SURGERY OF CEREBRAL TRAUMA AND ASSOCIATED CRITICAL CARE

Alex B. Valadka, M.D.

Department of Neurosurgery,
University of Texas Medical
School at Houston,
Houston, Texas

Claudia S. Robertson, M.D.

Department of Neurosurgery,
Baylor College of Medicine,
Houston, Texas

Reprint requests:
Alex B. Valadka, M.D.,
Department of Neurosurgery,
University of Texas Medical School
at Houston,
6410 Fannin Street, Suite 1020,
Houston, TX 77030.
Email: alex.valadka@uthtmc.edu

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The last 30 years have been both exciting and frustrating for those in the field of traumatic brain injury (TBI). Much has been learned, but no new treatment has been shown to improve patient outcomes despite the execution of many clinical trials. The overall incidence of TBI has decreased, probably because of intensive efforts toward prevention and education. Rigorous assessment of available research has produced several evidence-based guidelines for the management of neurotrauma patients. The creation of organized emergency medical services systems in many regions has improved prehospital care. Computed tomographic scans have become the gold standard for obtaining immediate images of patients with TBI, and ongoing advances in visualizing cerebral metabolism continue to be remarkable. The major current question regarding surgical treatment for TBI involves the role of decompressive craniectomy, an operation that first fell out of favor and has since (in the last three decades) enjoyed a resurgence of interest. Growing interest in the intensive care management of TBI patients helped to establish the new field of neurocritical care. Prophylactic hyperventilation is no longer recommended, and earlier recommendations for aggressive elevation of blood pressure have been softened to endorsement of a cerebral perfusion pressure of 60 mmHg. Recombinant factor VIIa is increasingly used for minimizing complications related to coagulopathy. Intracranial pressure monitoring is now recommended for the majority of TBI patients. At present, available technologies allow measurement of other aspects of cerebral metabolism including cerebral blood flow, brain oxygen tension, biochemistry, and electrical activity. Therapeutic interventions that are growing in popularity or are presently under investigation include administration of hypertonic saline, hyperoxygenation, decompressive craniectomy, and hypothermia. Rehabilitation has become accepted as an important part of the TBI recovery process, and additional work is needed to identify optimal interventions in this area. Socioeconomic factors will play a growing role in our treatment of TBI patients. Although much progress has been made in the last 30 years, the challenge now is to find ways to translate that progress into improved care and outcomes for TBI patients.

KEY WORDS: Computed tomography, Guidelines, Neurocritical care, Neurotrauma, Prehospital, Traumatic brain injury

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Surgical treatment of head injuries was almost certainly the first type of neurosurgical procedure performed by ancient peoples several millennia ago. Even as recently as last century, as neurosurgery was rapidly growing as a specialty and as new practitioners began to settle in more and more cities across the United States, trauma patients continued to be a major part of the clinical volume of many of these newly established practices.

The last three decades have been alternately exhilarating and frustrating for those with clinical and research interests in traumatic brain injury (TBI). Laboratory and bedside research has greatly improved our understanding of posttraumatic cerebral pathophysiology (*Fig. 1*). At the same time, these new insights have failed to make the transition to clinically useful therapies. Many of the major clinical trials of the last decades have been "negative" studies that have shown us what does not work. It has been extraordinarily difficult to demonstrate the efficacy of new treatments.

Identifying new treatments and proving their utility have been seemingly insurmountable obstacles. Progress has been made, however, in other arenas. Careful reevaluation of existing data and publications can help in identifying which prac-

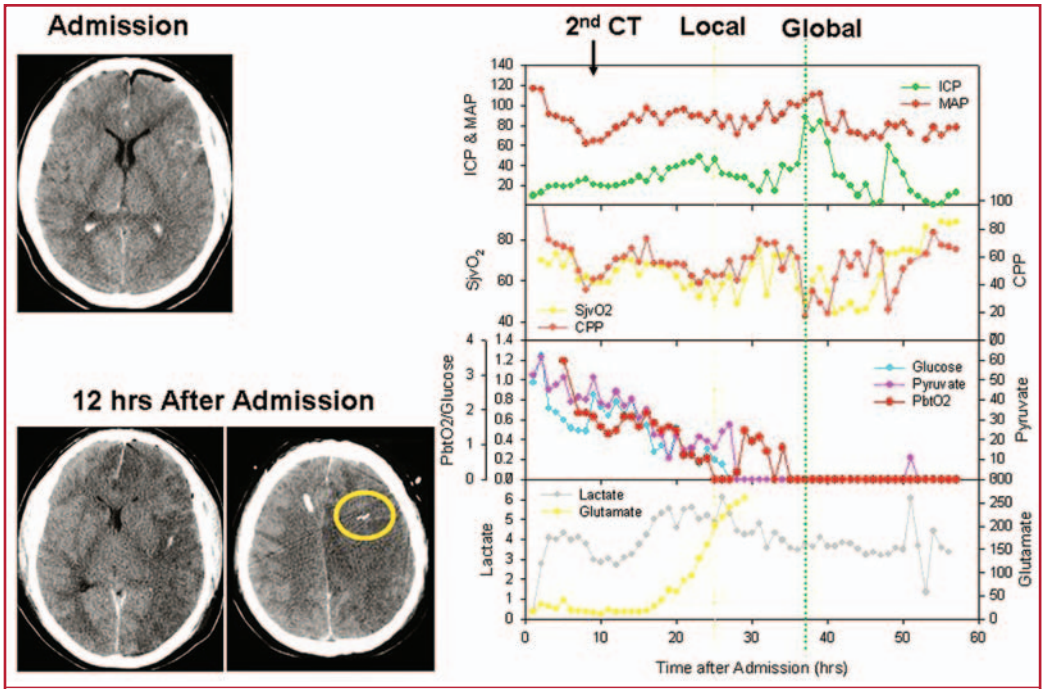

FIGURE 1. *Findings from a patient with fatal brain injury.* **A**, *computed tomographic scans were obtained at hospital admission and 12 hours later, showing local cerebral ischemia progressing to global cerebral ischemia. Location of brain tissue oxygen probe is shown* (yellow circle). **B**, *graphs showing progressive increase in ICP, decrease in brain oxygen level, and decreases in glucose and pyruvate levels in cerebral microdialysate, with a rapid increase in lactate and a later increase in glutamate levels.*

tices are supported by the best available evidence and which can be discarded or at least placed in an appropriate context that recognizes their limitations. Finally, emergency neurosurgical care, like emergency care in general, has benefited from sustained efforts at systems planning, integration, and cooperation. Prehospital and interhospital coordination are much more effective when protocols are established before they are needed, and are far better than the alternative of waiting until a patient deteriorates before deciding where to send and how to treat him or her.

These successes and disappointments are summarized in the following sections. They begin with discussions of epidemiology, prevention, and guidelines, and continue with a sequence of steps that a trauma patient would experience as he or she progresses through the emergency care system, including initial prehospital and emergency department care, imaging, surgery, intensive care, and rehabilitation.

EPIDEMIOLOGY

Mechanism of Injury

A welcome change in the epidemiology and demographics of TBI has been the steady decrease in incidence of severe closed-head injury in recent years. Unfortunately, this decrease has been paralleled by an increase in the numbers of gunshot wounds to the head (GSWH) (59).

Age

Another recent development has been the apparent increase in brain injuries among the elderly. Some of this increase is thought to reflect the growing number of elderly citizens in the population at large. Another likely contributing factor is the concurrent growth in the number of elderly patients taking anticoagulant or antiplatelet drugs.

Outcome

Some authors report a significant decrease in mortality rates attributed to TBI over the last few decades (33). However, such reports often exclude the most severely injured patients or those in whom a significant amount of time passed between injury and arrival at a hospital (19, 31, 38, 43, 71). Such exclusions are understandable because those studies were often designed to evaluate the efficacy of potential new therapies, which are unlikely to be effective in patients with devastating trauma. At the same time, however, the outcomes in these reports cannot be viewed as representative of the outcomes that would be expected when all patients with TBI are included. An additional concern about some studies is that the only outcome captured is survival versus death at hospital discharge. Detailed long-term outcome assessments by trained, blinded examiners are generally not performed.

The Traumatic Coma Data Bank (TCDB) was created when four academic centers with interest and expertise in TBI participated in a data collection project that began almost 30 years ago. At that time, prehospital care systems and improvements in emergency medical systems had evolved sufficiently to allow rapid transport of injured patients to hospitals.

Thus, it seems reasonable to use TCDB data as a reliable starting point for discussions of outcome after TBI (37). Like most such studies, however, these data suffer from at least two limitations. The first is that the data were gathered from academic trauma centers, which may not necessarily have comparable outcomes to nonacademic facilities or to facilities that are not designated trauma centers. The second is that patients enrolled in clinical trials—even the placebo group—tend to have better outcomes than other patients because of the extra attention that is given to all patients in a study. For these rea-

sons, TCDB data may be unduly optimistic if they are used to anticipate the likelihoods of different outcomes in patients who are not enrolled in clinical trials, who are treated at nonacademic facilities, or who are managed at a hospital that is not a trauma center.

The TCDB data suggest that death can be expected in roughly 30 to 36% of patients with severe closed TBI. A persistent vegetative state will occur in 5% or fewer of these patients. Severe disability will probably be the outcome for approximately 15% of patients; moderate disability can be expected in perhaps 15 to 20% of patients; and a good outcome will occur in at least 25% of patients. These results are comparable to those of some recently compiled series of unselected patients (55).

In patients with GSWH, the outcome distribution is more heavily skewed toward the extremes (62). Some studies report prehospital mortality rates of almost 90% for GSWH patients, and patients who are still alive upon arrival at a hospital may have mortality rates of 60% or higher. However, 30 to 40% of patients will achieve good outcomes or have only moderate disability. The "intermediate ground" of severe disability or persistent vegetative state occurs less commonly in GSWH patients than in those with closed TBI.

A major advance over the last few decades has been the growing awareness that a good outcome on the Glasgow Outcome Scale does not necessarily mean that a patient will recover without any deficits. Problems with judgment, impulse control, abstract thinking, short-term memory, and other areas may be devastating for patients and families, even when a patient outwardly appears to have made a good recovery.

PREVENTION

Without question, one of the most important developments in neurotrauma in the last 30 years or so has been the creation and growth of injury prevention programs. For example, ThinkFirst is a program that was created by organized neurosurgery with the goal of preventing injury via education, research, and policy. Some data suggest that this educational program not only increases children's knowledge about injury prevention, but also reduces their incidence of head and back injuries (69). Other injury prevention programs, including those at the local, regional, and statewide levels, also play important roles in injury prevention.

Because automobile accidents are a major cause of all types of trauma, one would expect that improvements in automobile safety would have a major impact on the incidence of TBI. Air bags, compulsory seatbelt laws, lower speed limits, and improvements in the overall safety and crash tolerance of automobiles may all have played a role in reducing the incidence of traffic-related TBI during the last three decades. Greater societal awareness of the dangers of driving while under the influence of alcohol or other drugs is probably another major factor. A wealth of epidemiological data indicates that motorcycle helmet laws are associated with lower rates of motorcycle operator fatalities.

Sports-related neurological injuries comprise a distinct group of traumas that occur at a predetermined time and place. Thoughtful analysis of these injuries is a science that is still in its infancy. In sports such as football, neurosurgeons have assumed the lead in modifying rules of play to increase safety without diminishing the enjoyment for participants or spectators (6). Improving the performance of safety equipment, such as football helmets, is another area of active investigation. The most pressing questions seem to center around when and whether an athlete can return to play, and whether repetitive minor brain injuries can have cumulative long-lasting effects. In addition to clinical evaluation and neuropsychological testing, computerized assessment tools have been developed to assist in answering these questions (36). Functional imaging techniques are also under investigation in this area.

GUIDELINES

The phrase "evidence-based medicine" has seen so much use in recent years that it has become a cliché. Basing patient care decisions on high-quality research data has always been the mainstay of clinical practice. During the last decade, attempts to codify and label these practices have been driven by several factors, including busy practitioners' desires to make sure that they are doing the right thing according to currently accepted practices, as well as cost-cutting attempts to reduce unwarranted variation. Of note, TBI was the subject of the first guidelines effort in neurosurgery (8). Several other neurotrauma guidelines have been produced subsequently, including those for pediatric brain injury, penetrating brain injury, surgical management of brain injury, and prehospital management of brain injury (1, 4, 13, 26).

These documents are quite useful as reviews of existing knowledge and categorization of the strength of evidence supporting various management practices. For a disease as complex as TBI, a common concern about applying the results of a clinical trial is the generalizability of the results to a particular patient or circumstance. It is often difficult to appreciate the nuances and determine when thoughtful deviation from guidelines is appropriate. The optimal practice of evidence-based medicine consists of making clinical decisions by integrating knowledge of the available evidence with a particular patient's circumstances, a physician's own training and experience, and the setting in which the care is being provided. Guidelines provide an excellent place to start setting treatment goals and formulating a therapeutic plan.

Several retrospective reports using historical controls suggest that standardization of care through protocols based on published guidelines may improve outcomes for TBI patients. In some cases, costs are reduced, but other reports describe increased costs if hospitals had not previously devoted many resources to acute TBI management. Also, despite widespread dissemination, the degree to which most hospitals and practitioners actually implement guidelines remains unclear.

Despite these caveats, the continuing maturation of guidelines efforts in neurosurgery has been a major development during the last decade. Many neurosurgeons and hospitals have used this opportunity to review their practices and revise

them when appropriate. The goals of these efforts are improved efficiency, reduced costs, and, most importantly, better outcomes.

PREHOSPITAL CARE

Organization of Prehospital Care

Thirty years ago, organized networks for prehospital care were little more than a promising idea. The subsequent years have witnessed definite improvement in the organization of prehospital care systems in the United States, and such networks now exist in many regions. Mortality is significantly reduced when injured patients receive care at a trauma center as opposed to a hospital that is not a trauma center (34). The obvious implication is that organized prehospital triage and referral systems can improve patient outcomes. However, major organizational gaps continue to affect the optimal prehospital care of many TBI patients.

In 1986, the Emergency Medical Treatment and Labor Act (EMTALA) became law. It was intended to prevent uninsured patients from being refused emergency assessment and treatment. As with many well-intentioned government regulations, unintended consequences soon appeared. For example, a remote hospital that is not a designated trauma center (and which does not have immediate access to operating rooms 24 hours per day) could be found to be in violation of EMTALA if personnel there were to deny a request for an emergency patient transfer with the reasoning that the patient would be much better served at a closer or more appropriate facility, such as a level I trauma center. Another unintended situation occurs when a trauma center becomes filled with patients who have relatively minor injuries because the center is statutorily required to accept all patients in transfer. As a result, the trauma center may be forced to go on ambulance diversion, which makes the facility and its specialty attention unavailable to the very people it was established to serve: severely injured patients who truly require immediate surgery and critical care.

Regional interhospital cooperation is an obvious solution. However, the frequently intense competition between hospitals and the resulting lack of cooperation are common barriers to regional coordination of services. Along with continued revisions of EMTALA, these barriers must be overcome if injured patients are to receive optimal prehospital care. The susceptibility of the acutely injured brain to secondary insults such as hypoxia and hypotension, as well as the frequency with which such insults occur, suggests that efficient and coordinated prehospital networks are especially important for optimal care of TBI patients.

Neurological Assessment

The first publication of Plum and Posner's classic monograph in 1966 (50) and the description of the Glasgow Coma Scale by Teasdale and Jennett in 1974 (60) had a major influence on the standardization of neurological assessment of emergency patients. However, the subsequent widespread adoption of prehospital sedation, paralysis, and intubation of emergency patients has made it impossible to perform an appropriate neurological evaluation on many of these individuals.

Good solutions to this problem remain elusive. Reliance upon prehospital providers' descriptions of the prehospital examination is often the only alternative, but these assessments may be incomplete or inaccurate. Marshall et al. (39) created a computed tomography (CT)-based classification scheme that categorizes the severity of brain injury. The Abbreviated Injury Scale used by general trauma surgeons is also based on anatomic criteria. Although useful, such schemes cannot supplant clinical assessments of neurological function. Instead, they are best thought of as supplementary sources of information.

Airway

The need to secure the airway of a severely brain-injured patient has long been a basic management principle. It seems intuitively obvious that establishing a secure airway will facilitate oxygenation, avoid hypercarbia, and prevent aspiration (18, 42).

Why, then, have several recent retrospective reviews reported an increase in mortality in severe TBI patients who were endotracheally intubated before reaching the hospital? The answer seems to lie in problems with implementation, not with the basic principle itself (25). In some regions, paramedics and other first responders may perform endotracheal intubation so rarely that the necessary skills cannot be maintained. In other situations, optimal ventilation may not be performed (21).

It seems safe to conclude that immediate intubation of patients with TBI is still an effective method of securing an airway, but only if the person performing the intubation is sufficiently skilled. A better choice for inexperienced responders may be using a bag-valve-mask device or a laryngeal mask airway to maintain the patient's ventilation.

Breathing

Recommendations for the use of hyperventilation in TBI patients have undergone several changes over the last decade. Early observations about the effectiveness of hyperventilation in lowering intracranial pressure (ICP) led to its widespread use. The mechanism appears to be a pH-mediated effect of constricting cerebral resistance arterioles which thereby decreases cerebral blood volume.

Subsequent laboratory work suggested that the vascular constrictive effect of sustained hyperventilation begins to wear off within a few hours (45). Moreover, once a low CO_2 partial pressure ($PaCO_2$) has been maintained for more than a few hours, any attempts to raise the $PaCO_2$ back to normal may cause the blood vessels to dilate and thereby increase blood volume and ICP.

Eventually, clinical data demonstrated worse outcomes in severe TBI patients who had been routinely treated with hyper-

ventilation (44). Thus, routine use of prophylactic hyperventilation is not recommended.

However, there remain at least two situations in which hyperventilation may be appropriate. The first is as a latter-stage treatment for refractory intracranial hypertension. Protocols vary as to the exact circumstances at which this therapy should be instituted, but most agree that it should only follow the failure of some other therapies, such as sedation, pharmacological paralysis, CSF drainage, and/or osmolar therapy. If advanced neurological monitoring capabilities are available, cerebral oxygen metabolism can be tracked to ensure that hyperventilation does not cause a reduction in oxygen delivery to the brain. Similarly, if cerebral blood flow (CBF) monitoring indicates that blood flow to the brain is normal or even elevated, then mild hyperventilation may be implemented early in the management of intracranial hypertension.

Another indication for hyperventilation is an acute neurological deterioration that is known or suspected to be caused by a large intracranial mass lesion. In theory, a brief period of hyperventilation may lower ICP long enough to allow sufficient time to transport a patient to an operating room for evacuation of a hematoma or contusion. The negative effects of a potential temporary compromise of CBF from vasoconstriction may be outweighed by the benefits of reducing ICP. In these patients, once a clot is removed, ventilation returns to normal. In patients without focal signs suggestive of the presence of a mass lesion (such as a significantly asymmetric motor exam or asymmetry of pupillary response), there is less indication to initiate immediate hyperventilation. Similarly, if a patient who has been hyperventilated as a preliminary treatment for a suspected acute hematoma is found to have no such lesion upon performance of CT, hyperventilation is usually best stopped while other treatments with more acceptable risk-benefit ratios are implemented.

Circulation

Similar to the breathing and ventilation strategies for treating TBI patients, the general consensus on blood pressure goals has undergone several changes during the last three decades. The 1980s and 1990s witnessed widespread dissemination of the belief that elevating blood pressure to maintain a mean cerebral perfusion pressure (CPP) of at least 70 mmHg improved outcome for patients with severe TBI. Anecdotes and case series supported this approach, and it seemed to be consistent with the concept that cerebral hypoperfusion caused by low blood pressure is a major source of secondary brain injury (53, 54).

Subsequent reports, however, including a prospective, randomized, controlled trial, demonstrated no improvement in patient outcome as a result of this practice (32, 52). Robertson et al. (52) found that this treatment strategy did seem to decrease the incidence of cerebral ischemia, but it did so at the price of increased pulmonary complications. The overall result for patients was no gain.

Meanwhile, a management protocol from Lund, Sweden, called for severe TBI patients to be maintained at lower blood pressures (5, 23). This protocol is based in part on the assumption that the hydrostatic pressures associated with elevated blood pressure may promote cerebral edema through passage of water from the circulation to the brain, whereas increasing blood oncotic pressure and increasing precapillary vasoconstriction may facilitate diffusion of water from the brain to the vasculature (*Fig. 2*). Again, however, support for these concepts is based only on uncontrolled case series.

Present thinking suggests that there probably exists a floor below which CPP should not decrease. However, efforts to increase CPP above this floor in all patients may increase complications without conferring any added benefit. A minimum CPP of 60 mmHg is probably reasonable for most patients. As with all such recommendations, however, individual patients may fare better with either higher or lower CPPs. Ideally, detailed cerebral monitoring could be used to identify those patients who require a higher CPP and, conversely, those who would not need to be subjected to the potential risks of aggressive efforts to increase CPP to an arbitrary level.

Of note, most of these studies were conducted in intensive care units (ICUs). It is reasonable to extrapolate them to the prehospital setting, but the reader should remember that specific treatment goals may have to be adapted to that setting.

IMAGING

A generation ago, CT was still a new technology. Published reports continued to explore the utility of this new imaging technique in brain-injured patients. Angiography and cranial radiography were beginning to fade from the scene as routine tools in the evaluation of trauma patients. Magnetic resonance imaging had not yet become available.

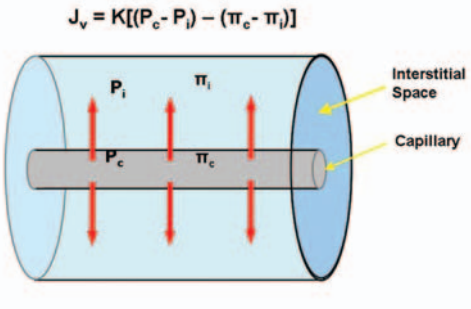

FIGURE 2. *According to the Starling hypothesis, fluid exchange (J_V) between a capillary and the interstitial space is determined by hydrostatic pressure within the capillary (P_c), hydrostatic pressure in the interstitial space (P_i), oncotic pressure within the capillary (π_c), and oncotic pressure within the interstitial space (π_i). K is a constant. Important parts of the Lund strategy for management of patients with severe TBI include manipulation of these parameters to attempt to minimize cerebral edema.*

Not too many years ago, performing emergency CT was a time-consuming affair. The neurosurgeons accompanying the patient had plenty of time to write their admission history and physical and their admitting orders while in the scanner. Neurosurgery residents who had some knowledge of computer programming could learn to operate the scanner. Debates in the literature and at meetings argued about the value of a single-slice computed tomographic scan through the center of the head as a way to identify mass lesions quickly, without the need to wait for the entire scan to be completed.

Subsequent advances in CT technology have been nothing short of remarkable. Scans of the brain can now be obtained in a matter of seconds. Touch-screen technology has made it possible for virtually any physician to perform CT with only minimal training. Image quality has improved greatly. The need to print images on film has disappeared, as the scans are accessible from any place that has Internet connectivity.

A key development in medical imaging has been our ability to visualize not only anatomic structure, but also function. CT, which remains the imaging modality of choice for patients with acute TBI, can be adapted to provide information about CBF, perfusion, and vascular anatomy, even in emergency settings (*Fig. 3*). Magnetic resonance imaging and magnetoencephalography can reveal selective activation of specific brain regions. Although positron emission tomography scanning remains the most powerful tool for acute study of CBF and metabolism after injury, as yet its application is not as widespread as that of CT and magnetic resonance imaging.

A common problem, however, is the need to transport critically ill patients to the radiology department to perform such studies. Patient transport has been reported by many authors to be associated with an increase in potentially adverse events. Portable CT equipment has been available for several years, but only recently have technological advances made these devices more user friendly. Important features include helical scanning capability, low radiation exposure, wireless links to a hospital's imaging network, operation via a touch screen, ability to run on battery power, and ability to perform perfusion and xenon-enhanced CT studies (48). Most importantly, this technology avoids the need to transport patients to the radiology department. Future applications may include placement of these scanners in emergency departments and even in certain types of ambulances.

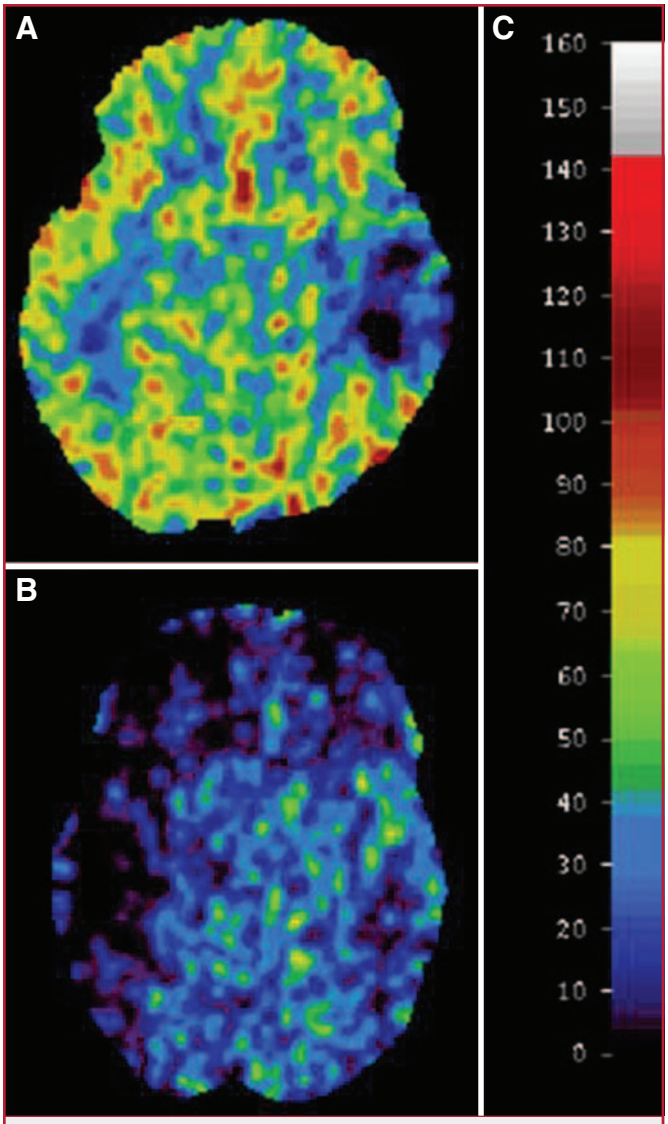

FIGURE 3. *Two examples of stable xenon-enhanced computed tomographic scans.* **A**, *scan shows left temporal ischemic area, but flows are elevated elsewhere in the brain.* **B**, *scan shows reduced flow throughout the brain, with large ischemic areas in the right temporal and frontal areas and smaller ischemic areas elsewhere* (left). **C**, *scale bar for CBF (units are milliliters per 100 grams per minute) is shown.*

SURGERY

Basic principles of surgical management have not changed much in the last generation. As articulated clearly by Becker and others, they include prompt evacuation of contusions and other mass lesions and use of large craniotomy openings for the evacuation of acute subdural hematomas (ASDHs).

Indications

Some of the most difficult decisions we make in neurotrauma care involve whether moderate-sized hematomas or contusions should be evacuated or simply observed. A surgeon may feel torn between performing an operation that may be unnecessary versus having a patient undergo neurological deterioration if surgery is delayed too long.

Several courses of action are possible in such situations. These include waiting a few hours to allow alcohol or other drugs to be metabolized; obtaining a follow-up computed tomographic scan within several hours to determine whether the lesions have enlarged; and/or inserting a ventriculostomy or parenchymal ICP monitor in search of elevated ICP, which might prompt an immediate craniotomy.

These decisions are often based on an individual physician's judgment and experience. It is often preferable to remove sizeable lesions early, before a patient's condition deteriorates. Prompt surgery also minimizes subsequent parenchymal edema around a contusion. Furthermore, a global measure such as ICP may be normal even while CBF and metabolism are focally impaired near an acute traumatic lesion.

Recently published evidence-based guidelines provide some direction (10–12, 14, 15). Patients with Glasgow Coma Scale scores of 8 or less with large mass lesions should undergo prompt lesion evacuation, especially if the results of their neurological examinations reveal deterioration, if their pupils exhibit anisocoria or are fixed and dilated, or if the lesions are causing focal neurological deficits. A midline shift of 5 mm or more and effacement of the basal cisterns are commonly used computed tomographic indicators of significant mass effect. Regardless of the patient's Glasgow Coma Scale score, evacuation is recommended for epidural hematomas larger than 30 mm^3, subdural hematomas greater than 10 mm in thickness or causing more than 5 mm of midline shift, and parenchymal lesions greater than 50 mm^3 in volume. Evacuation of frontal and temporal contusions greater than 20 mm^3 in size is recommended if the contusions are located frontally or temporally and are associated with compressed cisterns or a midline shift of 5 mm or more in patients with Glasgow Coma Scale scores of 6 to 8. A smaller size threshold is often used in assessing temporal lesions because of their potentially greater risk.

Anticoagulant and Antiplatelet Agents

An increasingly common problem involves the patient who develops an intracranial hemorrhage while taking Coumadin, Plavix, and/or aspirin medications (*Fig. 4*). Some neurosurgeons delay surgery until platelets can be administered or coagulation parameters normalized. Vitamin K is usually readily available, but obtaining platelets or fresh frozen plasma can be time consuming in some hospitals, and procurement of recombinant factor VIIa may require complex bureaucratic procedures because of its cost. Neurologically compromised yet treatable patients may not be able to tolerate such delays. We have sometimes enjoyed success with taking such patients promptly to surgery while the hospital's blood bank initiates the process of delivering fresh frozen plasma and/or platelets to the operating room. Blood products generally arrive in the operating room while the neurosurgeon is in the midst of the surgery, and their effect on clotting is usually immediate and obvious. Although laboratory tests of hemostatic function are helpful, the surgeon can gain useful information simply by watching how the blood is clotting in the surgical field.

Recombinant factor VIIa has received a great deal of attention recently for treatment of coagulopathy in trauma patients (22). An important neurosurgical application is the immediate treatment of warfarin-associated intracranial hemorrhage (9). This product may help with diffuse oozing, but brisk bleeding from a large vessel still requires direct treatment via cautery, ligation, tamponade, etc.

As neurosurgeons' experience with factor VIIa has increased, several questions have been raised. One is the possibility of inducing adverse reactions, such as thrombosis of stenotic coronary arteries, in susceptible patients. The number of such reports will undoubtedly increase as this agent sees greater use. Another concern is that the half-life of factor VIIa is only 3 to 6 hours. Thus, after its period of action has passed, the hemorrhagic diathesis may recur unless additional treatments are initiated, such as administration of fresh frozen plasma, vitamin K, or additional factor VIIa. The cost of the drug is high, especially for the doses required to treat bleeding in trauma patients. To control costs, some hospitals have implemented complex administrative-approval algorithms. The significant cost also raises important questions about appropriate indications, especially in elderly patients with devastating hemor-

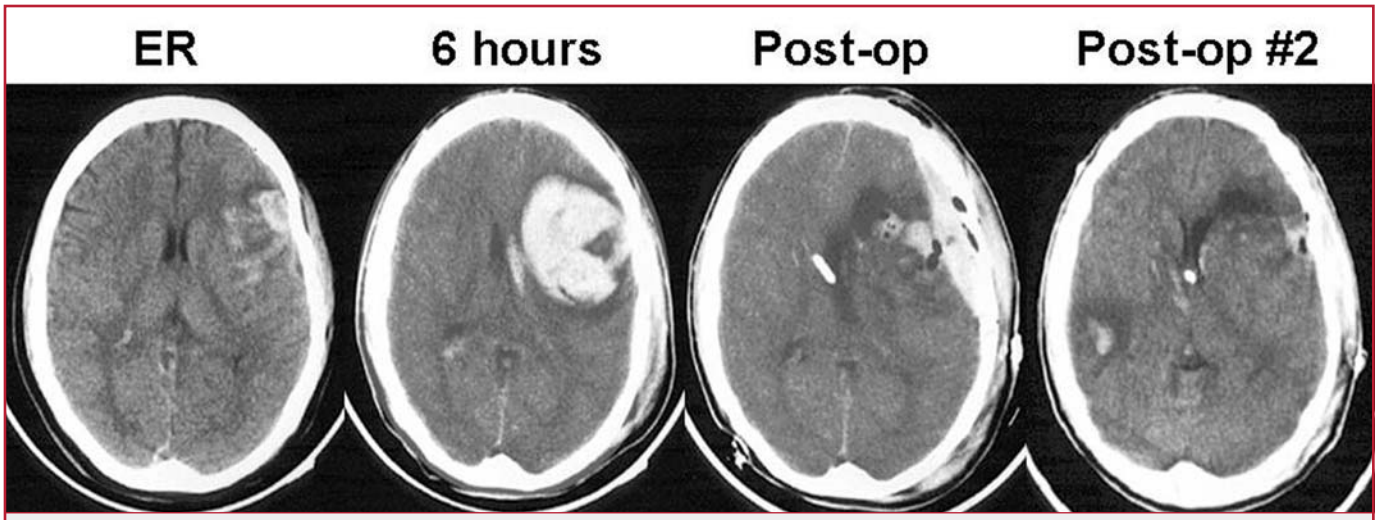

FIGURE 4. *Series of computed tomographic scans showing rapid enlargement of a contusion, which was surgically evacuated. A postoperative epidural hematoma developed, requiring the patient to return to the operating room.*

rhages that make meaningful recovery unlikely. These issues are important because such situations will likely occur with increasing frequency in the future as the population ages and the number of patients taking anticoagulants increases.

Subdural Hematomas

Although it has been reported (57) that reduced mortality can be expected if ASDHs are evacuated within 4 hours, other surgeons have not been able to replicate this effect (70). Some patients may fail to improve because of coexisting parenchymal brain injury that will not improve after evacuation of a mass lesion. Furthermore, even rapid progression of a patient through the emergency medical services system and to the operating room may not be fast enough to reverse damage caused by the mass effect of a clot. Nevertheless, clinical and laboratory evidence documents the adverse effects of a large acute mass lesion on cerebral metabolism (27). Prompt evacuation is not only common sense; it is also consistent with the common clinical observation that patients often improve after evacuation of large ASDHs. These same arguments apply to other types of traumatic mass lesions as well.

The use of large craniotomy flaps when performing ASDHs allows the surgeon to gain access to a variety of potential sources of bleeding. These include large draining veins near the superior sagittal sinus as well as contused tissue in the subtemporal and subfrontal areas and the temporal and frontal poles. A large craniotomy opening for evacuating an ASDH has been a standard recommendation for many years, but it is worth emphasizing in our present era of tiny incisions made possible by image-guidance systems and endoscopic instrumentation. The medial part of the scalp incision may be made on or near the midline, but it may be wise to keep the bony opening several centimeters off the midline to avoid arachnoid granulations and large dural and cortical veins near the midline. The midline placement of the scalp incision preserves the option of removing additional bone near the midline if subsequent uncontrollable bleeding near the superior sagittal sinus necessitates more medial exposure. It also ensures a sufficiently wide base for the scalp flap, which prevents necrosis of the posterior and superior edges of the flap from inadequate blood supply.

An exception to the general practice of using larger flaps may sometimes be found in coagulopathic patients with relatively focal subdural hematomas. Some authorities describe successful clot evacuation in such cases without excessive difficulty in obtaining hemostasis.

Surgical Technique

If epidural tack-up sutures are used in an emergency surgery, many surgeons prefer to wait until closing to place them so as not to delay evacuation of a large mass lesion. However, during the opening, brisk epidural bleeding may be encountered immediately upon removal of the bone flap, especially near the midline. The only way to achieve control may be by placing numerous, closely spaced epidural tack-up sutures at the troublesome area. It is often helpful to place small amounts of an absorbable hemostatic agent, such as Gelfoam (Pharmacia/Upjohn; Kalamazoo, MI) or Surgicel (Johnson & Johnson; Arlington, TX) sponges or fibrillar collagen, just under the bony edge. These materials provide some extra bulk that may act as tamponades in areas of bleeding.

Several maneuvers during opening of the dura may be useful for avoiding subsequent problems. The first is to open the dura in a slow, controlled manner. Going slowly at this point of the operation may seem counterintuitive to the need for rapid evacuation of a large clot. However, some experienced neurotraumatologists speculate that a relatively slow dural opening may allow a more gradual reduction of the pressure on the cerebral cortex. This gradual equilibration has been assumed to reduce the likelihood of sudden, massive herniation of brain through the craniotomy opening.

Along similar lines, it may be helpful to open the dura in a cruciate manner. Specifically, the four limbs of a cruciate opening may be made without connecting them at the center of the "X." This allows evacuation of the clot from all four quadrants of the exposure. If the brain appears to begin swelling slightly, and if intradural bleeding has stopped, these four smaller incisions can be closed quickly. Alternatively, two of these limbs can be connected to create a small dural flap if access to only a specific part of the opening is desired. Wider access can be gained by connecting all four limbs. If the surgeon wishes to close quickly, a single stitch in the center can pull all four dural leaves together. Although this approach is especially helpful if the surgeon is not initially planning to perform a decompressive craniectomy, it is completely compatible with a decision to proceed with decompression if unexpected intraoperative events indicate that it might be helpful.

Other surgeons attempt to prevent massive brain swelling by incising the dura with a reverse "U" incision anteriorly, inferiorly, and posteriorly; the dura near the midline is left intact (3). They report excellent results in terms of evacuating subdural hematomas and parenchymal lesions, with no cases of massive brain swelling.

Decompressive Craniectomy

In the last few decades, interesting swings have occurred in the neurosurgical community's opinion regarding decompressive craniectomy. It is clear that decompressive craniectomy can lower ICP in many cases (*Fig. 5*). However, it is equally clear that no well-done, randomized, prospective trial has been completed to answer the question of whether decompressive craniectomy truly improves outcomes for all patients, or even for certain selected subpopulations (56). Two prospective trials now in progress may provide important information about the effectiveness of decompressive craniectomy for TBI patients (29, 56).

Although the potential complications of decompressive craniectomy are familiar to those who perform these procedures, these issues have only recently received more than a cursory mention in the literature. Potential problems include

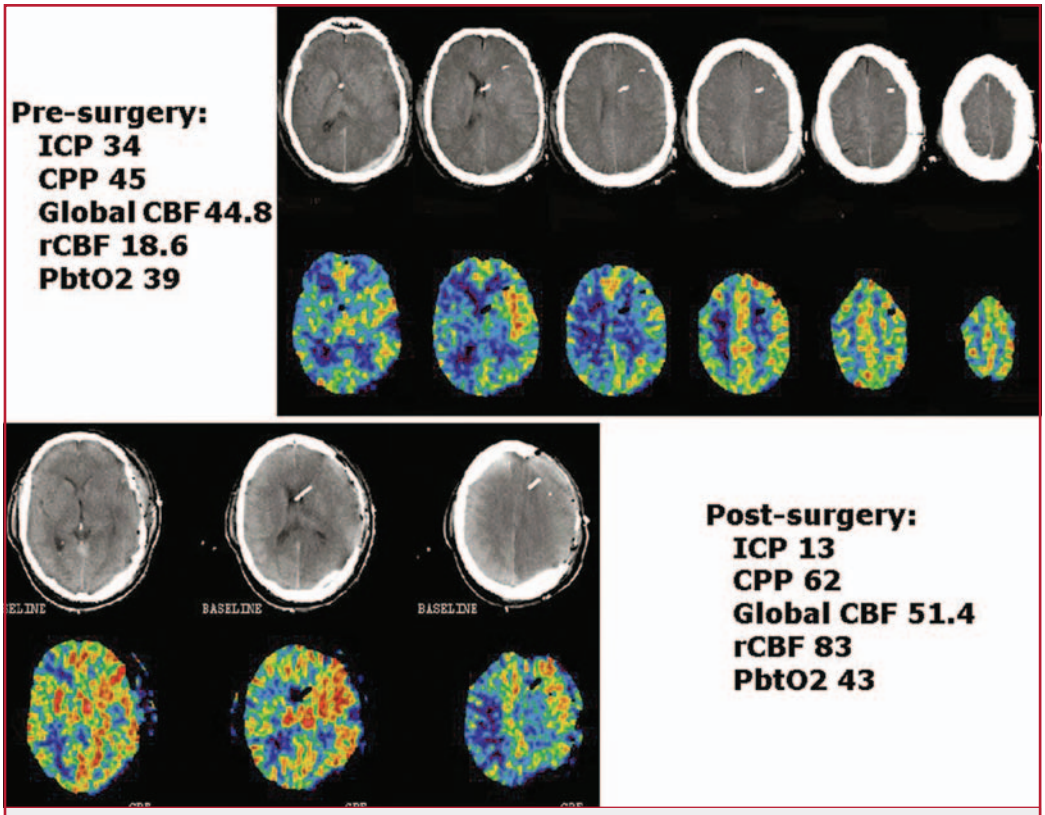

FIGURE 5. *Preoperative and postoperative conventional and xenon-enhanced computed tomographic scans from a patient who underwent decompressive craniectomy. ICP decreased, CPP and global CBF increased, and regional CBF increased dramatically.*

postoperative epidural/subgaleal hematomas, subdural fluid accumulation remote from the craniectomy site, brain injury at the edges of the craniectomy from impingement during outward brain swelling, lack of brain protection under the craniectomy site, possible impairment of cerebral metabolism from lack of overlying cranium, the need for subsequent surgery to replace bone, and potential resorption of the bone flap, among others.

Controversies

Several questions exist about the way these operations are performed. The first concerns timing. Some data suggest that patients fare poorly if they receive a decompressive craniectomy early in their course of treatment (2). It might be better to treat those patients with medical interventions that are as aggressive as possible; if these measures fail to improve outcome, then surgical decompression seems unlikely to have any better results. Other practitioners, however, feel that patients who arrive in the emergency department with poor neurological examinations and diffuse brain swelling as evidenced by CT have little to lose by undergoing prompt decompression.

A second controversy involves performing these operations routinely, whenever a patient undergoes a trauma craniotomy. Some surgeons leave bone flaps off as a routine part of their trauma operations. Unless the brain is markedly swollen, this practice may not be necessary in many cases. Mildly protruding brain can often tolerate watertight closure of the overlying dura, even if the brain has to be carefully protected and depressed with a malleable retractor during dural closure. Postoperative ICP is often lower than one might expect, which perhaps serves as clinical corroboration of experimental data that suggest decompressive craniectomy may actually increase edema of the underlying brain (20).

A third area that is less controversial is the size of the decompression. The general rule is "the bigger, the better." This must be kept in mind during the planning of the initial craniotomy. If the surgeon anticipates even a slight possibility of leaving the bone flap off, it is helpful to position the patient with the head turned as far laterally as possible. This may require significant turning of the head (if the cervical spine has been cleared) or positioning the patient in the lateral position (if cervical spine injury is known or has not been excluded). This extensive turning of the head allows access to the posterior and inferior regions of the cranial vault, which are often not well decompressed even by a standard large trauma flap. Another important point is to take the decompression to the floor of the temporal fossa. Extending the inferior margin of the craniectomy down to the temporal cranial base is recommended for achieving optimal decompression of the perimesencephalic cisterns (46). This recommendation is consistent with other results indicating that large craniectomies are more effective than smaller ones (31).

Technique

The importance of performing a sufficiently large decompression cannot be emphasized too strongly (*Fig. 6*). Craniectomies or dural openings that are too small may cause swollen brain tissue to herniate through the bony defect, thereby causing strangulation, infarction, and creation of additional brain swelling from inward tracking of the resultant cerebral edema (*Fig. 7*).

If a patient who has had a recent craniotomy is returned to the operating room for removal of the bone flap, the sur-

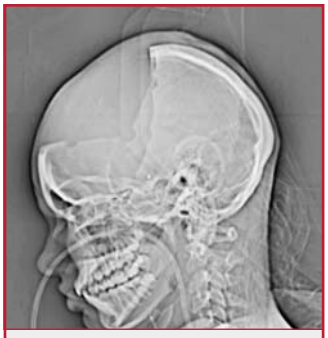

FIGURE 6. *Bifrontal decompression. The frontal craniectomy could have been extended inferiorly, but the surgeon deliberately chose not to do so to avoid the frontal sinus.*

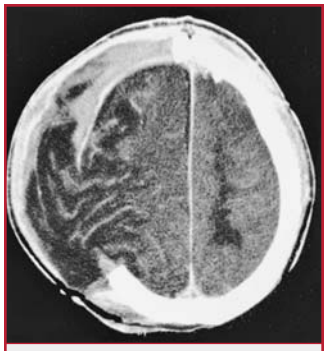

FIGURE 7. *Contrast-enhanced computed tomographic scan of a patient in whom a bony decompression was performed, but the dura was not opened widely. Necrotic brain tissue can be seen herniating through the defect.*

geon may wish to use a "T" incision to facilitate removal of more bone. In general, these "T" incisions begin at the posterosuperior part of the existing incision and curve gently toward the inion. The scalp on the two sides of the "T" can be reflected to expose additional bone medially, posteriorly, and inferiorly. This bone can be removed as a separate piece that can be secured to the original bone flap at the time of replantation.

The closing of a decompressive craniectomy is the ideal time to make preparations for subsequent replacement of the bone flap. Most surgeons perform a duraplasty or dural augmentation as part of these procedures. It may be wise to lay another sheet of dural substitute over the entire area of exposed dura. This maneuver prevents adhesions from forming between the dura and the scalp. These adhesions can make it difficult to expose the craniectomy site during subsequent surgery for bone flap replacement. A similar precaution may be used to minimize scarring and adhesion of the temporalis muscle to the scalp. Careful attention should be paid to the handling and preservation of the temporalis to optimize long-term cosmetic results.

In general, bone flaps should be replaced as soon as possible. The determining factor may be the persistence of cerebral edema, which may require weeks to subside sufficiently to allow cranioplasty. For other patients, bone flap replacement may be delayed by the presence of intradural CSF collection, which sometimes causes protrusion of the brain through the craniectomy defect. Extra-axial CSF collections along the midline or at the craniectomy site may respond to CSF drainage via a lumbar drain inserted the day before surgery. Another option for treating patients with hydrocephalus is insertion of a ventriculoperitoneal shunt with a programmable valve. The resistance can initially be set low to facilitate CSF drainage. After cranioplasty, the resistance can be set to normal to prevent excessive CSF drainage from creating an epidural "dead space" under the bone flap.

INTENSIVE CARE UNIT MANAGEMENT

Evolution of Neurocritical Care

The field of neurocritical care is rapidly becoming a distinct discipline. Traditionally, critical care medicine has been dominated by a focus on the heart and lungs. More recently, improved knowledge of central nervous system pathophysiology, as well as the availability of therapies for previously untreatable conditions such as ischemic stroke, have driven interest in the management of these patients within ICUs. The Neurocritical Care Society was created only a few years ago as a multidisciplinary group with the goal of improving the care of patients with life-threatening neurological illnesses (47).

In the last few decades, our knowledge and technology pertaining to ICUs have mushroomed (*Fig. 8*). Unfortunately, this wealth of information sometimes makes it difficult to filter important bits of data from the background noise. Knowledge does not necessarily equal wisdom. More information in and of itself is not automatically associated with a coordinated direction of patient care, and in fact, it may cause distraction and unnecessary confusion. An intensivist who concentrates on diseases of the nervous system may be uniquely able to balance management of the nervous system with cardiac, pulmonary, renal, and other critical care issues.

The growth of knowledge, procedures, and diagnostic tests available to intensivists has been intimidating for some neurosurgeons. However, a neurosurgeon's unique expertise and perspective on the management of his or her patients are more than adequate to offset a lack of intimate familiarity with current trends in ventilator or pressor management. The latter issues can be learned, but a neurosurgeon's judgment and accumulated wisdom cannot be duplicated by other physicians. Neurosurgeons should be confident that they bring a unique and much-needed perspective to the management of their patients, no matter how sick those patients may be. After all, most intensivists will not see patients several weeks or months after they leave the ICU, but the neurosurgeon may be in frequent contact with such patients and their families for years. This type of long-term feedback is invaluable as a means for reevaluating one's judgment and management practices.

The critical care community has benefited from several articles and abstracts that report improved care when ICUs are administered by board-certified intensivists as opposed to ICUs that are run by other physicians (64). However, some of these studies are methodologically suspect, and the anticipated advantages of hiring intensive care physicians to manage ICUs may not always materialize. For example, it is sometimes assumed that the presence of an intensivist will lead to greater efficiency and thus decreased costs of ICU care. However, the exact opposite may occur, as costs may increase significantly at hospitals that have previously not devoted appropriate resources to these types of patients (49). Another uncertainty is whether such reported improvements as decreased costs and shorter lengths of ICU stay are direct results of an intensivist's presence or whether they instead represent greater institutional adherence to standardized patient management prac-

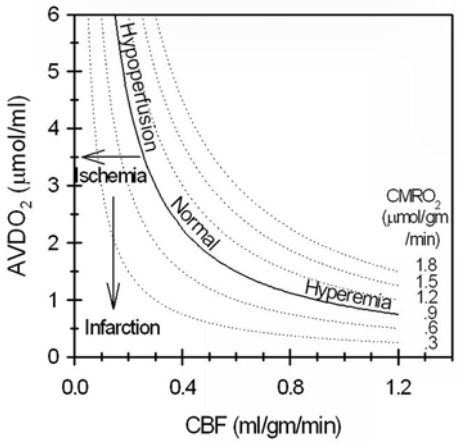

FIGURE 8. *Complex relationships have been discovered between CBF, cerebral metabolic rate of oxygen ($CMRO_2$), cerebral arteriovenous difference of oxygen content ($AVDO_2$), hyperemia, hypoperfusion, ischemia, and infarction. (*From, *Robertson CS, Narayan RK, Gokaslan ZL, Pahwa R, Grossman RG, Caram P Jr, Allen E: Cerebral arteriovenous oxygen difference as an estimate of cerebral blood flow in comatose patients.* ***J Neurosurg*** *70:222–230, 1989).*

tices, with a resultant reduction in the sometimes expensive idiosyncratic variation that exists among practitioners. If the latter is true, then the presence of an intensivist per se may not be as important as the commitment of a hospital and medical staff to reevaluate and refine existing patient management practices as necessary.

These external pressures are presently causing difficulty for some neurosurgeons who have served for years as directors of their local neurosurgery ICUs. In some cases, they are being displaced as medical directors and even prevented from serving as primary physicians for their patients while the patients are in the ICU.

Another practical issue facing ICUs relates to available personnel. There are at present far too few intensivists to fill current and projected needs. It remains unclear how recommendations to increase intensivist presence in ICUs will be reconciled with the relatively small supply of intensivists available. One potential solution is an electronic ICU, or "eICU." In this system, each bed from several different ICUs is electronically linked to a central area, which may be geographically remote, that has continuously available bedside monitoring data from each linked patient. Thus, a nurse or physician in this central area can simultaneously monitor many patients in different ICUs. Each bed may also have a dedicated video camera, microphone, and speaker, and progress notes and orders are available via fax or electronic medical record. Different institutions report varying degrees of success and satisfaction with this model. Obviously, this system cannot handle emergencies that require a physician's presence at the bedside, such as intubations, central venous access, chest-tube placement, etc. Another important variable in this system is the degree of neurological sophistication possessed by the eICU doctor.

Anticipation versus Reaction

Physicians are trained to prevent problems and also to anticipate them before they occur. Unfortunately, this goal of being proactive has not always resulted in improved patient outcomes. During the last few decades, well-conducted clinical trials have shown that attempts to prevent intracranial hypertension by immediate initiation of therapies that are often effective for treating established intracranial hypertension not only do not improve outcome; they may sometimes actually worsen outcome. The list includes hyperventilation, barbiturates, pharmacological paralysis, hypothermia, and artificial elevation of CPP (19, 28, 44, 52, 67). Decompressive craniectomy might also find its way onto that list if a prospective trial is conducted.

Thus, despite our natural inclination to control a situation by playing offense and initiating treatments before complications get out of hand, it might be best for us to sit back and play defense. The best that we can do may be to react immediately when circumstances change. Prompt treatment of established problems may be better for our patients than initiation of treatments for complications that have yet to happen. Of course, intensive efforts continue in the search for interventions that are truly effective when given prophylactically.

Tracheostomy and Ventilator Weaning

Management of the ABCs (airway, breathing, and circulation) was discussed in the context of prehospital care, but most of our understanding of these topics comes from research conducted in ICUs. An additional issue that arises in ICUs surrounds the timing of tracheostomy. Many trauma surgeons and intensivists push for early tracheostomy. Many of their patients, however, have significant pulmonary problems and do not suffer from brain injuries. It is usually best not to perform any procedures on patients with acute and severe TBI unless those procedures are essential. Furthermore, TBI patients will often remain in ICUs longer than other patients, because they require intracranial monitoring. Thus, performing early tracheostomy may not significantly shorten the length of ICU stay in these patients.

Patients who appear to be "waking up" may be given some extra time to see if they can be given a trial of extubation. The traditional teaching that a tracheostomy should be performed within 2 weeks is based more on dogma than fact. On the other hand, if it appears that a patient will likely not experience enough neurological recovery to protect his or her airway, it is reasonable to proceed expeditiously with a tracheostomy once the patient's cerebral metabolism appears to have stabilized.

Monitoring

Although detailed monitoring of cerebral pathophysiology is not yet performed at many hospitals that treat TBI patients, such monitoring represents the best way for evaluating a particular patient's metabolic pattern and, when necessary, for intervening in an appropriate manner (*Fig. 9*).

A concept that is gaining increasing recognition is the importance of regional heterogeneity of cerebral metabolism and the difference between regional and global measures of cerebral metabolism. Even relatively large areas of focal abnormality may not affect a global measure of cerebral metabolism, such as jugular venous oxygen saturation. Similarly, a focal monitor such as a brain-tissue oxygen sensor may not reveal the presence of a large abnormal area if the focal monitor lies within normal tissue. Those who use cerebral monitoring devices must be aware of their limitations as well as their potential usefulness.

Continuous electroencephalographic monitoring has been reported to detect seizures in more than 20% of patients with moderate and severe TBI during the first 2 weeks postinjury (66). These results suggest that adverse electrophysiological events may often be missed and may represent an important and underappreciated mechanism of secondary brain injury.

Intracranial Pressure

The most widely used monitoring techniques measure ICP. Parenchymal devices have become popular over the last few decades, but ventriculostomy remains the recommended form of ICP monitoring technology. The interested reader is referred to the excellent summaries contained in *Guidelines for the Management of Severe Traumatic Brain Injury* (7), which reviews both the different types of ICP monitoring technology and the basis for using 20 mmHg as the threshold value for treating patients with elevated ICP.

Brain Tissue Oxygenation

For many years, measurement of cerebral oxygen metabolism could be performed only via intermittently sampling blood from the jugular bulb and comparing its oxygen content to that of arterial blood. Subsequently, jugular venous oximetry allowed for continuous measurement of the oxygen saturation of blood flowing out of the brain (58).

Although direct monitoring of brain-tissue oxygenation was not even a dream 30 years ago, it is presently a widespread (and increasingly used) monitoring technique. New publications and ongoing discussions continue to inform us of the proper interpretation of these data, as well as treatment thresholds and optimal interventions for increasing brain-tissue oxygen tension ($PbtO_2$). A $PbtO_2$ reading of 10 mmHg probably represents a minimally acceptable value, although some would prefer a higher threshold, such as 15 mmHg or even 20 mmHg.

Although placement of these monitors in uninjured brain has been recommended, others have suggested that a more appropriate strategy is placement in brain that is at risk because of adjacent contusions, hematomas, or infarcts (*Figs. 10* and *11*). Some neurosurgeons have taken these monitors to the operating room to monitor tissue oxygenation during cerebrovascular procedures or other operations that may require temporary vessel occlusion.

Depending upon an individual patient's situation, appropriate ways to address a low $PbtO_2$ value might include elevation of arterial blood pressure, increase in the fraction of inspired oxygen administered via ventilator, transfusion of packed red cells, and reduction of ICP via evacuation of mass lesions or other interventions. Although it is difficult to conduct high-quality studies that demonstrate improvement in patient outcome as a result of $PbtO_2$ monitoring, many neurosurgeons have experience with at least a few patients for whom this seemed to be the case.

FIGURE 9. *A patient undergoing many different types of cerebral and metabolic monitoring.*

Cerebral Blood Flow

The role that CBF plays in influencing outcome from TBI has been intensely scrutinized for many years (*Fig. 12*). The collective efforts of many investigators over many years indicate that CBF passes through several changes after a severe TBI. It is often quite low during the first few hours after injury. After a few hours or days, CBF subsequently increases, often to supranormal levels. It then gradually decreases and may even pass through a phase of vasospasm before it finally normalizes (40).

Xenon-enhanced CT is a powerful technique for obtaining both global and regional quantitative CBF measurements, but it is presently not approved by the United States Food and Drug Administration. It is hoped that such approval will be forthcoming. Parenchymal or surface monitors use a variety of techniques to assess CBF, such as laser Doppler flowmetry, thermal diffusion, and others. These are useful technologies, but many of them are invasive. Transcranial Doppler sonography is a helpful measure of CBF velocity through the large arteries of the circle of Willis. Its limitations include a high degree of dependence on the operator's skill, and a lack of information about regional metabolic activity.

Microdialysis

Cerebral microdialysis is an invasive Food and Drug Administration-approved method of measuring biochemical changes in brain tissue (*Figs. 13* and *14*). For example, many investigators have reported that patients experience increases in

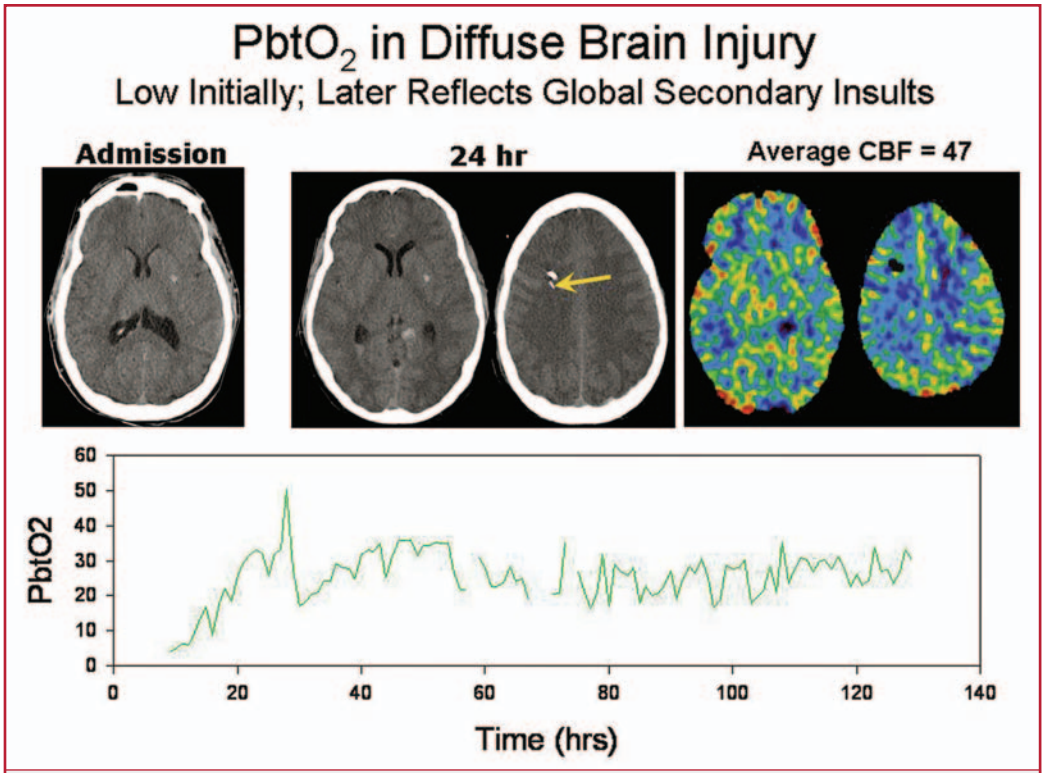

FIGURE 10. *$PbtO_2$ catheter* (yellow arrow) *was placed in a region that appeared to be uninjured. $PbtO_2$ values are often low immediately after injury, but then begin to increase. When placed in uninjured tissue, these monitors reflect global secondary insults.*

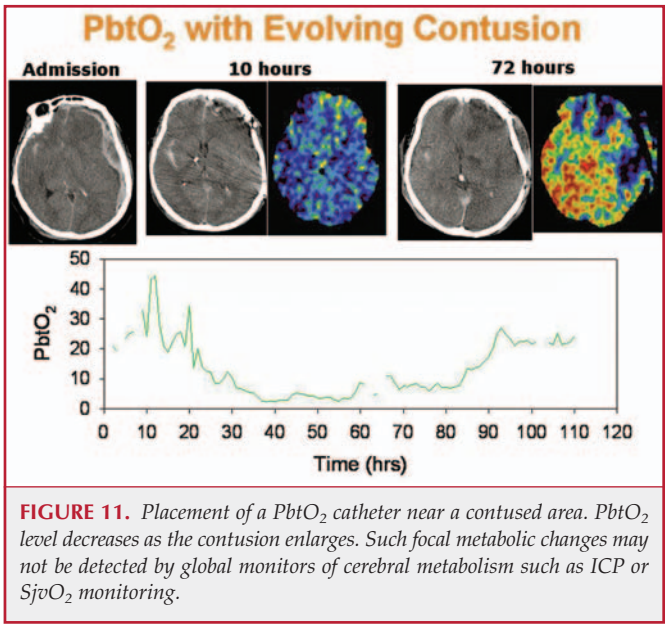

FIGURE 11. *Placement of a $PbtO_2$ catheter near a contused area. $PbtO_2$ level decreases as the contusion enlarges. Such focal metabolic changes may not be detected by global monitors of cerebral metabolism such as ICP or $SjvO_2$ monitoring.*

lactate, excitatory amino acids, and glycerol and decreases in glucose and pyruvate during periods of metabolic stress. Technical difficulties associated with performing microdialysis include the logistics of organizing, processing, and storing the many samples; for example, collecting dialysate every 30 minutes for 5 days generates 240 samples that must be tracked. These can be frozen and stored for later analysis. In general, most ICUs that perform cerebral microdialysis use the information not as a primary monitoring tool, but rather as a supplemental source of information that corroborates the impression provided by other monitors and may occasionally serve as an early warning that something is beginning to go wrong. Future applications could include detection of intraparenchymal drug levels, indirect measurement of activity of stem cells or cloned genes, and targeted delivery of therapeutic agents.

Treatment

From one perspective, little has changed in our management of patients with TBI over the last generation. The most important parts of management remain prompt detection and immediate correction of secondary insults. Our present approach to the treatment of patients with elevated ICP uses some of the same tools that we used 30 years ago, such as initiation of sedation, induction of pharmacological paralysis, administration of mannitol, drainage of CSF, hyperventilation, and induction of barbiturate coma. Despite intensive and very expensive efforts, no "magic bullet" has been discovered for the "cure" of brain injury.

Although this situation may sound bleak, nothing could be further from the truth. A great deal has been learned over the last three decades. Laboratory studies have deepened our understanding of the cellular and molecular events that follow injury. Appropriate preclinical testing has become even more recognized as an essential step to take before new therapies can be brought to clinical trials. Important principles of clinical trial design, execution, and analysis have been identified and accepted, and these will affect the design of future studies. Also, the shrinking availability of healthcare dollars in both the clinical and research arenas has led to greater awareness of possible conflicts of interest and establishment of appropriate guidelines for interaction of clinical and research physicians with industry, while simultaneously emphasizing the important role that industry funding plays in moving forward with new technologies.

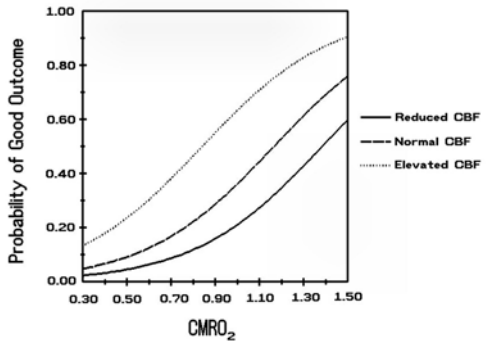

FIGURE 12. *Relationships between patient outcome, cerebral blood flow, and cerebral metabolic rate of oxygen ($CMRO_2$).* (From, *Robertson CS, Contant CF, Gokaslan ZL, Narayan RK, Grossman RG: Cerebral blood flow, arteriovenous oxygen difference, and outcome in head injured patients.* ***J Neurol Neurosurg Psychiatry*** *55:594–603, 1992. Reproduced with permission from the BMJ Publishing Group.)*

Although we have gained a deeper understanding of the precise roles for many new potential treatments, we have also eliminated a few things that were found not to work. Steroids are no longer recommended as part of the treatment of patients with TBI. Similarly, prophylactic hyperventilation is not recommended. The practice of deliberately dehydrating patients to prevent brain swelling has been replaced by an emphasis on maintaining normal intravascular volumes. On the other hand, we have also verified the benefit of some practices, such as administration of prophylactic anticonvulsants during the first week after a patient experiences TBI.

Perhaps most importantly, it has become clear over the last few decades that different TBI patients may vary in their pathophysiological profiles. Three patients who were riding in the same automobile during a crash can have very different types of head injury. One may have severe generalized cerebral edema, another may have primarily diffuse axonal injury with low ICP, and a third may have a large mass lesion that requires immediate surgery. The metabolic picture of the same patient may even fluctuate from day to day or hour to hour. Ideally, these patients might benefit from different approaches to treatment and from ongoing reassessment and changes in the therapeutic plan. However, the sophisticated monitoring techniques that can guide such physiologically targeted therapy are available in only a few hospitals. We hope that these techniques will spread to more facilities and thereby add to our knowledge of how to tailor management to an individual patient's pathophysiological profile. In the near future, treatment decisions may also be based on a patient's genotypically determined anticipated responses to specific interventions.

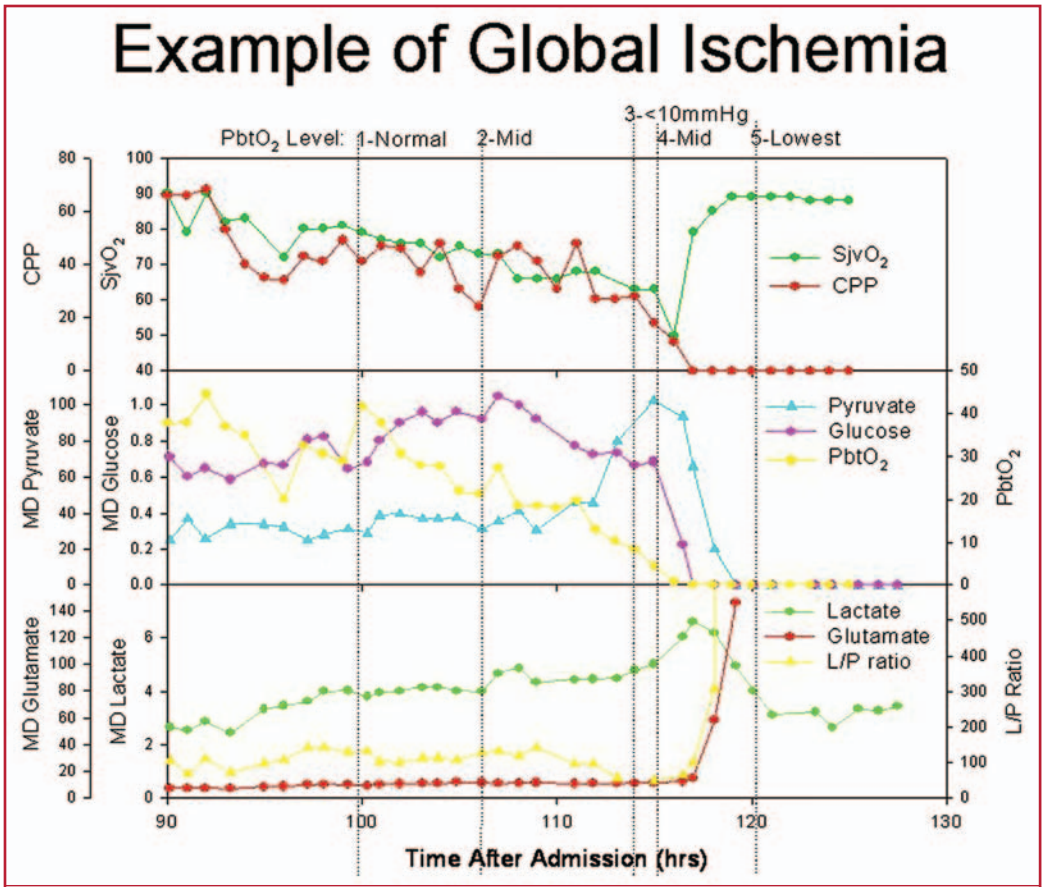

FIGURE 13. *Example of microdialysate changes during global cerebral ischemia. As cerebral perfusion pressure and $PbtO_2$ values decrease, pyruvate and glucose levels also decrease, whereas increases are seen in lactate and glutamate levels and the lactate-pyruvate ratio.* (From, *Hlatky R, Valadka AB, Goodman JC, Robertson CS: Patterns of cerebral energy substrates during ischemia measured in the brain by microdialysis.* ***J Neurotrauma*** *21:894–906, 2004.)*

Hypertonic Saline

Recent years have witnessed a growing use of interventions that continue to be investigated and debated. Many of these are older treatments that have undergone a resurgence of interest. Hypertonic saline is receiving increasing attention for its role in the treatment of patients (especially children) with elevated ICP.

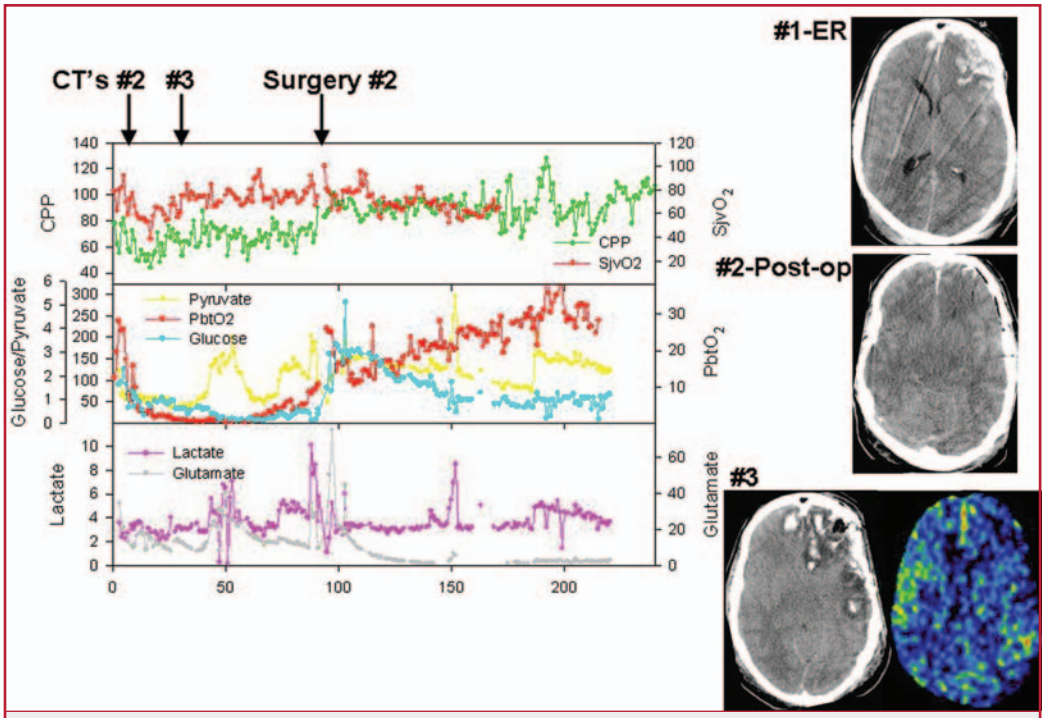

FIGURE 14. *Computed tomographic scans and microdialysate data from a patient who demonstrated postoperative ischemic changes. Xenon-enhanced computed tomographic scan* (bottom) *reveals decreased CBF in contused areas. Patient's biochemical profile improved after second surgery to evacuate contusions.* (From, *Hlatky R, Valadka AB, Goodman JC, Robertson CS: Patterns of cerebral energy substrates during ischemia measured in the brain by microdialysis.* ***J Neurotrauma*** *21:894–906, 2004.)*

The general literature on trauma also contains many reports that evaluate the effectiveness of low-volume resuscitation with hypertonic saline as opposed to larger-volume resuscitation with normal saline or other crystalloids.

A major difference between mannitol and hypertonic saline is that hypertonic saline tends to increase intravascular volume by redistributing free water, whereas mannitol pulls water into the vasculature for only a brief period before subsequent diuresis may deplete intravascular volume. Despite the publication of a fair number of reports, it is not possible to make recommendations at this time about whether mannitol or hypertonic saline should be used for a particular patient or whether one is "better" than the other. The optimal concentration of hypertonic saline also remains unclear. Published studies have used concentrations that vary from 3% up to 23.4% NaCl.

Glucose Control

After the publication of a widely cited article (63) that reported lower morbidity and mortality in surgical ICU patients who received a continuous insulin infusion to keep blood glucose levels between 80 and 110 mg/dl, many ICUs implemented the routine use of continuous insulin infusions in virtually all patients. Less clear, however, is the effect of this practice on patients with acute TBI, especially because only 4% of the patients in that study had a primary neurological disease as the reason for their admission to the ICU. Even a brief period of accidental hypoglycemia might represent a serious secondary insult in these patients. The UCLA group has reported that intensive glycemic control is associated with reduced glucose concentrations in cerebral microdialysate, along with increased glutamate levels and lactate-pyruvate ratios and increased oxygen extraction fractions, all of which are indicative of cerebral metabolic distress (65). Zealous efforts to lower serum glucose levels might reduce the availability of this cellular fuel at the precise time that the injured brain needs it most. This is one of many examples of a treatment that may be reasonable for most ICU patients, but which may also have a significant risk if used indiscriminately in those with acute TBI.

Hyperoxygenation

Presently, an area of great interest is treatment of low $PbtO_2$ values in patients with TBI. As discussed above (see Brain Tissue Oxygenation), use of this monitoring technique is increasing, but many clinicians are asking what to do with the information that it provides. An obvious answer is to increase the setting on the ventilator that controls fraction of inspired oxygen; this usually increases the $PbtO_2$ value. Menzel et al. (41) in Richmond have used cerebral microdialysis to demonstrate that cerebral extracellular lactate decreases after patients are given high levels of inspired oxygen early after injury, which suggests that metabolism is shifted from an anaerobic to an aerobic pattern. They also report a trend toward improved outcomes. On the other hand, Magnoni et al. (35) report that the lactate-pyruvate ratio remains unchanged when a patient receives an increased inspired oxygen fraction, which indicates that cerebral metabolism has really not been changed from anaerobic to aerobic. Such data suggest that a more effective approach might be to treat the underlying cause of the low $PbtO_2$ values, such as reducing the patient's ICP, raising mean arterial pressure, and evacuating a contusion or hematoma. The optimal use of increased inspired oxygen fraction is an important topic for future investigation.

Hypothermia

Many laboratory studies suggest that hypothermia is beneficial after a patient experiences TBI, and this conclusion is supported by various clinical trials. However, the North American Brain Injury Study: Hypothermia failed to detect a beneficial effect of hypothermia on patient outcome. Retrospective review of those results was used to initiate another North American Brain Injury Study: Hypothermia trial. Because the therapeutic time window for hypothermia may be very short, this newer hypothermia study initiates cooling in the prehospital phase when possible. Also, patients over the age of 45 are excluded from the study. Such modifications may identify specific patients and circumstances in which controlled therapeutic hypothermia may be beneficial.

REHABILITATION

Cognitive rehabilitation has become a routine part of the postinjury course for many TBI patients. Many families and patients have come to expect it. However, patients who are not sufficiently awake and interactive to participate in intensive inpatient rehabilitation programs may be transferred not to rehabilitation facilities, but instead to nursing homes, skilled nursing facilities, or long-term acute care facilities. If they subsequently improve, they may become candidates for inpatient rehabilitation at that time. Other patients function at too high a level to justify inpatient rehabilitation. Specialized outpatient programs for TBI rehabilitation may be available for these patients.

Families and even many healthcare workers often assume that cognitive rehabilitation will expedite a patient's recovery and help the patient achieve a higher level of recovery than would otherwise be possible. Clinical observations suggest that there may be such an effect, but it is very difficult to carry out studies that rigorously investigate the benefits of rehabilitation (17). Reasons for these difficulties include the ethical questions that would be raised by withholding rehabilitation in a control group, the relatively limited duration of the studied interventions compared with the protracted time course of recovery in these patients, difficulty with long-term follow-up, and uncertainties about possible selection bias among the studied patients. Another possible reason is that the rehabilitation process for each patient may be dynamic and fluid, with modifications made based on the individual patient's progress.

Some data suggest that compensatory training may help patients overcome some problems with memory, anxiety, self-concept, and interpersonal relationships (16). Smaller trials suggest that some cognitive interventions can improve recall, but links between such results and improved health outcomes, employment, and productivity have not been established (16). These results support the concept that even if specific cognitive rehabilitation interventions cannot improve the degree of ultimate recovery in some patients, they are clearly useful for helping patients to learn to function at as high a level as possible within the limits imposed by their deficits. It has also been argued that rehabilitation after brain injury is cost-effective (61). Importantly, rehabilitation also helps families learn to adapt and assist patients.

Stimulants are often administered to comatose patients to help them "wake up" after injury. They are also widely used in other rehabilitating TBI patients to improve attention, memory, information processing speed, and similar functions. An evidence-based review (68) found some support for using methylphenidate to treat problems with attention and speed of information processing and for using beta-blockers for the treatment of post-TBI aggression. Other therapies with some evidentiary basis include donepezil to enhance attention and memory, and bromocriptine to enhance executive functioning (68). As with cognitive rehabilitation, more well-designed trials are needed in this area.

A NEW SURGICAL SPECIALTY?

As with all health care, the socioeconomic aspects of the delivery of trauma care have come under intense scrutiny. Some of the proposed changes have come from trauma surgeons themselves. Few medical students and general surgery residents presently choose to enter careers that center solely or predominantly on trauma care (51). In contrast with the typical trauma surgery practice of several decades ago, trauma surgery has become a largely nonoperative specialty. The hours are long, the patients are often uninsured, and the scheduling of patient care is unpredictable and frequently disruptive.

In response, some surgeons have suggested that the field of trauma surgery should broaden its scope and become "acute care surgery" (24). Practitioners in this new specialty would theoretically become the providers of choice not just for trauma care, but also for nontrauma surgical emergencies as well, such as bowel obstruction, appendicitis, and other surgeries. This change would bring them more opportunities to operate. In addition, by following a shift-based work schedule similar to that used by emergency medicine physicians, they would have a controllable lifestyle.

The training curriculum for this new specialty is still under development. However, it will likely include strong encouragement that trainees receive instruction in the placement of ventriculostomy catheters and ICP monitors. This separation of neurosurgeons from patients with neurosurgical emergencies is opposed by organized neurosurgery as a group. The most important reason is patient safety. A general surgeon with a month or two of neurosurgical training cannot acquire the same degree of knowledge, judgment, and experience that neurosurgeons bring to their patients. These cognitive attributes are just as important—if not more so—than the technical details of ICP-monitor insertion.

A better solution is to identify and overcome the barriers that make it difficult for patients with neurosurgical emergencies to be transported expeditiously to a neurosurgeon. These include the Emergency Medical Treatment and Active Labor Act, concerns over medical liability, appropriate compensation to offset financial losses incurred by providing emergency care,

and lack of efficient regional coordination of neurosurgical resources. Of note, regionalization of emergency care is one of the recommendations contained in the Institute of Medicine report, *Hospital-Based Emergency Care: At the Breaking Point*, which was released in June of 2006 (30).

CONCLUSION

Have the last 30 years represented steady, linear progress in the care of TBI patients? Or have they seen us go round and round in circles like travelers lost in a forest, who expend a lot of effort without making any real progress? The answer is that we really have made significant progress in our knowledge and understanding. Much of this knowledge is only now being applied within the clinical setting. We have a great deal of work to do if we want those who review us in the future to report that substantial advances were made in the 30-year period that began in 2007.

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COMMENTS

This is an outstanding review of the current state of the art treatment of traumatic brain injury (TBI) provided by the two most accomplished neurotraumatologists I know. Highlights of the review include a very balanced and thoughtful commentary about the role of evidence-based guidelines. They correctly emphasize that the "one size fits all approach" is usually not appropriate, and that optimal care of TBI patients must first take into account the patient's unique clinical presentation; then, the neurosurgeon should consider guidelines, available resources, and other factors. But it is usually inappropriate to make diagnostic and therapeutic decisions solely because the "guidelines" say so. The review article also provides a thoughtful discussion of practical problems that have arisen as a result of the Emergency Medical Treatment and Active Labor Act and presents several ways of thinking about all of the major diagnostic and therapeutic challenges faced by the neurosurgeon who is acutely managing the patient with a severe TBI. This article should be read and re-read carefully by all neurosurgeons. It should be studied by neurosurgical residents, and should serve as an invaluable clinical resource for years to come, by all who treat TBI patients.

Donald Marion
Boston, Massachusetts

A great deal of progress has been made in advancing the field of neurotrauma care over the past three decades, and this review by Drs. Valadka and Robertson nicely summarizes where we have been and where we are headed.

In my opinion, a considerable measure of this progress has been driven by the guidelines efforts in neurotrauma. Not necessarily because the guidelines should be rigidly applied or universally adopted, but rather because they have forced us to examine our widely held expert opinions in the light of scientific rigor and, more importantly, established a framework for much needed future research to advance the field.

As noted and elaborated upon in this article, we have come to understand the importance of prehospital and intensive care management; we now appreciate the potential deleterious effects of previously widely held management tenets such as routine hyperventilation and aggressive cerebral perfusion pressure elevation; we have come to understand that traumatic subarachnoid hemorrhage and associated vasospasm is a potent contributor to secondary injury. Perhaps most importantly, we now apppreciate that different TBI patients differ in their pathophysiology and that even the same patient may manifest varying pathophysiology at differing timepoints in the evolution of his or her injury.

At the same time, there is much we need to learn. Does decompressive craniectomy improve functional outcome? Is there any role for hypothermia? What is the optimal method of monitoring a given patient? Will any neuropharmacological agent ever be found to be effective? The latter issue has been particularly frustrating given a decades-long series of very expensive clinical trials involving thousands of patients. However, all has not been for naught because, by carefully analyzing these failures, we are now in a position to design more appropriate trials in more homogeneous TBI subgroups with more sensitive outcome measures utilizing more targeted pharmacological agents.

Recently, Dr. Valadka commented that "neurotrauma is something you do if you don't know how do any other type of neurosurgery." This article clearly challenges such a notion. Indeed, the thoughtful and circumspect reader will hopefully appreciate that the lessons learned and to be learned in neurotrauma underpin almost everything else we do in neurosurgery.

Jack Wilberger
Pittsburgh, Pennsylvania

This is an up-to-date review of trauma to the human cerebrum. Our failure to capitalize on a much better understanding of the metabolic derangements that characterize brain injury cannot discourage us from working to continue to improve the outcome of our patients. The war in Iraq serves to illustrate that we also need to understand much more about a new mechanism of injury blast, which has irreparably damaged the lives of thousands of our troops. Thus, the need to continue to learn more about brain edema, flow, hyperglycolysis, and whether or not hyperoxygenation and hemicraniectomy are valuable treatments is even more urgent. Fortunately, a randomized trial of hemicraniectomy has begun in Europe and the possibility of a definitive answer on that subject within the next few years seems plausible. The authors should be commended for their objective and comprehensive review of this scourge which damages more young people than any other disease.

Lawrence F. Marshall
San Diego, California

The authors have prepared a very thoughtful, comprehensive, and timely review of the current treatment for traumatic brain injury (TBI). TBI remains a leading cause of death and disability in North America and Europe and is one of the fastest growing public health issues worldwide. In the United States alone, the direct and indirect costs of TBI been estimated to be nearly $60 billion. Despite these overwhelming statistics, there is still limited awareness of TBI, and the treatments for this devastating injury have changed little in the past 80 years. As the authors point out, the development of evidence-based guidelines, the evolution in critical care, and advances in neuromonitoring have led to an overall improvement in the outcome of TBI over the past 30 years.

However, there is still much to be done. Many communities still do not have access to the high-quality advanced neurotrauma care such as that delivered at the author's institution. Fundamental clinical research questions also remain to be answered, such as determining the dose-response of mannitol and refining the role of decompressive craniectomy. This review also highlights the important issue of heterogeneity in TBI. It can no longer be acceptable to simply lump patients in the broad categories of mild, moderate, and severe based on a clinical examination. We need to acknowledge the heterogeneity of TBI and develop a new pathoanatomical classification system that takes advantage of modern imaging techniques and other available biomarkers. An improved classification system will lead to a better understanding of the mechanisms of TBI and help target new and more specific therapies. This is an exciting time in the field of neurotrauma, with many opportunities to advance the field. This excellent review provides a useful reference for those interested in neurotrauma, and serves as a foundation for future work.

Geoffrey T. Manley
San Francisco, California

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