RESPIRATOR TREATMENT OF CRUSHED CHEST INJURIES*

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In recent years there has been an increasing awareness of the necessity for more specialized treatment of crushed chest injuries, with particular reference to internal pneumatic stabilization of the chest wall by intermittent positive-pressure respiration (IPPR). This form of treatment was introduced by Mörch *et al.*[1,2] and has gained widespread acceptance.[3-6] Since the advent of IPPR in the treatment of crushed chest injuries the mortality rate, which used to be high at 76%,[4] has improved to between 9·09% and 25%.[6-8] However, with the improved survival rates consequent on the successful management of the chest condition other medical problems which require specialized treatment have become manifest.

The purpose of this article is not only to discuss the management of the crushed chest, but also to outline the results of treatment and medical problems we encountered in 36 cases over a 33-month period from March 1964 to December 1966. In most centres the crushed chest is initially treated by the surgeon or anaesthetist, who then continues the maintenance therapy. The physician in our centre plays an important part in the management of these cases, as the Respiratory Resuscitation Unit falls under the auspices of the Department of Medicine.[9]

PATHOPHYSIOLOGY OF CRUSHED CHEST INJURY

Mörch *et al.*[3] discussed the management of the flail chest and the correction of the abnormality by IPPR. The pathophysiological changes are more widespread than they initially indicated, and involve not only mechanical instability of the chest wall but metabolic as well as cardiopulmonary abnormalities as outlined in Fig. 1.

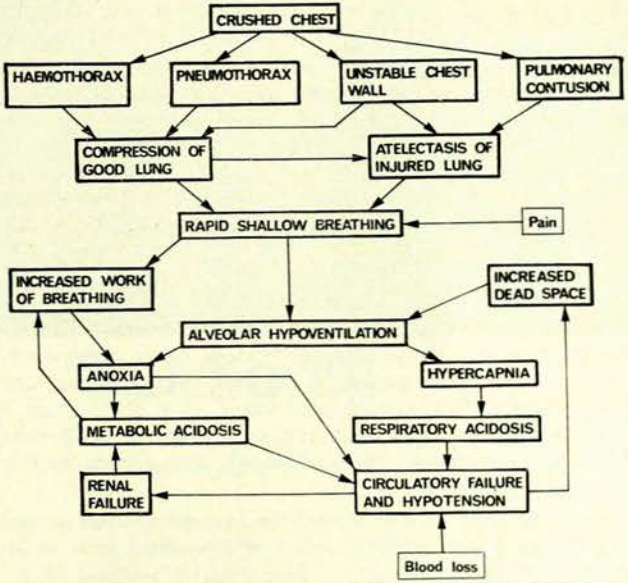

Fig. 1. Crush injury of the chest may be followed by respiratory, circulatory and renal failure. The interrelationship of these conditions is illustrated.

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Consequent on closed chest injury, pulmonary contusion, flail segment and haemopneumothorax are the most common occurrences. Mechanical instability results in the chest wall being sucked in during inspiration, making it impossible for the underlying lung to receive the correct proportion of the tidal volume. Haemopneumothorax, or bowel which occasionally herniates through a torn diaphragm, may lead to compression atelectasis of normal lung. Progressive tension pneumothorax is a particularly dangerous event and may occur before or during the course of treatment with IPPR. Pulmonary contusion results in bronchiolar and alveolar obstruction by oedema fluid and blood. As pulmonary arterial perfusion may continue in the contused and unventilated area, an effective right-to-left shunt may be created.[10] Splinting of the chest wall due to pain at the fracture sites, in addition to factors already considered, may lead to rapid, shallow respiration and alveolar hypoventilation. Hypercapnia and hypoxia may occur, followed by circulatory collapse, hypotension, renal failure and metabolic acidosis. Circulatory failure and hypotension give rise to an increased alveolar dead space and impaired gas exchange[11,12] which further aggravates the alveolar hypoventilation. Finally, blood loss, a common event in these cases, will aggravate cardiovascular collapse.

MANAGEMENT

Indications for Tracheostomy and IPPR

Indications for tracheostomy in crushed chest are overlapping, and usually they are present in combination with each other. More rapid healing and a better cosmetic result are often obtained when a flail chest is adequately ventilated. In the presence of a significant flail segment, respiratory failure or dyspnoea and cyanosis are frequently noted at an early stage, and should be regarded as an indication for tracheostomy and IPPR. In addition, these cases may become complicated by infection[13] or the natural course of pulmonary contusion.[14] Severe pain and distress, requiring heavy sedation, are often managed best when the patient is safely on a respirator and the danger of respiratory depression consequent on heavy sedation is minimized. Other methods of controlling pain, such as segmental epidural block,[15] have not been used by this unit. Ineffective cough and accumulation of secretions due to pain are a constant hazard and result in major bronchial obstruction. A less common but urgent indication for tracheostomy is trauma to the larynx or trachea.

Management of an Acute Case

In most instances closed chest injury results in an insignificant flail segment, and perhaps a small haemopneumothorax. These uncomplicated cases are easily managed on a conservative regimen of analgesia and physiotherapy. The complicated cases, with chest trauma, head injury and abdominal injuries, as well as long-bone fractures with blood loss and shock, are approached in the following manner:

1. A reliable airway should be secured at the earliest possible moment. After a cuffed endotracheal tube is inserted a tracheostomy is the most reliable method of ensuring that an upper respiratory obstruction by trauma, secretions or blood is prevented and corrected.

2. IPPR is instituted. Synchronization of the patient's breathing with a fixed-volume time-cycled machine, such as the Engström respirator, can be achieved by hyperventilation. If this fails, opiates in liberal dosage to suppress spontaneous ventilation should be used. When these techniques fail, the patient is paralysed with muscle relaxants. In only 1 case was it necessary to use a patient-triggered pressure-cycled machine such as the Bird respirator because of failure of synchronization with the Engström respirator.

3. Haemothorax and pneumothorax must be looked for at an early stage, and if found an underwater drain should be inserted before IPPR is commenced. The absence of a pneumothorax initially does not exclude the possibility of it developing soon after IPPR is commenced. The chest should, therefore, be examined radiologically initially and observed clinically repeatedly thereafter.

4. Blood loss and shock associated with long-bone fractures, ruptured abdominal viscera and intrathoracic bleeding, which frequently accompany closed chest injury, must be treated vigorously by transfusion. The early repletion of blood volume and maintenance of blood pressure will prevent the development of oliguric renal failure. The administration of 25 G of mannitol intravenously is a valuable adjunct in initiating and maintaining a urinary output. Furosemide, given intravenously, may also be used to promote a diuresis, or may be used initially when mannitol is contraindicated.

5. Abdominal injuries and fractures must be excluded if possible before the patient is transferred to the Respiratory Resuscitation Unit. However, treatment of haemorrhage and respiratory failure takes precedence over the exclusion of abdominal injuries. Paracentesis of all 4 quadrants of the abdomen may be carried out as a means of detecting free blood in the peritoneal cavity. X-ray of the abdomen after the introduction of Gastrografin, if necessary through a nasogastric tube, may show up visceral injuries as well as herniation of bowel through a torn diaphragm into the chest. Cystoscopy and retrograde pyelography are required where renal trauma or ureteric obstruction due to blood clot or crush injury is suspected.

6. All cases should be monitored for cardiac arrhythmias, as these may be lethal as well as potentially reversible.

7. Early and frequent measurement of pH and PCO_2,[16] as well as standard bicarbonate and base excess,[17-19] will indicate the adequacy of mechanical ventilation and assist in the management of acid-base balance. Changes in minute ventilation may be made on the basis of these results. When the patient's condition is stabilized, these estimations need to be carried out infrequently.

Apart from routine nursing care and skilled physiotherapy, tracheal lavage and aspiration, using 5 - 10 ml. warm sterile saline, is carried out every 15 - 30 minutes, depending on the pulmonary condition. Specimens of tracheal aspirate are cultured bi-weekly to detect the onset of superadded pulmonary infection. Daily white cell counts and estimations of haemoglobin, urea and electrolyte concentrations are carried out until the patient's condition is stabilized.

It is necessary to emphasize that close cooperation be-

tween surgeon, anaesthetist and physician is essential in the early management of the complicated case.

ANALYSIS OF 36 CASES

Average Age and General Health of Patients

Age alone appeared to have no influence on the mortality rate, the oldest patient being 77 years and the youngest 18 (average 49·8 years). Nine patients had a background illness before admission (Table I). No deaths

TABLE I. CHRONIC ILLNESS BEFORE ADMISSION

Age in years	*Sex*	*Illness*	*Outcome*
66	M	Chronic airways disease, diabetes mellitus, essential hypertension, chronic renal failure	Recovered
48	M	Deep vein thrombosis (on Warfarin)	Recovered
55	M	Diabetes mellitus	Recovered
55	F	Diabetes mellitus, angina pectoris, chronic pyelonephritis	Recovered
55	M	Chronic airways disease	Recovered
66	M	Chronic airways disease	Recovered
51	M	Alcoholism, cirrhosis	Recovered
66	M	Chronic airways disease, cor pulmonale, diabetes mellitus, chronic pyelonephritis	Died 1 month after discharge
77	M	Ischaemic heart disease	Died 5 days after admission ? myocardial contusion

occurring during the course of hospitalization could be directly attributed to the presence of chronic illness. One death occurred at home 1 month after discharge in a man with chronic obstructive airways disease. As no details of his death are known, it is impossible to say what part the thoracic injury played in it.

Mode of Accident

There were 27 instances of motor vehicle accidents, with a mortality rate of 27%. Of the 5 pedestrians who were run over, 3 died; a mortality rate of 60%. One fatal accident resulted from a mentally defective male standing in the path of an oncoming train. Three patients experienced unusual accidents: an elderly woman fell and injured her chest in a household accident; a motor-scooter fell on a patient's chest while he was repairing it; and the last case was the result of a farmer falling off his tractor and being run over by it. All 3 patients recovered.

Distribution of Chest Injuries

Table II shows that all patients suffered thoracic cage

TABLE II. NATURE OF CHEST INJURY

Site	*No. of cases*
Cage only	5
Cage + contusion	9
Cage + pleura	4
Cage + contusion + pleura	13
Cage + contusion + cardiac	3
Cage + pleura + cardiac	2

injuries, i.e. fractured ribs with a flail segment, and 69% of the cases had evidence of pulmonary contusion. Criteria used for the diagnosis of the pulmonary contusion are similar to those outlined by Alfano and Hale,[14] viz. the onset of dyspnoea, cyanosis, a bloody tracheal aspirate and crepitations or evidence of consolidation usually in the first 24 hours after injury. Radiological changes vary from solitary areas of patchy infiltration to signs of atelectasis or consolidation. Pleural injury consisted of pneumothorax alone, or with haemothorax, and was present in 53% of cases. Evidence of cardiac trauma was found in only 5 cases, i.e. 14% (Table III). These injuries

TABLE III. CARDIAC ABNORMALITIES ATTRIBUTABLE TO TRAUMA

Age in years	*Sex*	*Abnormality*
77	M	Atrial fibrillation, ventricular extrasystoles
41	M	Pericarditis
74	M	Pericarditis and myocardial contusion
66	M	Multiple ventricular extrasystoles
63	M	Myocardial contusion

consisted of myocardial contusion as evidenced by electrocardiographic changes of ST segment depression and T wave inversion in 2 cases; pericarditis was noticed clinically in 2 cases; and the presence of arrhythmia attributable to myocardial contusion was noted in 1 case soon after admission. No cases with cardiac tamponade, valvular damage or aortic rupture were seen.

It is evident from Table IV that more than half the

TABLE IV. DISTRIBUTION OF INJURIES (LOWER LIMB FRACTURES NOT INCLUDED)

Site	*No.*	*Mortality*
Thorax only	16	0
Thorax + abdomen	2	0
Thorax + head	14	9 (64%)
Thorax + abdomen + head	4	2 (50%)
Total	36	11 (30·6%)

cases were complicated by abdominal or head injuries. Thoracic injury alone had a good prognosis, whereas head and abdominal injuries were associated with a high mortality rate.

Causes of Death

These are listed in Table V. Four patients died of the

TABLE V. CAUSES OF DEATH IN 11 PATIENTS

Age in years	*Cause of death*	*Survival time (days)*
18	Head injury	8
18	Head injury	8
28	Head injury	5
66	Head injury	1
51	Generalized candidiasis	39
60	Postgastrectomy bleed	16
36	Tracheo-oesophageal fistula	50
68	Abdominal gas gangrene	90
25	Renal failure, staph. pneumonia	14
77	Arrhythmia—contusion of myocardium	5
25	Ruptured main bronchus	2

effects of severe head injuries. At the time of their death the chest condition had improved or was improving rapidly. Five other patients died from complications not directly related to the initial chest injury.

Of the 11 deaths, only 2 can be attributed directly to the chest injury. A 77-year-old male showed evidence of myocardial contusion and an arrhythmia. He died from an arrhythmia on the 5th hospital day. A 25-year-old male who sustained a severe head injury and was in a coma with a left hemiplegia, also had a flail chest with bilateral pneumothoraces. On instituting IPPR it was evident that, although bilateral intercostal drains were allowing a large quantity of air to escape, the pulmonary collapse was progressive. Two further intercostal drains were inserted and a bronchoscopy was carried out. A bronchial rupture was not detected, but after the patient had died from progressive respiratory failure it was demonstrated at autopsy.

Mechanical Complications of Tracheostomy and IPPR

Table VI lists complications encountered after tracheostomy and during the treatment with IPPR. Ten cases developed a significant complication, an incidence of 27%.

TABLE VI. MECHANICAL COMPLICATIONS OF TRACHEOSTOMY AND IPPR

Complication	*No.*
Tracheal stenosis	2
Tracheo-oesophageal fistula	1
Surgical emphysema	4
Tension pneumothorax	3
Total	10 (27%)

Tracheal stenosis occurred in 2 cases. In 1 patient this was at the level of the larynx and associated with evidence of severe soft-tissue trauma and could be attributed to the trauma sustained during his accident. The other occurred close to the site of the tracheostomy. A tracheo-oesophageal fistula occurred in 1 case at the level of the tracheostomy. Surgical emphysema developed after IPPR was instituted in 4 cases. In 1 case its onset was rapid (within 30 minutes) and extensive, involving arms and trunk, requiring drainage through the scrotum by trochar and cannula. When surgical emphysema occurs, the possibility of tension pneumothorax, bronchial rupture and, most commonly in our experience, malposition or dislocation of the tracheostomy tube, should be excluded.

On admission, 12 cases were noted to have either pneumothorax or haemothorax. Eleven cases had underwater drains inserted before or immediately after IPPR was commenced. Nevertheless, within 24 hours of commencing IPPR, despite our awareness of this condition, 3 further cases developed a tension pneumothorax which necessitated urgent treatment.

Complications Requiring Medical Management

The fact that the immediate mortality rate has been improved dramatically by the advent of IPPR, and patients who would have died in the first few days are surviving, has led inevitably to the development of other complications related to the injury itself or the presence of previously existing disease. These cases are outlined in Table VII. Frequently more than 1 complication occurred in the same patient.

TABLE VII. COMPLICATIONS REQUIRING MEDICAL MANAGEMENT

Condition	*No.*
Acute renal failure	6
Chronic renal failure	3
Hepatic disease	1
Cardiac	
Supraventricular tachycardia	3
Congestive cardiac failure	2
Pulmonary infection	22

Of 6 cases with acute renal failure, 1 underwent haemodialysis 3 times and then prolonged peritoneal dialysis; 1 needed peritoneal dialysis only; and 4 cases were managed conservatively on a regimen for acute renal failure. These 4 patients recovered. Three cases were admitted with a background of chronic renal failure, 1 patient having diabetic glomerulosclerosis and the other 2 chronic pyelonephritis. One patient with a strong history of alcoholism and poor hepatic function presented with persistent hypokalaemia. Apart from oral potassium supplementation, 100 - 150 mEq. potassium were given intravenously daily to prevent the onset of dangerous hypokalaemia. Three cases developed a supraventricular tachycardia soon after admission; 2 responded to the administration of digitalis, but 1 was resistant to drug therapy and required cardioversion. Two patients with chronic obstructive airways disease developed congestive cardiac failure which responded well to a routine anti-failure regimen.

Pulmonary infection was the most common, and often a serious, complication. In a previous report[8] this high incidence was already apparent. Nine different organisms were cultured on a total of 32 occasions, the most common infecting bacteria being *Staphylococcus aureus* and *Pseudomonas pyocyaneus*. A wide variety of antibiotics was administered. On an average, each case received 4 different antibiotics in combination or serially. In 3 cases death could be attributed to the infection: 1 case with systemic candidiasis; the second with bronchopneumonia after development of a tracheo-oesophageal fistula; and the third with staphylococcal pneumonia in the presence of acute renal failure.

DISCUSSION

In the series presented there was an over-all mortality of 30·6%. This is a little higher than most figures quoted since the advent of IPPR. Crushed chest injuries have been classified into 3 categories by Reid and Baird[10] and Lloyd *et al.*[20] and indications for ventilatory therapy are based on these classifications (Table VIII). Many authors

TABLE VIII. CLASSIFICATION OF CHEST INJURIES (AFTER CAMPBELL)[21]

Classification		*Clinical features and treatment*	
Descriptive	*Numerical*	*Lloyd et al.*[20] *(1965)*	*Reid and Baird*[10] *(1965)*
Mild	1	One or two fractured ribs. Cough is adequate. No ventilatory impairment. Relief of pain only	Extent of injury varies. Cough is effective. Reduced oxygen and carbon dioxide in arterial blood. Relief of pain and oxygen therapy required
Moderate	2	May have floating segment. Cough inadequate. Ventilatory impairment. Tracheostomy required	More serious chest injury, often other injuries too. Reduced oxygen and carbon dioxide in arterial blood. Cough ineffective. Tracheostomy required and humidified oxygen
Severe	3	As in 2, but require IPPR in addition	Chest injury severe as in 2. Arterial oxygen low; respiratory acidosis uncompensated. IPPR required

quote mortality figures in relation to the classification into which the injury falls. For example, class 1 has a 100% survival rate in the hands of Reid and Baird, as well as in the hands of Campbell.[21] In class 2 the mortality is 37·5%,[10] 7·1%,[20] and 41·7%.[21] Class 3 has the highest mortality in the experience of these authors, i.e. 53·6%, 27·3% and 50%, respectively. All cases admitted to, and treated in, the Respiratory Resuscitation Unit of Johannesburg Hospital fell into class 2 or class 3. As can be seen from the figures presented, many of these patients had severe complications, such as head injury and other respiratory complications later in the course of their illness. Thus, our mortality rate of 30·6% is similar to that of the other series mentioned, if the figures for mild chest injuries (class 1) are excluded.

It is evident that patients with chest injuries alone have

a very much better chance of surviving than those with multiple injuries. A notable exception to this is the patient who suffers a bronchial tear which goes undetected or manifests itself several days after the initial injury. Bronchoscopy may fail to reveal the injury because of an excessive amount of blood clot in the region of the rupture.[22] Increasing awareness of intrathoracic complications, such as bronchial rupture, aortic rupture and myocardial contusion, may result in the recognition and correction of these less common, but often fatal, events.

Management and Complications

Class 1 patients are not normally admitted to the Resuscitation Unit, and are usually managed by means of parenteral analgesia or local intercostal block to prevent pain, in addition to vigorous physiotherapy. It was felt that there was sufficient justification for giving ventilatory assistance to patients in class 2, even without severe respiratory decompensation. The correction of hypercapnia and hypoxia in a patient with widespread trauma and metabolic upset will contribute materially to his survival. Hypoxia, if not treated, will aggravate head injury as well as oliguric renal failure. For these reasons we have not adhered closely to the suggestion that only class 3 patients[10,20] should be treated on a ventilator.

The early management of severely ill patients will have a bearing on the ultimate outcome. If vigorous resuscitative measures are carried out in respect of restoration of blood volume and maintenance of blood pressure, renal failure and metabolic acidosis will be prevented. It is essential to have blood pH, PCO_2 and standard bicarbonate measurements at an early stage, as the clinical assessment of acid-base balance in such complicated cases is difficult. For example, a mid-brain injury may result in an excessive ventilatory drive, which may be confused with compensatory hyperventilation due to a metabolic acidosis.

It may be desirable to avoid tracheostomy when possible, as in class 1 cases, because of the attendant complications of the procedure. In our experience, tracheostomies in all categories of cases have a complication rate of 14·3%.[8] In the present series the complication rate was 27%, 1 patient dying as a result of a tracheo-oesophageal fistula. A very much higher tracheostomy complication rate of 49·3% has been reported by McClelland.[23] However, the value of the procedure far outweighs its disadvantages, despite a reported mortality rate of 3·4%,[23] and 3% in the present series. Tracheostomy and IPPR, when indicated, should be carried out without hesitation, a careful watch being kept for the development of complications.

Thirty-seven complications occurred during the course of the management of 36 patients (Table VII). Many of these complications were severe, and of a medical nature, being outside the experience of the general or orthopaedic surgeon in terms of practice in our hospital. In particular, management of acute renal failure, requiring repeated dialysis, and the correction of cardiac arrhythmias, as well as cardiac decompensation, needed close attention. Infection was a considerable problem, but in the majority of instances did not lead to severe morbidity. Three patients died as a result of infection, all having strong predisposing factors. The high incidence of infection (61%) is not surprising, as the majority of patients in whom tracheostomy is performed and IPPR is carried out have severe respiratory abnormalities. Respiratory failure itself may be regarded as a predisposing factor to infection.[13] Some of the other factors operative in the pathogenesis of the infection are: firstly, clean and already infected cases were not separated, as they were nursed in a very small unit; secondly, tracheostomy and IPPR tend to remove the protective mechanisms of the upper respiratory tract; and, thirdly, a nidus for infection was often already present in the form of pulmonary contusion or atelectasis. As a rule, routine antibiotic prophylaxis for pulmonary infection was not employed, even in cases where there was evidence of pulmonary contusion. Infection was diagnosed on clinical criteria, bacterial culture and sensitivity being used as a guide to therapy.

SUMMARY

A series of 36 cases with crushed chest injuries is presented. The mortality rate of 30·6% is similar to that of other series with cases of comparable severity. The prognosis was poorest in the group of patients with associated head and abdominal injuries. All patients with chest injuries alone survived. The usual attendant complications of tracheostomy and IPPR do not warrant these procedures being withheld, as they confer greater benefits than disadvantages. A regimen of early and vigorous resuscitation is recommended. As a result cases are surviving longer, and more complications, both medical and surgical, are now being encountered.

It is evident that with the advance in modern methods of resuscitation and the improved understanding of acid-base metabolism, renal failure, cardiac abnormalities, and infection, the physician has an increasingly important part to play in the management of an initially traumatic condition.

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