Review

The Neglected Prehospital Phase of Head Injury: Apnea and Catecholamine Surge

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The prehospital phase of head injury, also called the *critical phase*, consists of trauma-induced apnea and stress catecholamine release. This immediate period after head injury remains poorly summarized in the literature and essentially ignored with respect to treatment. A MEDLINE search of the literature on apneustic response and catecholamine surge after head injury and a review of literature from my acquired references revealed 116 references (from more than 600) that were pertinent. Apnea induced by head injury produces hypoxia, hypercarbia, and subsequent cardiac failure and hypotension, which, along with substantially elevated catecholamine values, promote secondary mechanisms of organ injury. Treatment for this immediate period after head injury requires a rapid response to the scene of trauma and development of treatment options that can be instituted at the scene of injury.

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EMS = emergency medical service; ICP = intracranial pressure; NPE = neurogenic pulmonary edema

Patients with severe traumatic head injury experience immediate alterations in cerebral and systemic physiology that substantially influence neurologic outcome. In this review, the first 10 minutes after severe head injury is referred to as the *critical phase of head injury*. This phase of head injury is rarely witnessed by medical personnel, and it remains poorly discussed in the clinical literature. After a MEDLINE search of the literature on apneustic response and catecholamine surge following head injury and a review of my acquired references, I found 116 references (of more than 600) that were relevant. The purposes of this article are to summarize this literature and to suggest future avenues of research. I hope that this review fosters improved treatment options for patients with head injuries in the prehospital environment. If highly vulnerable brain tissue can be preserved, functional outcome will be improved.

CRITICAL PHASE OF HEAD INJURY

The critical phase of head injury is arbitrarily defined in this article as the first 10 minutes after the onset of a severe head injury since patients live or die based on the pathophysiology that occurs during this period. The phases of severe head injury are outlined in Table 1.[1,2] Miller[1] and Overgaard and Tweed[2] noted that both ischemic and hypoxic brain injury are substantial before hospital admission, and they emphasized the importance of this critical phase in patient outcomes.

Two immediate pathophysiological events occur with onset of severe head injury that substantially affect subsequent outcome: head injury–induced apnea and a stress-related massive sympathetic discharge (Figure 1). The combined effects of hypoxia, hypercarbia, acidosis, and blood pressure surge, as well as the direct effects of catecholamines on tissue, lead to a synergistic injury effect in the host.

The extent of apnea and catecholamine surge after severe head injury is directly related to the amount of energy transmitted to the brain stem. As a result, a large number of patients with severe head injury live or die at the scene based on resumption of breathing, and prolonged apnea-induced hypoxic brain and cardiac injury augmented by appreciably elevated stress catecholamines modulates morbidity and mortality in survivors. Therefore, the condition of the patient that the medical and surgical team treats is determined, in large measure, by physiological events that begin at the trauma scene, before medical assistance is rendered. The modern aggressive care delivered in the hospital and directed at optimizing cerebral perfusion, although scientifically grounded, may often be too little, too late.

The following sections critically examine apnea and catecholamine surge induced in the critical phase of head injury. From this analysis, conclusions for clinical management are made.

Apnea

Apnea resulting from concussive head injury has been recognized experimentally for more than a century. In

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Table 1. **Phases of Head Injury***

Critical phase

Apnea

Always occurs with concussive head injury; the more energy delivered to the brain, the longer the subsequent apnea and the poorer the respiratory recovery

No respiratory recovery; dead at the scene unless early resuscitation

Prolonged apnea and poor respiratory recovery foster hypoxia and hypercarbia leading to early, massive brain swelling due to increased cerebral blood volume because of vasodilatation from hypercarbia; profound hypoxia may take minutes to occur but affects the neuronal environment substantially

Early intervention may dramatically alter course

Catecholamine surge

Appreciably elevated blood pressure occurs immediately because of massive sympathetic discharge; this augments hypercarbia-induced cerebrovascular dilatation and promotes early vasogenic edema, endothelial injury, and blood-brain barrier disruption; progressively increased intracranial pressure (ICP) occurs depending on the magnitude of epinephrine release and carbon dioxide retention

Intense vasoconstriction of other susceptible vascular beds produces ischemic gastric mucosal ulceration (stress ulcers, previously known as Cushing ulcers) and neurogenic pulmonary edema, along with catecholamine tissue injury such as myocardial necrosis

Primary brain injury—fracture or tearing of bones, meninges, brain parenchyma, and blood vessels occurs in varying degrees as forces converge through various vectors

Secondary brain injury mechanisms initiated—vasogenic edema, astrocytic swelling with altered excitatory amino acid uptake and potassium alterations, hemorrhage, neuronal and oligodendroglial ischemia, thromboplastin release with altered coagulation, subarachnoid hemorrhage (SAH) and progressively increased ICP, various molecular cascades

Exponential phase

Respiratory recovery frequently leads to hyperventilatory drive; any respiratory recovery may prolong life; early ventilation intervention may alter outcome

Catecholamine surge abates and blood pressure decreases to mid- or high-normal levels; however, brain may be massively swollen because of hypercarbic-induced vasodilatation and subsequent blood pressure surge and any hemorrhage that may have been augmented; ischemic injury to gastric mucosa or myocardium and neurogenic pulmonary edema may produce complications

Molecular cascades continue to progress, such as buildup of excess excitatory amino acids, lipid peroxidation, possible apoptosis of select cell populations

Hemorrhages progress or injured vessels thrombose; ICP may continue to increase due to progressive edema, mass effect, SAH; nonviable or ischemic brain undergoes cellular swelling; marginally compensated parenchymal cells live or die depending on cellular milieu; diffuse axonal injury matures; seizures may augment cerebral blood volume and ischemic cascade

Plateau phase

Intracranial pressure stabilizes or may increase because of gradual transition from vasogenic edema to cellular edema; delayed intracerebral hematoma may develop from dead or injured brain and blood vessels; dead parenchyma continues edematous swelling; SAH and erythrocyte lysis may precipitate vascular injury, which may lead to vasospasm; molecular cascades may slow or stop; 75% of deaths due to head injury occur in the first 48 to 72 hours

Resolution phase

Collagen and gliotic repairs progress; SAH-induced vasospasm may evoke ischemia and infarction; previous infarctions or dead parenchyma reach maximal swelling and resolve; continued risk for 1 to 2 weeks of delayed intracerebral hematoma; cellular edema becomes a greater component of swelling vs vasogenic edema and may slowly subside; posttraumatic hydrocephalus may evolve short or long term

*Data from Miller[1] and Overgaard and Tweed.[2]

1874, Koch and Filehne[3] reported that repeated small blows to the head of an animal led to death by respiratory paralysis, with no visible structural abnormality in the brain. Polis[4] showed in 1894 that concussive head injury in the cat, dog, and rabbit was followed by respiratory arrest and a significant increase in mean arterial blood pressure levels. If respirations did not recover, the animal died, even though there were no gross anatomical lesions in the brain. In 1896, Kramer[5] also reported that an animal receiving a blow to the head experienced respiratory paralysis. In 1927, Miller[6] repeated Polis' work, and findings were identical. However, Denny-Brown and Russell[7] in 1941 clearly revealed that immediate death from severe experimental head injuries was due to respiratory failure. Using respirometric methods, they showed that increasing degrees of energy delivered to the brain produced increasing durations

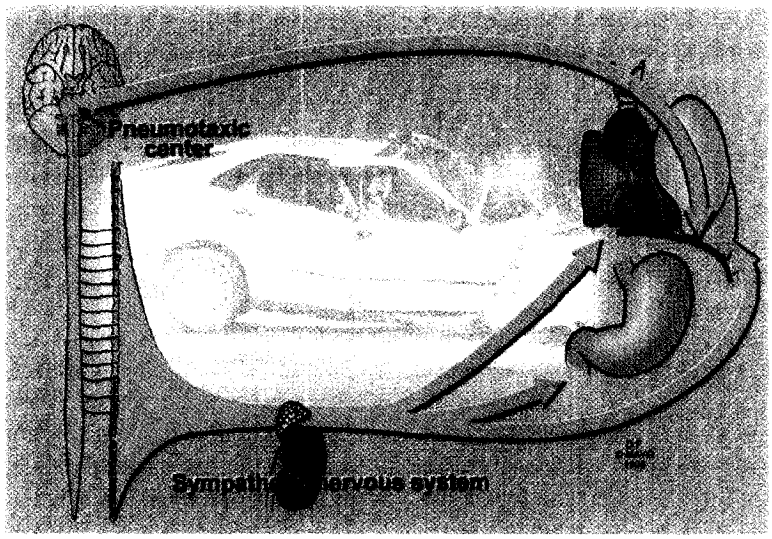

Figure 1. Severe head injury sequelae of disturbance in medullary-driven diaphragmatic ventilation and massive sympathetic stimulation. The magnitude and severity of both events are directly proportional to the magnitude of energy transmitted to the brain stem.

of apnea. A light blow produced a respiratory gasp, a moderate blow produced varying degrees of apnea and respiratory recovery, and heavy blows produced respiratory arrest and subsequent death due to hypoxic cardiovascular collapse. There were no observable lesions in the brains when sectioned. Denny-Brown and Russell concluded that the response was brain stem mediated because it occurred in decerebrate preparations of animals. They also believed that it was energy dependent, based on the force and rate of change (acceleration) transmitted to the brain stem, and that it had nothing to do with physical disruption of the brain or development of space-occupying hematomas. In 1944, Walker et al[8] published a classic report on the physiological basis of concussion in several different animal species. Using hammer, weight-drop, and projectile techniques, they confirmed that the respiratory response was energy dependent and characterized by a respiratory gasp at low energy, and prolonged apnea at higher energy. They also demonstrated that this response was brain stem mediated and was not related to increased intracranial pressure (ICP).

Sullivan et al[9] showed that animals subjected to fluid percussion injuries exceeding the lethal threshold for apnea recovered normal function with respiratory support. Gennarelli[10] developed a head accelerating machine and found that, in primates, increasing the magnitude of acceleration caused apneustic changes in respiration, and at higher forces, the animals died without ventilatory support. Carey et al[11] found the same conclusion with a projectile mechanism of brain injury in cats. Respiratory arrest was a constant physiological response, even though the missile did not injure the brain stem directly. The duration of apnea was directly proportional to the energy transmitted to the brain. He concluded that the integrity of the medullary respiratory center after head injury determines very early whether the animal lives or dies regardless of the degree of other parenchymal injury and that, if respiratory support is delayed, both secondary hypoxic brain and cardiac damage ensue resulting in pronounced morbidity or death.

Andersen et al[12] combined mechanical brain injury with controlled injury-induced hypoventilation followed by resumption of normal respiratory factors in an attempt to simulate a more realistic model of head injury. They found substantial alterations in cerebral blood flow, cerebral metabolic rate of glucose, and brain ischemia not seen with either head injury or hypoxic injury alone. This was further delineated by Ito et al,[13] who showed that weight-drop brain injury–induced hypoventilation and hypotension in laboratory animals produced severe ischemia in the brain. Magnetic resonance imaging diffusion-weighted techniques identified aberrations that were not visualized with head injury alone. Kim et al[14] and Levasseur et al[15] produced graded respiratory responses to fluid percussion head injury and showed a pronounced increase in fatalities in animals treated with ethanol. They postulated that increased alcohol-related traumatic fatalities were due to synergistic respiratory depression as a result of head injury combined with ethanol. Other investigators have also substantiated the increased morbidity and mortality resulting from head injury when combined with ethanol.[16-18] Kim et

al[14] and Levasseur et al[15] verified that mechanical ventilation after head injury is essential in reducing immediate death after experimental head injury. To date, all experimental head injuries induced by any method in a spontaneously breathing model produce apnea as a consistent response, and the degree of respiratory paralysis and recovery has consistently been shown to be directly related to the amount of energy delivered to the brain[19] (Figure 2). In fact, the lethality of the respiratory response after head injury is used as a benchmark for testing new techniques in laboratory mechanisms of brain injury.[20]

Despite overwhelming experimental evidence of apnea and dysfunctional respirations immediately after head injury, there is minimal corroborating evidence derived from clinical studies. Johnson et al[21] examined intentional closed head injury (ie, child abuse) in 28 children and found that 57% had a verifiable history of apnea before hospitalization. The conclusion was that trauma-induced apnea causes cerebral hypoxia and ischemia, and these were more important in modulating outcome than was the mechanism of primary brain injury itself (ie, subdural hematoma, subarachnoid hemorrhage, diffuse axonal injury, or contusions). Severe closed head injury–associated hypoxia (19%), hypotension (24%), or both (7%) were reported in the Traumatic Coma Data Bank as strong predictors of morbidity and mortality.[22-24] However, these percentages are certainly underrepresentative because they were recorded on admission of patients to the emergency department after resuscitation in an ambulance, and they do not reflect changes at the scene of head injury. The most powerful testimony to the association of apnea with clinical head injury results from eyewitness accounts recorded by physicians who were at the scene of injury.[25] Two patients with head injury, both of whom were rescued at the scene with early ventilation, had initial Glasgow Coma Scale scores of 3 with fixed dilated pupils, no corneal reflexes, and no respirations or pulse. Both patients had uneventful recoveries. The authors summarized that, without early ventilatory assistance, these 2 patients would have died or had serious brain damage due to respiratory failure as a result of their nonlethal head injuries.

Catecholamine Surge

Catecholamine surge is irrefutably a stress response to head injury, and it represents an important and neglected contribution of morbidity and mortality associated with head injury. Pronounced increases in blood pressure and heart rate are universal responses to head injury and have been documented for more than a century. For example, in 1894 Polis[4] described substantial increases in blood pressure and heart rate with experimental head injury. Furthermore, blood pressure and heart rate increases are discussed as a concomitant response in all previously reported studies on head injury–associated apnea.[4,7-20]

The blood pressure and dynamic response of the heart to head injury was labeled early in this century as the *Cushing response*[26] because of Cushing's early work with experimentally induced intracranial mass lesions, a continuation of Spencer and Horsley's work.[27] However, the Cushing response, although mediated by a catecholamine surge, is a response to increased ICP and the diminution of cerebral perfusion. Subsequent early studies concentrated on this sympathetic discharge resulting from immediately increased ICP. In 1937, Grimson et al[28] reported that the elevation in blood pressure from increasing ICP could be abolished by total sympathectomy. Freeman and Jeffers[29] repeated this experiment by creating sudden increased ICP by pressure saline injection into the cisterna magna of dogs. They discovered that the systemic blood pressure response was prevented by sympathectomy. Roozekrans and van Zwieften[30] were able to block the Cushing response with α-adrenergic blockade (phentolamine), in a manner similar to Cushing's blockade of the splanchnic response of the intestines to blood pressure surge by cocainization of the medullary centers.[26]

The aforementioned studies clearly demonstrate that elevated ICP results in activation of the sympathetic nervous system with pronounced catecholamine release. However, it has become clear that massive catecholamine surge is an immediate brain stem–mediated response to severe head injury in the absence of increased ICP, as vividly described by Walker et al[8] in brain stem–injured animals. Massive sympathetic discharge with subsequent appreciable increase in mean arterial blood pressure and heart rate has proved to be a consistent immediate response in any experimental model of severe head injury, such as fluid percussion injury,[9] acceleration,[10] projectile,[11] or weight-drop techniques.[19] The benchmark experimental study conducted by Rosner in Becker's laboratory at Medical College of Virginia[31] confirmed what Beckman and Iams[32] had concluded earlier. They documented as much as a 500-fold increase in plasma epinephrine levels and a 100-fold increase in plasma norepinephrine levels with severe head injury. The conclusion was that both epinephrine and norepinephrine plasma levels increased as a direct response to energy delivered to the brain and paralleled a function of injury severity. The systolic arterial blood pressure directly correlated with the level of circulating catecholamines, was an instantaneous response to all but the most lethal of head injury sequelae, and did not correlate with elevated ICP.

Furthermore, in the clinical setting, many patients continue to have increased circulating catecholamines for several days after isolated head injury. Hörtnagl et al[33] found elevated plasma epinephrine and norepinephrine levels in

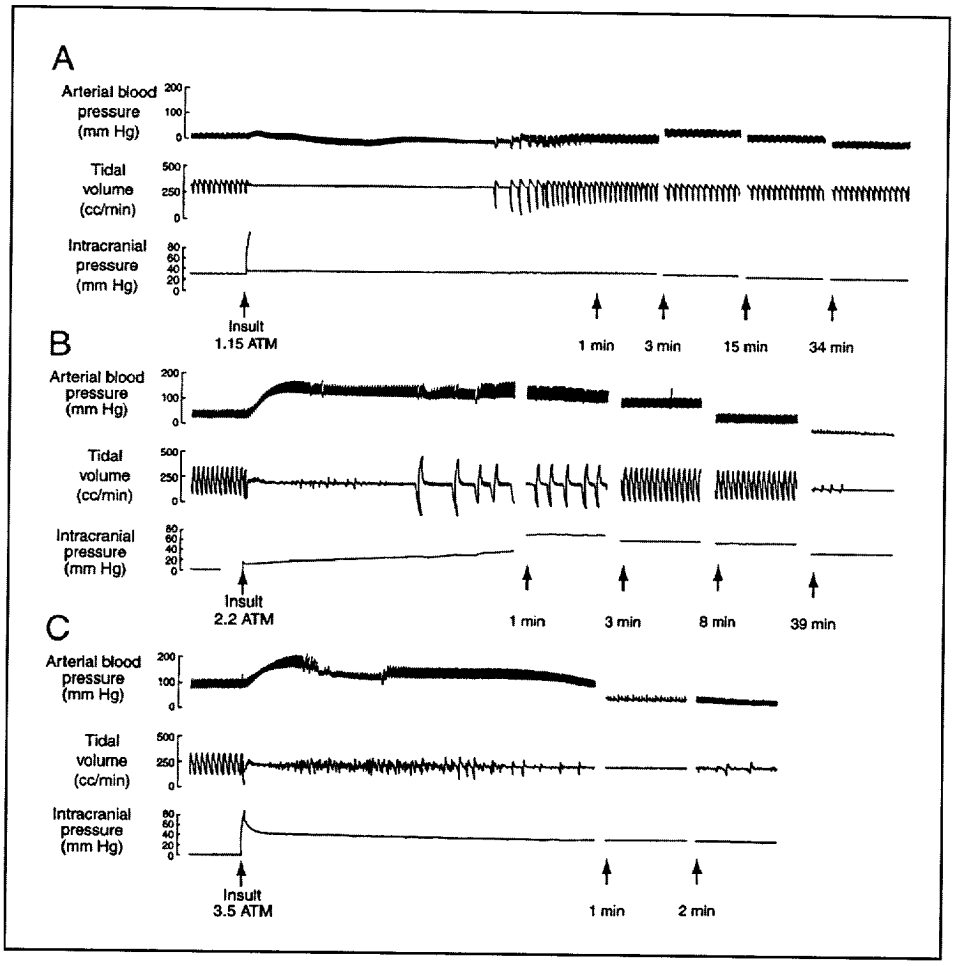

Figure 2. Rat model of fluid percussion head injury with increasing magnitudes of energy delivered to the brain and corresponding responses of blood pressure, spirometry measured tidal volume, and intracranial pressure (ICP). A, 1.15 ATM of pressure delivered to the brain, with 45 seconds of apnea followed by rapid resumption of normal respiratory pattern and no clinically important change in the mean arterial blood pressure or ICP. B, 2.2 ATM of pressure delivered to the brain, with 45 seconds of apnea followed by very slow resumption of normal respiratory pattern with immediate, pronounced elevation in blood pressure and rapid (1 to 3 minutes) elevation in ICP to 10 times the baseline level. C, 3.5 ATM of pressure delivered to the brain, with immediate apnea not followed by any organized respiratory effort with immediate and substantial elevation in blood pressure and ICP. Animals in this group die of hypoxic cardiovascular collapse but can be salvaged if mechanically ventilated. There were no space-occupying hematomas identified in any of the groups (adapted from Atkinson et al[19] with permission).

15 patients with severe head injury and suggested that long-standing overactivity of the sympathetic nervous system is a characteristic feature in the clinical course of head injury. Schulte Esch et al[34] also found a hyperdynamic state after head injury due to overactivity of the sympathetic nervous system. Clifton et al[35] reported that, in patients with isolated head injury, circulating catecholamines were significantly elevated and that blood pressure levels were directly proportional to plasma norepinephrine concentrations. Subsequent clinical work from the same institution found that increased circulating catecholamines are common in patients with head injury, but they do not correlate with either the Glasgow Coma Scale score or increased ICP.[36,37] Robertson et al[38] suggested that rational treatment includes β-blockade in these patients to decrease hypertension and the catabolic effects of this hyperdynamic state. Increased circulating catecholamines have also been confirmed in other stress conditions, such as subarachnoid hemorrhage,[39,40] shock,[41] or severe thermal burns,[42] and have been reconfirmed in clinical head injury.[43,44] Serum

catecholamine levels have been used as markers to assess the severity of head injury in alcohol-intoxicated patients in the emergency department.[45] Recommended treatment of this hyperdynamic, sympathetically mediated response to head injury[43,44] is β-blockade.[46-48]

Many studies suggest that the early elevated ICP seen after severe head injury, in the absence of space-occupying masses, is due to a substantial increase in cerebrovascular volume and breakdown of the blood-brain barrier.[49-53] A logical theory is that an apneic patient with profound hypercarbic and hypoxic cerebrovascular dilatation, in the setting of probable impaired autoregulation and subjected to massive blood pressure elevation, would experience a rapid increase in cerebral blood volume and resultant increased ICP. In many patients with no space-occupying hematomas, elevated ICP on admission to the emergency department may have been fostered and augmented by these conditions immediately after a head injury.

In animal studies, increasing energy transmitted to the brain yields different physiological results (Figure 2). As shown in Figure 2, B, 2.2 atm of pressure is delivered with an immediate substantial elevation in blood pressure; however, the ICP increase closely parallels hypoventilatory-retained carbon dioxide and subsequent gradual cerebrovasodilatation and increased cerebrovascular volume. Figure 2, C, shows a rapid and considerably elevated ICP that is graphically representative of absent autoregulation in the setting of massive blood pressure surge and a resultant pronounced increase in cerebral blood volume. There were no space-occupying hematomas in these animal studies.[20]

In summary, head injury induces an instantaneous stress response by massive sympathetic discharge. The response is dose dependent, and clinically this hyperdynamic state may last for hours or even days in many patients with severe head injury. Negative ramifications of this catecholamine surge include stress-induced hyperglycemia. Injuries to the gastroduodenum, heart, and lungs are discussed in the subsequent sections.

Hyperglycemia and Brain Injury

Although a head injury–induced stress response results in pronounced hyperglycemia mediated in part by catecholamine surge, stress-induced cortisol may have a role.[31,54] Hyperglycemia existing before ischemic brain injury significantly worsens outcome.[55-57] Serum glucose levels correlate directly with the magnitude of head injury and can rise to as much as 400 mg/dL by 1 hour after injury in experimental animals.[31] This slow rise in glucose may be too late for an adverse effect on cerebral hypoxic ischemia immediately after brain injury, but it may worsen any secondary ischemic mechanisms of brain injury, such as focal ischemia derived from evolving space-occupying lesions. Cherian et al[58,59] convincingly demonstrated in animals that cortical impact injury followed by ischemic insult in the presence of hyperglycemia significantly increases brain ischemic volume, contusion volume, and mortality and decreases functional outcome in survivors. Hyperglycemia needs to be adequately addressed in the clinical setting of head injury.

Gastric Mucosal Ulceration

Gastroduodenal mucosal injury frequently develops after severe head injury, and frank ulceration is common. Esophagogastroduodenoscopy soon after severe head injury reveals these lesions in a high percentage of patients.[60-62] These ulcerations occur very early after head injury and are similar to catecholamine stress ulcers produced experimentally[60,63,64] or by other systemic stress injuries such as burns or sepsis.[65,66] The mechanism may be a combination of factors, such as increased vagal activity resulting in increased gastric acidity or slowed gastric emptying or increased circulating pancreatic polypeptide levels.[67,68] However, the predominant theory of gastric ulcerogenesis in patients with head injury is that catecholamine-induced vasoconstriction causes decreased splanchnic blood flow with resultant ischemic mucosal injury.[69,70] Regardless of the mechanism, pharmacological prophylaxis of further mucosal erosion should be considered in these patients.[60-62]

Myocardial Injury

Isolated head trauma–induced cardiac injury is well documented in the pathologic literature and may be found at autopsy in up to two thirds of patients who die of acute head injury only.[71-73] The catecholamine surge that accompanies head injury,[74-76] spinal cord injury,[77] or subarachnoid hemorrhage[78-81] can precipitate these cardiac lesions. The injuries vary from disorganization, clumping, and necrosis of myocardial cells to extensive areas of necrosis with hemorrhage, particularly in the ventricular septal region.[72,73,82] The most common clinical manifestations are electrocardiographic abnormalities such as ST-segment depression or elevation, QT-interval prolongation, and inversion of T waves.[78,80,82,83] The lesions, if sufficiently extensive, can contribute to or cause death.[72,83,84] There is evidence that pretreatment with catecholamine blocking agents will substantially reduce the cardiac injury induced by stress catecholamine surge and help prevent further extension of myocardial damage.[85,86]

Neurogenic Pulmonary Edema

A retrospective review of the Traumatic Coma Data Bank suggests that pulmonary lesions, resulting from fac-

tors other than direct pulmonary trauma, are common.[87,88] Although neurogenic pulmonary edema (NPE) may be mediated by various mechanisms, the prevailing theory is that it is caused by a massive catecholamine surge.[89] Severe pulmonary congestion and edema have been noted in autopsy series of head injuries[90] and are known to be a response in animals after massive autonomic discharge.[91] This theory suggests that acute cardiac failure results from a catecholamine-induced increase in cardiac preload due to venoconstriction and increased cardiac afterload by massive arterial constriction. In conjunction with catecholamine-induced cardiac injury, these mechanisms produce edema in the lungs by increasing pulmonary capillary pressures. Early experiments showed that pulmonary edema could be prevented by adrenergic blocking agents or cordotomy and that vagotomy by itself had little, if any, effect.[91-94] The conclusions of the classic series of head injuries in the Vietnam War were that acute pulmonary edema after severe head injury was rapid in onset, resulted from a massive sympathetic discharge that produced a fluid shift from the periphery to the lungs, and was augmented by transient left ventricular failure and loss of left ventricular compliance from catecholamine-induced myocardial injury.[89]

Since that landmark article, evidence has grown in support of catecholamine surge as the major pathway in NPE. Any cause of massive stress-induced autonomic discharge can produce NPE, including seizures, head injury, subarachnoid hemorrhage, or major stroke.[95-97] Experimental models of head injury or subarachnoid hemorrhage continue to show massive sympathetic discharge as the primary mediator of NPE,[98-102] and this etiology permeates the literature in clinical and summary articles as well.[101,103-105]

DISCUSSION

Maciver et al[106] stated 40 years ago that the staggering morbidity and mortality of severe head injury could be substantially reduced by simply providing ventilation to such patients at the accident scene. When this measure was undertaken, the 90% mortality rate in these patients was dramatically decreased to 40%. Arguably, the most substantial reduction in trauma morbidity and mortality in the United States occurred with the 1966 publication of *Accidental Death and Disability: The Neglected Disease of Modern Society* and the subsequent legislative development and continued refinement of the emergency medical service (EMS).[107] When isolated head injury is reviewed within trauma resuscitation systems, morbidity and mortality have continued to decline during the past decade almost exclusively because of improvement in the rapid response of the EMS, which, in turn, facilitates timely medical and surgical intervention.[108] Even when neurosurgical trauma care and patient outcome are compared in countries as medically diverse as the United States and India, timely care in the field and expeditious transport to trauma centers are the most important criteria separating the morbidity and mortality statistics of head injuries in these 2 countries.[109]

Brain ischemia is a major focus of research on brain injury. This research has been stimulated by the neuropathologic findings reported by Graham et al.[110,111] They discovered that ischemic brain lesions were a common autopsy finding in humans who died after traumatic brain injury. More than one half of the ischemic brain lesions found in head injury fatalities were of the arterial boundary zone type. Such lesions are most often seen in patients with a known clinical episode of hypoxemia or hypotension due to hypoxic cardiac failure. These investigators' explanation for this type of ischemic brain injury was that the responsible events probably occurred immediately after head injury, but before arrival of medical personnel to the scene of trauma. Other autopsy series have clearly documented the same findings of ischemic brain injury, substantiating that factors occurring during the critical phase of head injury are the initiating events.[71,112] These same pathological cascades are believed to initiate injury to the gastrointestinal tract, heart, and lungs.[71]

Clinical and laboratory research should obviously be directed to decrease patient morbidity and mortality and improve outcome after traumatic head injury. However, the vast majority of medical care is directed to patients who survive long enough to arrive at the emergency department, while the critical phase has essentially been ignored in the current spectrum of treatment.[113] This approach is exemplified by the fact that 17 clinical trials on head injury targeting therapies to patients on their arrival to the hospital have all failed to improve outcome substantially[114] (R. Bullock, MD, PhD, oral communication, April 1999).

The purposes of this article are to highlight the critical phase of head injury and emphasize the importance of immediate events after head injury in determining patient outcome. Apnea and catecholamine surge are clearly the initial factors that medical or surgical intervention must address. Therefore, treatment options must be directed to patients with traumatic head injuries in the prehospital setting.

Head Injury Prevention

Continued and greater emphasis must be placed on preventing head injury. For every head injury that is prevented, treatment is unnecessary, and an individual and family are spared the tragedy of morbidity or death associated with such injury. Educational programs for head injury prevention, such as Think First, and the passage of mandatory helmet laws are attempts to minimize the incidence of head injury.

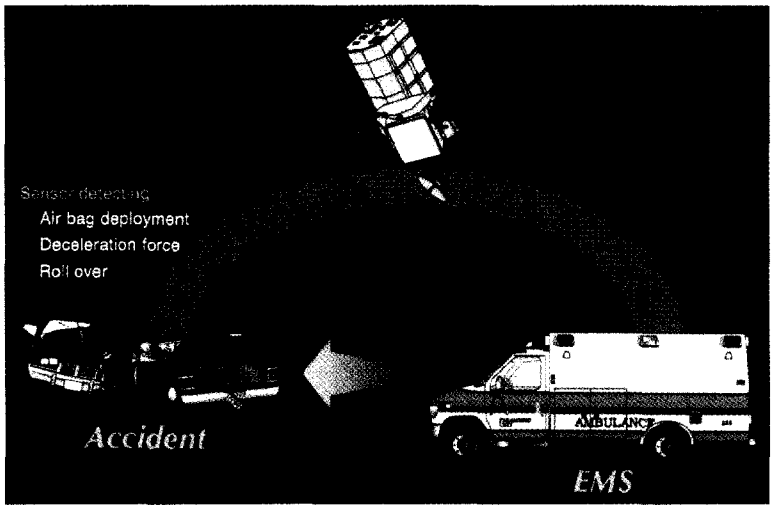

Figure 3. The Mayday program uses a motor vehicle–mounted sensor that detects collision events strongly suggestive of occupant injury and sends immediate notification to the nearest emergency medical service (EMS) for rapid response deployment of service to the exact satellite-depicted location of the crash.

Improved EMS Response

A faster response by the EMS would be extremely beneficial for any traumatically injured patient. Specifically, unwitnessed motor vehicle crashes (ie, single vehicle), especially in rural areas, would benefit from immediate notification and response of the EMS to the exact location of injury. Endeavors such as the Mayday experiment at Mayo Clinic and other institutions are an attempt to improve response time (Figure 3), but other ideas must be generated.

In an effort to refine the EMS care during the critical phase of head injury, efforts must be made to gather information at the scene of injury. Such field measurements might include Po_2, Pco_2, pH, and level of circulating catecholamines in an effort to determine the magnitude of energy the brain has received and any hypoxic injury before arrival of medical help. This information would help the treating neurosurgeon and trauma surgeon in the emergency department in determining the severity of injury during the critical phase and in targeting therapy to the brain and other organs. Data gathered at the scene might also spur laboratory development of treatments that could be initiated expeditiously in the field, rather than on arrival of the patient to the trauma care facility.

Treatment of apnea in the field is difficult to address. Patients in whom ventilation resumes early after head injury are not at a pronounced apneic hypoxic risk, but they may have aspiration or other risks of pulmonary injury. The patient who has apnea for some time followed by a functional but poorly coordinated respiratory effort may sustain life independently for a longer period while awaiting arrival of the EMS.

Patients who do not resume respirations after the initial apneic episode die unless they receive ventilation early after their head injury. These patients may benefit most from cardiopulmonary resuscitation performed by first responders to the scene. Continued education that cardiopulmonary resuscitation at the scene may be lifesaving in patients with head injury should be emphasized. For the patient with prolonged apnea, it is doubtful whether the EMS response, regardless of how rapid, will make a substantial difference in outcome. Ventilatory support must be provided early by the first responders at the scene of injury, or multisystemic hypoxic injury will occur.

Target Therapy

There is clinically important evidence that early generalized increased ICP and severe brain swelling on initial computed tomographic scans of patients with head injury reflect an increased cerebral blood volume. Often, head injury may be pathologically characterized by a state in which the cerebrovasculature is maximally vasodilated by hypercarbia and hypoxia, in the setting of head injury–induced dysfunctional vascular autoregulation. Thus, when catecholamine-induced blood pressure surge occurs, the already increased cerebral blood volume of the brain will increase substantially. As the pressure surge enters a maximally dilated, unresponsive cerebrovascular bed, the result could lead to an appreciably elevated ICP with or without disruption of the blood-brain barrier.[49-53] Better methods of providing triage care to injured patients, based on information gathered at the scene about the critical phase of head injury, should help to select patients who merit maximal

resuscitation efforts vs those with little or no likelihood of survival. Imaging is definitely a powerful tool in determining prognosis, and newer magnetic resonance imaging techniques may improve diagnostic and prognostic capability.[115,116] Target therapy could then be directed to foster recovery in predicted survivors and, as clinical information of the pathophysiology during this phase of head injury accumulates, potentially redirect future therapy to be rendered at the scene of head injury.

CONCLUSIONS

The critical phase of head injury determines life or death at the scene. Even among persons who survive and are treated in a hospital, the critical phase of head injury sets into motion physiological and biochemical cascades that influence medical care and determine outcome. We must begin efforts to improve outcome of head injury by addressing this period, which has been relatively neglected despite overwhelming evidence of its importance. If we respond to head injury as rapidly as possible and begin treatment as early as possible, perhaps the morbidity and mortality associated with head injury will be reduced to a level not yet achieved.

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