

Diffuse cerebral swelling following head injuries in children: the syndrome of "malignant brain edema"

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✓ The commonest initial computerized tomography (CT) finding in head-injured children is bilateral diffuse cerebral swelling. Cerebral blood flow and CT density studies suggest that this swelling is due to cerebral hyperemia and increased blood volume, not to edema. The clinical history, course, and outcome of 63 children with this CT pattern are reviewed. Fourteen children had a Glasgow Coma Scale score of greater than 8; all made a complete recovery and follow-up CT scans were normal. Forty-nine children had Glasgow Coma Scale scores of 8 or less. Fifteen had a history of a lucid period following the initial unconsciousness. One of these children died of delayed brain swelling, the others recovered well with minimal neurological deficit. Thirty-four children were rendered immediately and continuously unconscious. There was a high incidence of second lesions on the CT scan, 50% of this group developed intracranial hypertension and five died. All of the others were in coma for periods ranging from weeks to months. Follow-up CT scans showed an extracerebral collection with a density of cerebrospinal fluid in 27% of the patients, and ventriculomegaly with large sulci in 35%, whereas this pattern was seen only once in those with a lucid period. The difference between those with and without a lucid period is related to the degree of primary diffuse impact injury to the white matter.

KEY WORDS • children • head injury • cerebral edema • computerized tomography • cerebral blood flow • hyperemia • cerebral blood volume

IN pediatric patients, rapid neurological deterioration has been well described, beginning several minutes to several hours following head injury.^{25,31} The clinical picture is similar to the syndrome observed with an expanding intracranial hematoma, yet a surgical mass lesion is rarely found. This secondary clinical deterioration, while frequently self-limiting,^{25,31} may progress rapidly to coma and death.³⁰ As many as 50% of children who die following head trauma are conscious on admission,¹³ and 75% of deaths occur in the first 48 hours.³² With aggressive resuscitation in the face of secondary deterioration, the incidence of "talk and die" in the pediatric age group has been cut to zero in our experience^{6,7} and in that of others.⁴ This fact suggests that a reversible pathological sequence was responsible for these deaths. In children who are conscious, and who then rapidly become unconscious and die, pathological studies show diffuse generalized brain swelling

with little evidence of brain injury.¹ Among all children who die from head injury, diffuse cerebral swelling manifested by obliteration of the intracranial cerebrospinal fluid (CSF) spaces and venous congestion is the commonest autopsy finding.¹⁹ Diffuse brain swelling has been recognized for a long time to be a common cause of secondary deterioration, and the brain swelling has been attributed to brain edema often prefixed with the word "malignant" because of the inexorable clinical course of so many children with this syndrome. Adult patients who deteriorate following a lucid interval almost always have an intracranial clot as the cause of the secondary deterioration rather than diffuse cerebral swelling, whereas in children the reverse is true.

Another group of severely head-injured children more closely resemble adults with head injuries. Unconsciousness occurs immediately at the time of injury and, although the patient's clinical status may

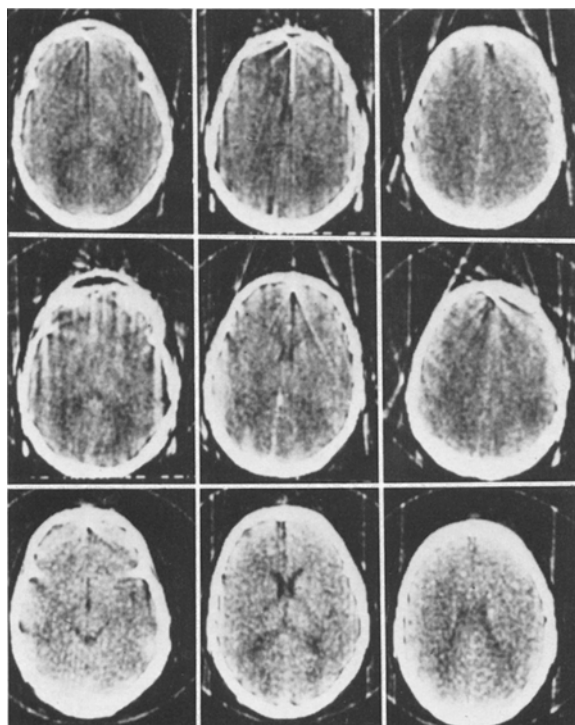


FIG. 1. Initial computerized tomography scans. *Upper:* Scan at 26 hours after injury shows diffuse swelling, small ventricles, and compression of the perimesencephalic cisterns. *Center:* Scan at Day 4 shows little change. The patient was still in coma. *Lower:* Scan at Day 26 shows return of the cisterns and ventricles to normal. The patient was awake and alert.

wax and wane, most of the injury to the brain appears to have been sustained at or shortly after the impact.^{2,34} Presumably this group of patients have sustained a greater diffuse cerebral impact injury than the former group.

The purpose of this report is to document diffuse enlargement of the brain in children with the classical syndrome of "malignant" brain edema and present evidence that diffuse swelling in these circumstances is not, in fact, due to brain edema. Rather, it appears to be caused by severe cerebrovascular congestion. At this time, we are at a loss to explain the etiology of the vascular congestion based on knowledge of the control of the cerebral circulation in the normal state and under pathological conditions. The hyperemic syndrome is also documented in a number of children with no lucid period after trauma.

Clinical Material

Serial computerized tomography (CT) scans were performed on 214 children and adolescents, aged 6 months to 18 years, admitted to the Children's Hospital of Philadelphia (CHOP) between 1975 and 1979. Sixty-three of these patients had an initial CT scan per-

formed in the first 24 hours after injury that showed evidence of diffuse cerebral swelling. The CT scan criteria for inclusion in the category of diffuse cerebral swelling are: 1) an initial CT scan showing small ventricles and cisterns with compression or absence of the perimesencephalic cisterns, and 2) a follow-up scan, 7 to 20 days later, showing return of the ventricular system and cisterns to normal size (Fig. 1).

The patients' clinical histories were reviewed for presence of a lucid interval (period of improved consciousness), early posttraumatic seizures, systemic shock (mean blood pressure below 50 torr), and evidence of other systemic injuries (such as long-bone fractures or ruptured viscus). The follow-up period was at least 2 months in all patients, and those with Glasgow Coma Scale (GCS) scores of 8 or less have been followed from the time of injury to present. All patients were graded using the GCS,¹⁵ and 24 had a cumulative score of 5 or less, 25 had between 6 and 8, and 14 had greater than 8. Recovery was graded using the criteria of Jennett and Bond:¹⁴ good recovery, moderate disability, severe disability, vegetative survival, and death.

The initial CT scan was reviewed for evidence of other cerebral lesions besides diffuse swelling. The follow-up scans were examined for the appearance of extracerebral collections of fluid; the appearance of abnormal, progressive ventricular enlargement, and evidence of enlarged sulci; and the resolution of this latter pattern with return to a normal CT scan. In 12 patients with serial, motion-free and artifact-free scans, all of which were performed on the EMI Mark I scanner,* the Hounsfield value of the deep frontal white matter on the initial scan was compared with that obtained after resolution of the diffuse swelling. The normal values of six children (aged 5 to 12 years) were calculated from a mean of 150 to 350 pixels taken from the deep frontal white matter.

The intracranial pressure (ICP) was monitored in 29 of the 63 patients, 21 with GCS scores of 5 or less, and eight with GCS scores of 6 to 8. A subarachnoid bolt was used in 28 cases and a ventricular cannula in one. All patients in whom ICP was monitored had an endotracheal tube in place and were receiving controlled hyperventilation to a PaCO₂ of approximately 25 to 30 torr at the time of insertion of the monitor.

The cerebral blood flow (CBF) was measured in six patients using the intravenous xenon-133 method²³ and a 16-probe detector system.† In all six patients, at least two CBF determinations were performed, one acutely and one after the diffuse swelling had resolved.⁵ Three of these patients also had measurements of cerebral metabolic rate for oxygen (CMRO₂) concomitant with the measurements of CBF.

*EMI Mark I scanner manufactured by EMI Corp., Northbrook, Illinois.

†16-probe detector system manufactured by Harshaw Chemical Co., 6801 Cochran Road, Solon, Ohio.

TABLE 1
Incidence of subarachnoid hemorrhage (SAH)

Glasgow Coma Scale Score	Total Cases	Age (yrs)	SAH
3-5	24	5.4 ± 3.8	20
6-8	25	5.7 ± 4.4	11
> 8	14	6.7 ± 4.5	1

Indium cisternograms were performed on five patients during the period when extracerebral collections were identified on CT scan. One child who developed hydrocephalus 1 year after trauma had a second indium cisternogram performed prior to any surgical therapy.²¹

Results

The CT pattern described as diffuse cerebral swelling was seen in 29% of all the children and adolescents studied. This pattern, however, was seen in only 15% of those with a GCS score of greater than 8, and in 41% of those with a score of 8 or less. Diffuse swelling occurred throughout the age range studied, which was 6 months to 18 years, and the mean age of patients with diffuse swelling was 5.9 years. There were 24 patients with a GCS score of 5 or less, 25 with a score of 6 to 8, and 14 with a score of greater than 8 (Table 1). The median GCS score was 7. The mean ages of the three groups of patients were not significantly different (Table 1).

Subarachnoid hemorrhage was the commonest associated finding, being demonstrated in 32 patients. Subarachnoid hemorrhage was seen as an area of increased density in the posterior portion of the interhemispheric fissure and occasionally over the tentorium. This finding was present in only 7% of the patients with GCS scores of greater than 8, in 44% of patients with scores of 6 to 8, and in 83% of patients with scores of 5 or less. Twenty-seven of the 63 (44%) initial CT scans showed evidence of another cerebral lesion (Table 2). These lesions ranged from depressed skull fractures through scattered small hemorrhages

in the corpus callosum and deep white matter, which has been described as diffuse impact injury.³⁶ The type and frequency of the lesions are shown in Table 3.

In the 12 patients in whom CT Hounsfield values were measured, there was a significantly higher value on the initial CT scan showing diffuse swelling than on the follow-up scan ($p < 0.01$). Furthermore, the Hounsfield number of the deep white matter on the initial scan was higher than the normal range defined from the control hemispheres of children with normal CT scans (Table 4). This increase in Hounsfield density cannot be accounted for by an increase in water content of the tissues, as this would decrease the tissue density.³⁵ Measurements of regional cerebral blood volume demonstrated an increase in one patient with a return to normal values on recovery.¹⁶ This same study did suggest that 48 hours or more after injury diffuse swelling could be seen in the absence of a documented increase in blood volume.

The six patients in whom CBF was measured showed an increased CBF (Table 5). The mean value for the fast component of CBF was not only higher than in patients with similar GCS scores and no diffuse swelling, but was also higher than in a control group of awake volunteers. Repeat CBF studies after resolution of the diffuse swelling in those patients who survived showed a decrease in CBF in all patients. Thus, a true hyperemia was present in association with the pattern of diffuse swelling. A measured decrease in CBF in response to a reduction in PaCO_2 was found in three patients in whom a CO_2 response was tested.

Intracranial pressure was measured in 21 patients with GCS scores of 5 or less and in eight with scores of 6 to 8. All patients were receiving controlled hyperventilation to a PaCO_2 between 25 and 30 torr at the time of insertion of the intracranial monitor. The initial ICP was > 20 torr in nine patients, and rose above 20 torr at some time in the first 3 days posttrauma in 17 of the 29 patients (59%). No patient died from uncontrollably elevated ICP, although 12 required maximum therapy: hyperventilation to a PaCO_2 in the low 20's (torr), osmotherapy to a serum osmolality level of 320 mosmols or more, hypothermia to 32°C , and pentobarbital infusion to levels of 3 mg% or higher to maintain a normal ICP. In all patients the intensive care unit protocol was to maintain the ICP below 20

TABLE 2
Evidence of other lesions

Glasgow Coma Scale Score	Total Cases	CT Scan		Systemic Injuries		Shock		Seizures	
		No.	Percent	No.	Percent	No.	Percent	No.	Percent
3-5	24	13	54	10	42	4	17	0	0
6-8	25	8	32	6	24	2	8	6	24
> 8	14	6	43	1	7	0	0	4	29

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torr regardless of the arterial pressure and not to concentrate on cerebral perfusion pressure, since an adequate perfusion pressure in the damaged brain has never been defined.

Follow-up CT scans showed unilateral or bilateral extracerebral collections of CSF density in 17 patients (27%); none with GCS scores of less than 8, 24% with GCS scores of 6 to 8, and 46% with GCS scores of 3 to 5 (Table 6). These collections resolved without therapy in 16 of the 17 patients. In one patient, burr holes were made, and slightly xanthochromic CSF was obtained from both sides. The ICP was measured in eight of these patients during the period that the extracerebral collections were present, by lumbar tap in five, and by tap of the collections in three. In no patient was the ICP over 10 torr, and in those in whom the collection itself was tapped, the pressure in the collection was subatmospheric.

Cisternography was performed on five patients using indium ethylenediaminetetraacetate (EDTA). The collections were found to fill rapidly with the indium, although there was some mild delay in clearance of the isotope from the region of the sagittal sinus in three patients.²¹ Three of the 17 patients with extracerebral collections developed progressive ventriculomegaly, two at 2 months, and one at 1 year after injury. These three patients had ventriculoperitoneal shunts inserted. The clinical condition of the children at the time of insertion of the shunt was vegetative or severely disabled in two who developed early ventriculomegaly. In these patients, the shunt had no effect on the clinical state. The third patient developed symptomatic hydrocephalus with vomiting and lethargy 1 year postinjury, at which time she had made a good neurological recovery. The insertion of the ventriculoperitoneal shunt led to complete resolution of her new symptomatology. These extracerebral collections seemed to not be a function of hydrocephalus nor to be subdural in site and, in general, required no surgical therapy.

Twenty-two (35%) patients developed a mild increase in ventricular size with enlarged Sylvian fissures and frequently also cortical sulci; none of these had GCS scores greater than 8, 32% had GCS scores of 6 to 8, and 58% had GCS scores of 3 to 5 (Table 6). In 10 of these patients, the ventricles returned to a

TABLE 3

Other lesions seen on computerized tomography

Lesions	No Lucid Period*	Lucid Period*	All Patients†
epidural	1	0	0
acute subdural	2	2	0
intracerebral hematoma or contusion	3	4	2
infarct	1	1	0
diffuse impact injury	5	0	0
linear skull fracture	0	0	3
depressed skull fracture	1	1	1

*Patients with Glasgow Coma Scale scores of 3 to 8.

†Patients with Glasgow Coma Scale scores of greater than 8.

TABLE 4

*White-matter density in patients with diffuse cerebral swelling and edema**

Group	No. of Cases	Hounsfield Value	Mean Change to Recovery
diffuse swelling	12	34.6–36.4	–3.2†
control	9	29.2–33.2	

*Computerized tomography findings.

†Significant at the $p < 0.01$ level (paired comparison t-test).

TABLE 5

Cerebral blood flow (CBF) and arterial blood gases in adults and children with acute head injury

Group	No. of Cases	PaCO ₂	CBF(FI)* (ml/100 gm/min)
control	20	33	66
diffuse swelling (16–21 yrs)	6	35	75
no diffuse swelling (17–21 yrs)	8	35	43
adult	13	33	38

*FI = fast component of flow.

TABLE 6

Computerized tomography findings

Glasgow Coma Scale Score	Total Cases	Extracerebral Collection		Increased Ventricles		Decreased Ventricles	
		No.	Percent	No.	Percent	No.	Percent
3–5	24	11	46	14	58	7	29
6–8	25	6	24	8	32	3	12
> 8	14	0	0	0	0	0	0

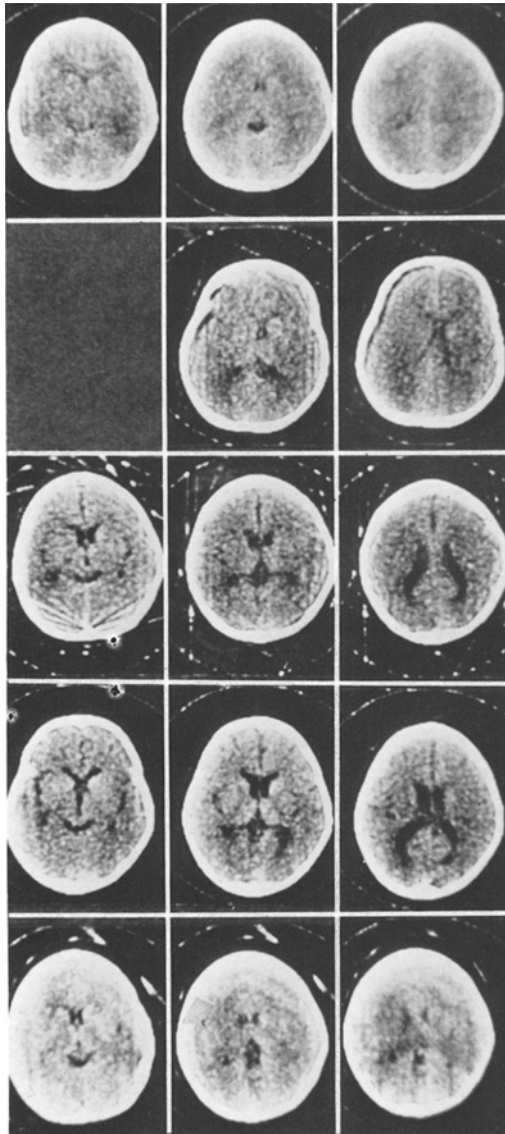


FIG. 2. Serial computerized tomography scans in a patient with a Glasgow Coma Scale score of 5 and no lucid interval. *Top Line:* Initial scan shows bilateral diffuse swelling. *Second Line:* Scan on Day 9 shows an extracerebral collection on the left. *Third Line:* Day 16. *Fourth Line:* Scan on Day 37 shows an atrophic pattern with large ventricles and Sylvian fissures. *Fifth Line:* Scan on Day 231 shows return of the brain to normal. Reproduced with permission from S. Karger AG, Basel, publishers, from Bruce DA, *et al*: Pathophysiology, treatment and outcome following severe head injury in children. *Child Brain* 5: 174-191, 1979.

normal size with a decrease in the size of the sulci within 6 months to 1 year after trauma (Fig. 2). Clinical recovery had usually begun by the time the ventricular enlargement was noted, and there was no close correlation between clinical recovery and return of the ventricles to a normal size. Subarachnoid

hemorrhage was seen as frequently on the CT scans of the severely injured patients without diffuse swelling as it was on those with diffuse swelling, although no such pattern of extracerebral collections was seen in the former group. Ventriculomegaly was seen during recovery in 10 of 67 patients without initial diffuse swelling and cumulative GCS scores of less than 8. Diffuse enlargement was seen in only two, and this was minimal. Both of these children were shaken babies. Eight patients showed evidence of focal ventricular enlargement: five were shaken babies, and three had epidural hematomas. Intracranial hypertension was recorded in seven of the 10 patients. Thus, extracerebral collection and diffuse ventricular enlargement were not related simply to intracranial hypertension, subarachnoid hemorrhage, or GCS scores.

Early posttraumatic seizures (within the first 12 hours) were recorded in only 10 (16%) of the patients, and systemic shock (mean blood pressure less than 50 torr) in only six (9.5%). Other systemic injuries (such as abdominal bleeding or long-bone fractures) were present in 17 patients (27%) (Table 2).

Clinical History, Coma Score, and Outcome: Correlation With CT Findings

When the clinical history was reviewed, 23 patients (37% of the group) had a clear history of a lucid period following trauma. In eight patients with GCS scores of greater than 8, this lucid interval consisted of a period of talking and complete consciousness for minutes to hours after injury. There was then the onset of vomiting, headache, frequently pallor, and sweating associated with decreased alertness. The patients exhibited evidence of decreased spontaneous motor activity, loss of spontaneous speech, and loss of spontaneous eye opening but none progressed to become comatose (lack of eye opening and speech to deep painful stimulation). All of these patients made a good recovery, as demonstrated by normal follow-up CT scans.

Fifteen patients with an initial GCS score of less than 8 also had a well documented history of a lucid interval, defined as a period of improved consciousness. All of these children were unconscious following their trauma, then had a lucid period associated with recovery of eye opening, occasional words, and more spontaneous motor function. Rapid secondary deterioration occurred within minutes to hours after trauma, manifest by a deteriorating level of consciousness, loss of eye opening, and worsening motor responses, frequently with intermittent pupillary dilatation. Of this group of patients, 25% experienced episodes of apnea. A history of seizures was obtained in only 27% of the patients (Table 7), and systemic shock was not recorded in any of these patients. Eleven of these 15 patients had endotracheal intubation performed as part of their emergency resuscitation. One child in this group died as a result of delayed

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TABLE 7
Relationship of lucid interval to shock, seizures, and other lesions

Consciousness*	No. of Cases	Age (yrs)	Shock	Seizures	Other Lesion on CT
lucid interval	15	6.3 ± 4.1	0	4	4
no lucid interval	34	5.2 ± 3.8	6	2	17

*All patients had a Glasgow Coma Scale score of less than 8.

TABLE 8
*Relationship of lucid interval to extracerebral collections, increased ventricular size, and outcome**

Consciousness	No. of Cases	Extracerebral Collections	Increased Ventricles	Decreased Ventricles	Outcome†				
					GR	MD	SD	V	D
lucid interval	15	1	1	1	14	0	0	0	0
no lucid interval	34	16	21	9	18	8	2	1	5

*All patients had suffered severe head injury and had a Glasgow Coma Scale score of less than 8.

†GR = good recovery, MD = moderate recovery, SD = severely disabled, V = vegetative, D = dead.

brain swelling. The others all made a good recovery. The mean hospital stay of this group was 14 days.

Thirty-four patients with GCS scores of 8 or less had no evidence of secondary deterioration and were immediately rendered unconscious. Thirty of these patients received endotracheal intubation as part of the emergency resuscitation. Seizures were recorded in 6%, and evidence of systemic shock was found in 18% (Table 7). Five patients in this group died, three were left in a severely disabled or vegetative state, and 26 made a good recovery or were moderately disabled (Table 8). The average hospital stay was 22 days, and 21 of the 29 survivors were transferred to a rehabilitation center following their acute hospital stay. The immediate unconsciousness, lack of a lucid period, longer hospital stay, and poorer recovery (Table 8) all suggest a greater degree of cerebral injury in these patients than in those with a lucid period, much of which might be accounted for by primary impact injury.² Indeed, four patients in this group had clear evidence of small scattered hemorrhagic areas within the deep white matter and corpus callosum on initial CT scan, and in three of the five patients who died, lesions of the corpus callosum or white matter were found at autopsy. These callosal lesions have been associated with diffuse impact injury to the brain.^{2,34,36}

Table 6 demonstrates that the frequency of extracerebral collections and abnormally increased ventricular size and sulci is related to the initial GCS score. No child with a score above 8 demonstrated either abnormality. Table 8 shows the association of extracerebral collections and increased ventricular size in patients with a GCS score of 8 or less and the presence or absence of a lucid period. There is a highly significant

correlation between the appearance of extracerebral collections, loss of cerebral substance as manifest by increasing ventricular and sulcal size, and the immediate onset of unconsciousness. Patients who developed secondary deterioration did not develop extracerebral collections or evidence of cerebral atrophy. There was no difference in the incidence of seizures or other systemic lesions between the two groups, although shock was more frequently encountered in the continuously unconscious patients.

Discussion

The use of serial CT scanning in a series of pediatric patients with severe head injury has allowed us to define an anatomical pattern that is seen in approximately 41% of such children. This pattern, which we have called "diffuse cerebral swelling," is rarely seen in the adult and, when it is seen, frequently involves only one hemisphere. The CT appearance is associated with a decrease in CSF and an increase in the bulk of the brain. There are only three components to the intracranial cavity: CSF, brain, and blood. Thus, an increase in brain bulk associated with a decrease in CSF spaces must be due to either an increase in brain water content or an increase in brain blood volume. A picture not dissimilar from that seen after head injury has been described in patients with pseudotumor cerebri. A decrease in ventricular volume is seen in these patients, and an increase in interstitial brain water content is believed to represent the major pathology and be the cause of the increase in brain bulk.^{27,28} The CT scans in these patients, however, rarely show the lack of CSF in the cisterns, and

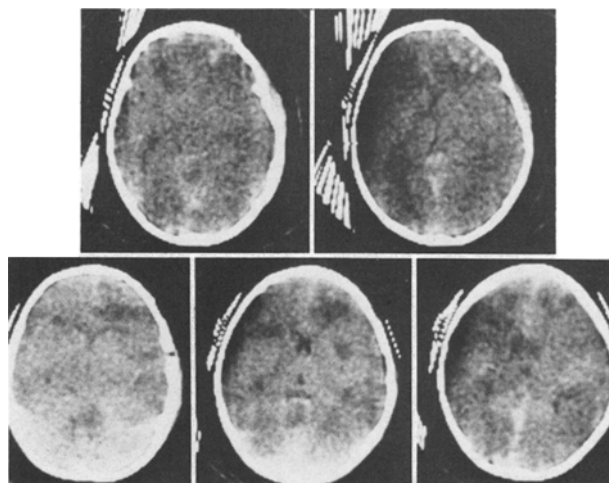


FIG. 3. Computerized tomography scans 3 days apart in a patient with a Glasgow Coma Scale score of 4 and no lucid period. *Upper:* Scan on Day 1 shows a depressed right frontal fracture with underlying hemorrhagic contusion, blood around the tentorium, and bilateral diffuse cerebral swelling. *Lower:* Repeat scan on Day 3 shows multiple areas of lucency scattered throughout both cerebral hemispheres consistent with cerebral edema. Some resolution of the diffuse swelling has occurred, as shown by the slightly larger ventricles. The area of decreased density under the bone of the left frontal area is an artifact since it is not seen on all cuts. Reproduced with permission from Bruce DA, et al: Acute brain swelling and cerebral edema in children, in de Vlieger, et al (eds): *Brain Edema*. New York: John Wiley and Sons, Inc, 1980 (In press).

never show the compression in the perimesencephalic cisterns seen in patients with brain swelling following trauma. Studies of regional cerebral blood volume in patients with pseudotumor cerebri demonstrate an increase in volume, but this was not considered adequate to account for the increase in ICP.²⁷ Measurements of CBF demonstrated a reduced CBF,²⁷ despite a normal metabolic rate and normal neurological function. While there is a superficial similarity between the CT picture of pseudotumor cerebri and that of diffuse swelling, a close comparison of the physiological studies reveals some major differences, which suggest a different underlying pathophysiology. In diffuse swelling after trauma, CT scan density is increased. A decrease in Hounsfield value that is linearly related to increases in water content of the brain has been demonstrated even under circumstances where increased protein content of the edema is found.^{9,35} Thus, there is no evidence that brain edema is present on the initial scan in patients with acute, diffuse brain swelling. Cerebral blood flow studies have shown an increase in CBF, not the decrease seen in patients with pseudotumor cerebri. In one patient, studies showed increased cerebral blood volume in the acute phase.¹⁶ Finally, the level of consciousness is invariably impaired, and the ICP may or

may not be elevated, although we suspect intracranial compliance will always be reduced.

The increase in Hounsfield value, the clinical history of rapid deterioration, and the rapid recovery of the less severely injured patients all favor a transient, reversible physiological basis for the changes seen. Evans and Scheinker¹¹ and Langfitt, *et al.*,¹⁸ have suggested that acute cerebral swelling is produced by vascular engorgement, and we conclude this appears to be the best explanation for the diffuse cerebral swelling seen following head trauma in children. Unfortunately, we do not have any insight into the basic triggering mechanisms of the diffuse swelling. Since this picture is seen across the spectrum of clinical injury, it cannot be directly related to the degree of primary brain injury. The mechanism of injury appears to be important since all the children had acceleration/deceleration type of injuries. This might imply that movement around the brain stem is the common factor involved in the production of the vascular engorgement. Several authors have demonstrated that brain-stem stimulation can increase CBF without increasing cerebral metabolism or altering the electroencephalogram.^{17,20,26} Most recently, Raichle, *et al.*,²⁶ have suggested that locus ceruleus stimulation may change both CBF and cerebral capillary permeability, probably via central vascular aminergic pathways. Foltz, *et al.*,¹² have previously demonstrated that a concussive blow to the head may produce delayed conduction via the reticular formation, with evidence of a biphasic neuronal response. Thus, acute vascular changes may be precipitated by alterations in reticular formation or locus ceruleus function. These may be delayed in onset and may be independent of the degree of primary injury and dependent only on the mechanism of trauma.

Other explanations, however, may be considered. The most obvious is that of defective autoregulation. Although this possibility has not been specifically tested yet, we believe it is unlikely. A number of children who had minimal disturbance of consciousness and relatively minor injuries were seen and, when scanned, showed a pattern of diffuse cerebral swelling. It is difficult to believe that they had global loss of autoregulation. The ICP in unconscious patients with GCS scores of 5 to 8 was normal (under hyperventilation to 25 to 30 torr), despite a blood pressure that was above normal for the age. Indeed, in the select group of the most severely injured patients, a high blood pressure was associated with a high perfusion pressure (greater than 80 torr) and good outcome.²⁹ If autoregulation were defective, we would expect an elevated blood pressure to be associated with an increased ICP or a passive systemic arterial pressure (SAP)/ICP couple.

Other explanations, such as chemicals released by trauma into the CSF which percolate to reach the third or fourth ventricle and then trigger sudden vasodilation, cannot be ruled out. This has been shown to

occur with irritation within the third ventricle,²² and can be produced by chemical stimulation of the brain-stem areas discussed in the above section. Since we have no evidence for or against this explanation, it remains a possible one. Another explanation is that the hyperemia seen is a result of transient hypoperfusion and is a reactive hyperemia or is due to continuous seizures. Only a small percentage of our patients exhibit evidence of shock or seizure activity, and we consider this explanation unlikely. Finally, it is possible that the effects of trauma upon the cerebral vessels produce alterations in cerebrovascular tone which account for the hyperemia.²⁹ The reason why these vessels retain CO₂ responsiveness, and autoregulation is not lost, is that they are not truly flaccid vessels but simply have a new resting tone. There is evidence to show that systemic sympathetic stimulation can affect resting cerebrovascular tone and can affect response of the blood vessels to alterations in systemic arterial pressure.³

We conclude that the pattern of initial bilateral diffuse swelling following trauma in children is produced by vasodilatation and initial hyperemia. The increase in total intracranial blood volume may not be very high, since severe intracranial hypertension is rarely seen at the time of the initial CT scan. However, a redistribution of blood from the subarachnoid and pia vessels into the parenchyma would be adequate to account for the increase in brain bulk.

The clear difference in history, clinical presentation, acute and chronic course, and follow-up CT scans between patients with a GCS score of 6 to 8 versus those with a score of 3 to 5 requires an explanation. We believe that in the former group of patients, relatively little primary diffuse impact injury to the white matter has occurred. Therefore, when the hyperemia, decreased compliance, and high ICP are controlled, a rapid recovery occurs with little residual neurological damage, and follow-up CT scans show a rapid return to normal. In the second group, with a GCS score of 3 to 5 and immediate unconsciousness, a significant amount of primary impact injury to the white matter has occurred. The delayed rise in ICP at 2 to 3 days in this group is probably due to the presence of multifocal brain edema (Fig. 3) around areas of disrupted blood-brain barrier and small petechial hemorrhages. As the edema resolves, a loss of cerebral substance occurs with some evidence of CSF outflow obstruction leading to a period of increased CSF spaces. Extracerebral collections of CSF are seen that resolve spontaneously, leaving a pattern of apparent brain atrophy. In 43% of cases, presumably those with least axonal damage, reestablishment of brain bulk occurs. This event often occurs after physical recovery is well advanced but intellectual recovery is still underway. We have no proof of the mechanisms for this; possible explanations include a resolution of transient external hydrocephalus (unlikely because of the isotope scan findings),

remyelination of white matter as occurs after experimental hydrocephalus,¹⁰ and changes in brain protein composition or amount.⁸ This concept of greater primary injury is supported by the time to recovery and limitation of recovery seen in the group of patients with GCS scores of 3 to 5, and by a recent pathological study on the brains of children who died after demonstrating diffuse swelling on CT scan.³³ By the time death occurred, areas of secondary ischemia were frequently seen, probably due to increased ICP.³³ The findings of diffuse impact injury are supported by the autopsy findings in our own patients.

We conclude that acute, diffuse brain swelling is very frequent in children and teenagers following acceleration/deceleration injury to the brain. The swelling is produced mainly by an increase in intracerebral blood, either as a true increase in cerebral blood volume or as a redistribution of intracranial blood from the pia to the intraparenchymal vessels. When associated with a lucid period, minimal underlying cerebral injury is likely, and hyperventilation for 24 to 48 hours may be all that is required. These children should all make a rapid and essentially complete recovery. In children in immediate deep coma, a significant degree of primary impact injury is present, and superimposed on this is the hyperemia. Thus, control of the swelling with hyperventilation is not adequate, and delayed increases in ICP occur due to true cerebral edema. These patients pass through a slow recovery with a series of specific CT appearances, but usually can be expected to recover to a self-sufficient state without further surgical intervention.

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