The management of increased ICP remains a challenge. Experimentally, the investigation of brain edema has been based on a large number of different models. It is generally considered that many factors are known to modify the edema process. These include cerebrovascular permeability, cerebrovascular conductivity, brain metabolism, tissue hydraulic conductivity, compliance, and tissue and cerebrovascular osmotic and hydrostatic pressure. Mediators, such as excitatory amino acids released after cell trauma, also modify the influx of certain ions, which may invariably damage important cell structures linked to energy metabolism.

Conservative treatment options, which include hyperventilation, mannitol or hypertonic saline solution, and barbiturate coma, often cannot control rapidly increasing ICP resulting from severe brain swelling after TBI. Techniques of neuromonitoring certainly have improved the management of comatose patients. The clinical status of the patient can be monitored continuously, and the resulting therapy will be adjusted accordingly. However, faced with the constant increase in ICP despite aggressive medical treatment, a critical situation arises. The last option a neurosurgeon is left with is decompressive craniectomy. One important drawback of this operation seems to be the unsatisfactory long-term outcome. Therefore, we have examined the long-term results of acute decompressive craniectomies after TBI depending on the indication, timing, and operative procedure. We were interested to find whether the long-term outcome justifies such a procedure.

**Methods**

**Patient Population**

In the 3-year period from 2000 to 2002, 33 patients (20 males and 13 females) with severe TBI underwent a decompressive craniectomy to control raised ICP. The mean age was 36.3 years (range 13–60 years). The inter-
val between operation and postoperative reexamination was 3 years. For the postoperative assessment the Barthel Index was used. This study was authorized by the local ethics committee.

**Timing and Indications for Surgery**

To establish a diagnosis, a cranial CT scan was obtained. Compression of the cortical gyri or basal cisterns, signs of incipient herniation, or immediate cerebral swelling were indicators of raised ICP.

On admission, all patients underwent TCD ultrasonography. Normal flow with a systolic and diastolic pattern can deteriorate and indicate an increase in ICP. In the presence of brain swelling, the change from a diastolic to an only systolic flow pattern indicated worsening of the pressure situation. When only systolic spikes were present, a further deterioration in the patient’s status was obvious. The TCD ultrasonography studies served as an important adjunct in decision making in our setting. After completing the diagnostic procedures, the patients either underwent emergency emergency surgery or were admitted to the ICU. In the ICU, an intraparenchymatous ICP monitor (Camino OLM 110–4BT) was inserted.

Early evoked potentials (somatosensory and acoustic evoked potentials) were also examined when patients were admitted during routine hours. The following protocol for treating raised ICP was used. The patient’s head was elevated up to 30°. Patients were ventilated artificially, and the PaCO2 was kept between 32 and 35 mm Hg. Extensive hyperventilation was avoided. Hyperosmotic solutions such as mannitol were used as bolus infusions up to 6 times per day. If mannitol was not sufficient in solutions such as mannitol were used as bolus infusions. Extensive hyperventilation was avoided. Hyperosmotic formed if the patient met the aforementioned criteria. If their conditions deteriorated and ICP could not be controlled, a decompressive craniectomy was performed if the patient met the aforementioned criteria.

**Pupillary Status.** The pupillary status was assessed on admission and hourly afterward by the staff of the ICU. Of the 33 patients 14 initially had normal-sized pupils, 12 showed unilateral wide pupils (4 mm in diameter), and 7 patients had bilaterally dilated pupils. All patients who un-
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derwent an emergency decompressive craniectomy (27.3%) had dilated pupils (4 mm in diameter). Patients with mid-size pupils, with an examination suggesting midbrain damage, were not excluded from operation.

Indication and Operative Procedure

In 9 patients (27.3%) the operation was undertaken as an emergency procedure. In 26 patients (78.8%) the operative decision was based on the results of cranial CT scanning, TCD ultrasonography, and ICP monitoring. In 4 of the patients, cranial CT scanning and TCD ultrasonography were performed, and, finally an uncontrollably elevated ICP resulted in the decision to operate.

A large hemicraniectomy was performed in 17 cases (8 on the left side and 9 on the right). A bifrontal craniectomy was done in 16 patients. The decision of when to do a bifrontal craniectomy or a hemicraniectomy was based on the extent of the swelling and additional pathological findings. In the case of massive global swelling a bifrontal craniectomy was performed. In patients with an additional small subdural hematoma, a hemicraniectomy was undertaken on the side of the pathological entity.

Timing of Decompressive Cranectomy

In 18 patients the decompressive craniectomy was performed within 12 hours posttrauma. One half of these patients underwent emergency surgery after completing the diagnostic procedures. Eight patients were operated on over the period of 13–48 hours. A later decompressive craniectomy (48 hours–6.5 days) was performed in 7 patients (see Fig. 3).

Postoperative Complications

Early and Delayed Complications. Postoperative early complications resulting in a reoperation occurred in 5 patients (15.2%). In 3 patients who had undergone a previous hemicraniectomy and also who had undergone postoperative ICP monitoring, a repeated craniectomy had to be performed because the ICP was still not controlled postoperatively. Postoperative cranial CT also showed massive midline shift despite previous decompression. Postoperative ICP monitoring was only used in patients with hemicraniectomy who still had massive swelling on the postoperative control scan. This occurred in 5 patients only. Patients with a bifrontal decompressive craniectomy did not need a repeated craniectomy. In 1 patient with a coagulation disorder, contusions had to be removed postoperatively.

Late Complications. Five patients (15.2%) showed late complications, 4 needed a ventriculoperitoneal shunt for hydrocephalus, and 1 patient presented with meningitis 51 days after the operation. These complications were not attributable to the previous operation but were rather problems that arose from severe trauma without surgery.

Long-Term Results

At the time of the reexamination 7 patients (21.2%) had died. Five patients died within the 1st week after decompressive craniectomy. These patients had undergone emergency surgery; prior to the operation their pupils had been dilated. One patient died 5 weeks postoperatively due to multiorgan failure, and another patient died 3 months after craniectomy due to a pulmonary embolism.

Twenty-six patients survived. Seven of the 26 patients had an apallic syndrome and speech could not be assessed. Thirteen of the surviving patients scored between 90 and 100 on the Barthel Index. These patients could communicate well and showed only mild deficits of speech or speech discrimination. Of the remaining 4 surviving patients, 2 had a motoric dysphasia and could only speak single words (Fig. 1). Their ability to understand was hardly affected. Two patients had a global dysphasia and could only express their affection or dislike. A further communication was not possible.

All patients had deficits in concentration and short-term memory of varying degrees. Three of the patients had additional moderate calculation problems. Assessment of more directly receptive functions, such as perceptual organization and the integration of sensory input, also revealed mild deficits in 6 of 13 patients.

Four patients were fully rehabilitated and returned to their former occupation, and 1 patient could continue his former schooling (Fig. 2). These patients had no restrictions regarding their work or school situations. Another 4 patients had to change their employment postoperatively because they were not able to maintain their previous performance. However, they found a new occupation at a lower level than their previous one and were permanently employed. Two patients had already retired prior to the operation but were also able to continue with their previous activities (Fig. 2). Fifteen patients (45.5%) were unable to resume work postoperatively. Of these patients 7 presented with an apallic syndrome. Nineteen patients (56.2%) revealed mild deficits in 6 of 13 patients.

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Discussion

The management of posttraumatic uncontrollable brain swelling remains a challenge for neurosurgeons, anesthesiologists, and intensivists. Cerebral ischemia seems to be one of the most important factors in regard to posttraumatic secondary brain damage and brain swelling. Faced with constantly rising ICPs, only few treatment options exist. A uni- or bilateral decompression with a dural graft for the treatment of malignant brain swelling after trauma has been used less often since the early 1980s. This was mainly due to the unsatisfactory long-term results.

Since the 1990s, however, decompression has again been used more frequently. In the guidelines of the European Brain Injury Consortium dating from 1997, a decompressive craniectomy is regarded as an ultima ratio measure only. Therefore, decompressive craniectomy on a routine basis is used merely in few neurosurgical centers. The factors on which an indication for a decompressive craniectomy is based are not clearly delineated. However, most authors agree that a decompressive craniectomy should be performed when the control of ICP is ineffective and the patient’s condition continues to deteriorate clinically, despite maximal conservative management. The age per se seems to determine later outcome.

We also examined the 9 patients in the older age group (> 50 years) in our series regarding outcome separately. Only the 3 patients who had delayed raised ICP revealed a good result (Barthel Index > 90), whereas those who underwent emergency surgery (6 patients) either died (2 patients) or showed an apallic syndrome (4 patients). There may be a subset of older patients who may benefit from such a procedure when ICP increases slowly over several days. However, more data are required to answer this specific question. In our series in younger patients long-term outcome seems to justify a decompressive craniectomy more when conservative measures fail in controlling ICP. In the literature age is mainly defined as a factor related to survival but not to quality of outcome.

Gaab et al. performed a decompressive craniectomy routinely in younger patients (range 4–34 years) with brain swelling. The age limit in his study was 40 years. Meier et al. stated that a decompressive craniectomy should not be performed in patients > 60 years because of the functional unsatisfactory results. Schneider and his colleagues determined the age limit for a decompressive craniectomy at 50 years. Nearly all of his patients < 30 years (91.6%) survived the trauma. According to the literature there is no clear limit regarding age. Most of the reports discussing the influence of the age are based on small studies only. Therefore, a statistical comparison between different age groups seems difficult in many of the reports. The 2 age limits quoted most often are 40 and 50 years.

Time Interval Between Trauma and Decompressive Craniectomy

Another important factor, which has been emphasized in the literature, is the time interval between trauma and a decompressive craniectomy. In 18 of our 33 patients, a decompressive craniectomy was performed within...
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12 hours. Half of these patients underwent emergency surgery after the diagnostic steps were completed. Thirteen of all these patients recovered completely, and 7 were severely disabled. The mortality rate decreased to 14.3% in the patients who underwent a delayed decompressive craniectomy (48 hours–6.5 days). A full recovery was achieved in the delayed group in 4 patients who underwent surgery at 13–48 hours) and in 5 patients who underwent surgery at 48 hours–6.5 days after trauma. Six patients in the emergency surgery group had a poor postoperative outcome. This was significantly higher when compared with the delayed surgery group (2 patients). The worse results in the emergency group are mainly due to the much more severe injury when compared with the delayed group. We also think that the time interval between injury and decompression per se is not an accurate parameter but rather the period of raised ICP. The variability in interval from injury to surgery is significant as well and will impact on the results. Regarding long-term outcome, delayed decompression revealed better results in this series and we think under these circumstances such a procedure is certainly justified.

In the literature the time interval between trauma and operation remains controversial.9,20,24,25 According to the findings of Polin et al.,16 patients who underwent surgery within 48 hours posttrauma had a significantly better outcome. Münch et al.14 reported similar results. The authors recommend a decompressive craniectomy for the functionally better results and better quality of life compared with the conservative treatment. However, the timing of a decompressive craniectomy seems to remain crucial for the survival and a satisfactory postoperative result.17,18,21,22

Emergency operations in our series as well as in others have revealed high mortality and morbidity rates especially when the pupils were already dilated. In the presence of constantly elevated ICP, TCD ultrasonography can indicate the point of further deterioration when the flow pattern starts to worsen. We only operated on these patients when at least a systolic flow pattern was present on TCD ultrasonography. If systolic peaks appeared we decided against surgery except for the patients in the emergency group. Here, 80% of the patients who died had presented with systolic peaks on TCD ultrasonography. These patients did not benefit from a decompression and should not have undergone surgery. Therefore, TCD ultrasonography served as a valuable tool in the timing of a decompressive craniectomy in our series.

Conclusions

Decompressive craniectomy is an ultimate measure to relieve conservatively uncontrollable ICP. It produces an increase in the volumetric compensatory capacity of the intracranial cavity. Following such a procedure the brain tissue, when exposed through bone removal, develops a high hydraulic conductivity and compliance. This implies that the ICP decreases when the skull has been opened. The indication for this procedure should be based on several diagnostic and clinical measures such as cranial CT scanning, TCD ultrasonography, ICP monitoring, and clinical signs. According to most authors the patients should not be > 50 years. Although decompressive craniectomy remains controversial, it certainly plays a role in the control of trauma-induced raised ICP that proves to be unresponsive to conservative treatment. Regarding long-term results this procedure was justified except for emergency decompression when signs of brainstem compression were already present. However, the study presented here is a case series and does not provide definite information about long-term effects of decompressive craniectomy. Further study will be required to define the parameters of use including the timing of surgery, the physiological thresholds, the choice of procedure, and the age limit.

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Disclaimer

The authors do not report any conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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