weight are meticulously recorded to monitor fluid balance. A nasogastric tube is frequently necessary to avoid abdominal distension. The patient must be watched, and treated immediately, for fluid overload, sepsis, heart failure and intravascular coagulation.[23]

At present, controversy exists regarding the optimum fluid therapy following an inhalation injury.[31] Differences of opinion also exist as to whether patients should be given more or less fluid if pulmonary involvement complicates a thermal injury.[31,32] Clear evidence supporting either approach is not currently available. However, because of increased edema of the lung parenchyma, fluids are generally restricted to some degree during early treatment.[31] We regulate fluids so as to keep the hourly urine output at about 0.5 ml per kilogram of body weight.

In earlier years the probability that pulmonary edema and subsequent gram-negative pneumonia would develop in patients with inhalation injury suggested experiments to test the advantages of the prophylactic administration of steroids and antibiotics.[3] Experiments in animals with inhalation injury alone showed that the mortality was lower in those given steroids with high glucocorticoid activity (methylprednisolone and dexamethasone) than in those given steroids with mineralocorticoid activity.[33] Subsequent clinical trials with these agents, given either systemically or in aerosol form, failed to demonstrate a beneficial effect and, in fact, indicated that their use in patients with serious burns could be hazardous, resulting in an increased risk of infection[6] and death.[4] Therefore, the prophylactic use of steroids and antibiotics for inhalation injury in patients with serious cutaneous burns is currently contraindicated.

Conclusions

The overall mortality following inhalation injury remains high. The association of serious cutaneous burns with inhalation injury increases the expected mortality to between 48% and 86%. Reductions in both mortality and morbidity are unlikely until there is an increase in the extent to which the fundamental pathogenesis of the disorder is understood; this may require studies of the toxic effects of smoke and of pulmonary cellular function. Earlier diagnosis of injury to lung parenchyma or terminal airways, perhaps by means of direct measurements of ventilation/perfusion ratios, compartmental analysis and study of the elimination of multiple inert gases, may also improve the prognosis.[21]

References

1. MARGOTTA R: *An Illustrated History of Medicine*, Hamlyn, Middlesex, Engl, 1967: 86
2. AUB JC, PITTMAN H, BRUES AM: Symposium on management of Cocoanut Grove burns at Massachusetts General Hospital. Pulmonary complications: a clinical description. *Ann Surg* 1943; 117: 834–840
3. PHILLIPS AW, COPE O: Burn therapy. II. The revelation of respiratory tract damage as a principal killer of the burned patient. *Ann Surg* 1962; 155: 1–19
4. MOYLAN JA, CHAN C-K: Inhalation injury — an increasing problem. *Ann Surg* 1978; 188: 34–37
5. AGEE RN, LONG JM III, HUNT JL, PETROFF PA, LULL RJ, MASON AD JR, PRUITT BA JR: Use of ^{133}xenon in early diagnosis of inhalation injury. *J Trauma* 1976; 16: 218–224
6. LEVINE BA, PETROFF PA, SLADE CL, PRUITT BA JR: Prospective trials of dexamethosone and aerosolized gentamicin in the treatment of inhalation injury in the burned patient. *J Trauma* 1978; 18: 188–193
7. MELLINS RB, PARK S: Respiratory complications of smoke inhalation in victims of fires. *J Pediatr* 1975; 87: 1–7
8. LUCE EA, SU CT, HOOPES JE: Alveolar–arterial oxygen gradient in the burn patient. *J Trauma* 1976; 16: 212–217
9. PRUITT BA JR: Pulmonary complications in burn patients. A comparative study of 697 patients. *J Thorac Cardiovasc Surg* 1970; 59: 7–20
10. DIVINCENTI FC, PRUITT BA JR, RECKLER JM: Inhalation injuries. *J Trauma* 1971; 11: 109–117
11. MORITZ AR, HENRIQUES FC JR, MCLEAN R: The effects of inhaled heat on the air passages and lungs: an experimental investigation. *Am J Pathol* 1945; 21: 311–331
12. HOROVITZ JH: Abnormalities caused by smoke inhalation. *J Trauma* 1979; 19 (suppl): 915–916
13. MOYLAN JA: Supportive therapy in burn care. Smoke inhalation. Diagnostic techniques and steroids. Ibid: 917
14. STONE HH, RHAME DW, CORBITT JD, GIVEN KS, MARTIN JD JR: Respiratory burns: a correlation of clinical and laboratory results. *Ann Surg* 1967; 165: 157–168
15. STONE HH: Management of respiratory injury according to clinical phase. In POLK HC, STONE HH (eds): *Contemporary Burn Management*, Little, Boston, 1971: 111–123
16. ZIKRIA BA, BUDD DC, FLOCH F, FERRER JM: What is clinical smoke poisoning? *Ann Surg* 1975; 181: 151–156
17. STEPHENSON SF, ESRIG BC, POLK HC JR, FULTON RL: The pathophysiology of smoke inhalation injury. *Ann Surg* 1975; 182: 652–660
18. NIEMAN GF, CLARK WR JR, WAX SD, WEBB WR: The effect of smoke inhalation on pulmonary surfactant. *Ann Surg* 1980; 191: 171–181
19. BALIS JU, SHELLEY SA: Quantitative evaluation of the surfactant system of the lung. *Ann Clin Lab Sci* 1972; 2: 410–419
20. ARTURSON G: Respiratory responses to burn injury. *Burns* 1974; 1: 254–260
21. POWERS SR JR: Supportive therapy in burn care. Consensus summary on smoke inhalation. *J Trauma* 1979; 19 (suppl): 921
22. ROBINSON TJ, BUBNA-KASTELIZ B, STRANC MF: Alterations in pulmonary ventilation and blood gases in acute burns. *Br J Plast Surg* 1972; 25: 250–260
23. PRUITT BA, ERICKSON DR, MORRIS A: Progressive pulmonary insufficiency and other pulmonary complications of thermal injury. *J Trauma* 1975; 15: 369–379
24. HUNT JL, AGEE RN, PRUITT BA JR: Fiberoptic bronchoscopy in acute inhalation injury. Ibid: 641–649
25. MOYLAN JA JR, ADIB K, BIRNBAUM M: Fiberopic bronchoscopy following thermal injury. *Surg Gynecol Obstet* 1975; 140: 541–543
26. PRUITT BA JR, MOYLAN JA JR: Current management of thermal burns. *Adv Surg* 1972; 6: 237–288
27. BARTLETT RH, NICCOLE M, TAVIS MJ, ALLYN PA, FURNAS DW: Acute management of the upper airway in facial burns and smoke inhalation. *Arch Surg* 1976; 111: 744–749
28. WANNER A, CUTCHAVAREE D: Early recognition of upper airway obstruction following smoke inhalation. *Am Rev Respir Dis* 1973; 180: 1421–1423
29. GREENFIELD LJ: Adult respiratory distress syndrome: *Am Surg* 1978; 44: 133–136
30. KIRBY RR, DOWNS JB, CIVETTA JM, MODELL JH, DANNEMILLER FJ, KLEIN EF, HODGES FM: High level positive end expiratory pressure (PEEP) in acute respiratory insufficiency. *Chest* 1975; 67: 156–163
31. MONCRIEF JA: Replacement therapy. In ARTZ CP, MONCRIEF JA, PRUITT BA JR (eds): *Burns: a Team Approach*, Saunders, Philadelphia, 1979: 186–198
32. ZAWACKI BE, JUNG RC, ROYCE J, RINCON E: Smoke, burns, and the natural history of inhalation injury in fire victims. A correlation of experimental and clinical data. *Ann Surg* 1977; 185: 100–110
33. DRESSLER DP, SKORNIK WA, KUPERSMITH S: Corticosteroid treatment of experimental smoke inhalation. *Ann Surg* 1976; 183: 46–52