Glial swelling following human cerebral contusion: an ultrastructural study

R Bullock, W L Maxwell, D I Graham, G M Teasdale, J H Adams

Abstract
The ultrastructural features of cerebral cortical contusions seen three hours to 11 days after head injury were studied in 18 patients undergoing surgery. Massive astrocytic swelling ("cytotoxic" oedema) was seen three hours to three days after injury, maximal in perivascular foot processes and compressing some of the underlying capillaries. The tight junctions were not disrupted. Neuronal damage was most marked three to 11 days after injury. The pathophysiological mechanisms leading to oedema formation and neuronal degeneration are discussed.

Cerebral cortical contusions are generally regarded as the pathological hallmark of head injury and are clinically important for several reasons. Extensive swelling of the cortical ribbon and underlying white matter may occur acutely after cerebral contusions and may cause mass effect, brain shift and raised intracranial pressure, and these events may cause secondary ischaemic brain damage or death. When widespread, contusions cause extensive destruction of the cortical ribbon particularly at the tips of the temporal and frontal lobes and the orbital surface of the frontal lobes, and this may lead to post traumatic epilepsy, and to the neuropsychological and behavioural sequelae, typical of severe head injury.

Although previous studies have focused upon the pathogenesis, histopathology, distribution and quantification of cerebral contusion, many aspects remain unresolved. Why do some cerebral contusions swell and generate raised intracranial pressure, while others do not? What proportion of the neuronal necrosis which is seen adjacent to cerebral contusions is due to primary contact damage, and how much of it is due to secondary factors, such as delayed reduction in blood flow to the contused area?

In studies in which we have mapped cerebral blood flow following human cerebral contusion, zones of profoundly reduced regional blood flow (rCBF) have been found adjacent to contusions, and this may be a factor in the ischaemic neuronal necrosis which is a prominent finding in pathological studies. Alterations to the microvascular bed adjacent to cerebral contusion may therefore be an important determinant of such changes.

The purpose of this study was to determine ultrastructurally the changes in neuronal, glial and microvascular morphology which occur with time following human cerebral contusion, and to determine their role in the pathogenic processes which are known to damage the brain after severe head injury.

Patients and methods
Eighteen patients with severe cerebral contusion were studied. Clinical details are shown in table 1B. In each patient, contusions were shown on CT scan, and in seven patients, mass effect, acute clinical deterioration and associated haematomas necessitated urgent operation, at which the contusion was resected, and biopsy taken from the margins of the resected tissue. In a further four patients, ICP monitoring was initially performed to ascertain the need to remove the contusion, and ICP rose necessitating surgery. In the remaining seven patients, delayed neurological deterioration occurred up to 11 days after injury, precipitating the operation. Specimens of resected cerebral contusion from these patients were compared with specimens processed in an identical manner, from four control patients, with macroscopically and radiologically normal brain tissue at the site of biopsy, who had either temporal lobectomy for epilepsy or resection of deep temporal glioma. Clinical details of these patients are shown in table 1A. Rongeur specimens around 2 cubic mm in size were taken from contused grey and white matter and immediately immersed in buffered glutaraldehyde (350 m osm). Specimens were then stored at 4°C for two to seven days until processing for electronmicroscopy. The site from which the biopsy was taken was recorded by the surgeon and related as closely as possible to the CT appearance on the pre-operative scan. The study was approved by the Ethics Committee of the Institute of Neurological Sciences, Glasgow.

Processing for electronmicroscopy
After immersion fixation, specimens were cut into 200 µ thick sections using a vibrotome, and ultrasonicated to dislodge non-adherent blood components from the vessel lumina.

Table 1A Control patients—clinical data

<table>
<thead>
<tr>
<th>Case</th>
<th>Age (years)</th>
<th>Tissue biopsied</th>
<th>Indication for surgery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65</td>
<td>Cortex and white matter right temporal tip</td>
<td>Deep temporal glioma, seizures</td>
</tr>
<tr>
<td>2</td>
<td>56</td>
<td>Left frontal cortex</td>
<td>Partial left frontal lobectomy for glioma</td>
</tr>
<tr>
<td>3</td>
<td>36</td>
<td>Posterior right temporal cortex and white matter</td>
<td>Right temporal lobectomy for glioma</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>Right temporal cortex</td>
<td>Right temporal lobectomy for severe epilepsy</td>
</tr>
</tbody>
</table>
Table 1B Patients with cerebral contusion—clinical data

<table>
<thead>
<tr>
<th>Case</th>
<th>Age (years)</th>
<th>Interval between injury and biopsy</th>
<th>CT diagnosis and clinical details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67</td>
<td>3 hours</td>
<td>Fall. Right temporal contusion, small acute subdural haematoma, high ICP (died)</td>
</tr>
<tr>
<td>2</td>
<td>33</td>
<td>6 hours</td>
<td>Fall. Right frontal lobeotmy for massive brain swelling when acute subdural haematoma removed. (Alcoholic with clotting defect—died)</td>
</tr>
<tr>
<td>3</td>
<td>68</td>
<td>13 hours</td>
<td>RTA. Right temporal contusion with deterioration of consciousness. Good recovery.</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>16 hours</td>
<td>RTA. Large traumatic, right frontal intracerebral haematoma and overlying contusion, deterioration of consciousness. Good recovery.</td>
</tr>
<tr>
<td>5</td>
<td>52</td>
<td>17 hours</td>
<td>Found unconscious and drunk. Left temporal contusion (&quot;Burst lobe&quot;) and acute subdural haematoma. Disabled.</td>
</tr>
<tr>
<td>6</td>
<td>18</td>
<td>23 hours</td>
<td>RTA. Bifrontal contusions. Left frontal intracerebral haematoma, deteriorating consciousness. Disabled.</td>
</tr>
<tr>
<td>7</td>
<td>29</td>
<td>27 hours</td>
<td>Assault. Partial right parietal and depressed fracture. Good recovery.</td>
</tr>
<tr>
<td>8</td>
<td>17</td>
<td>28 hours</td>
<td>RTA. Left hemispheric swelling and temporal contusions—ICP monitoring → high ICP. Disabled.</td>
</tr>
<tr>
<td>9</td>
<td>59</td>
<td>31 hours</td>
<td>RTA. Acute right extradural, subdural haematomas and right frontal contusion. Deteriorating consciousness. Disabled.</td>
</tr>
<tr>
<td>11</td>
<td>68</td>
<td>37 hours</td>
<td>RTA. Right temporal contusion, small acute subdural. ICP monitoring → high ICP. Good recovery.</td>
</tr>
<tr>
<td>12</td>
<td>42</td>
<td>42 hours</td>
<td>Found unconscious. Delayed deterioration. Bitemporal contusions. This left acute subdural. Good recovery.</td>
</tr>
<tr>
<td>13</td>
<td>46</td>
<td>46 hours</td>
<td>Fall. Delayed confusion. Right temporal contusion. ICP monitoring → high ICP. Good recovery.</td>
</tr>
<tr>
<td>14</td>
<td>59</td>
<td>49 hours</td>
<td>Alcoholic epileptic. 7 Fall. Delayed confusion. Bifrontal contusions, mass effect. Disabled.</td>
</tr>
<tr>
<td>15</td>
<td>40</td>
<td>72 hours</td>
<td>Fall. Right parietal acute subdural. Delayed ICP rise → new low density. Right temporal → re-opening craniotomy and right temporal lobeotmy. Disabled.</td>
</tr>
<tr>
<td>16</td>
<td>64</td>
<td>77 hours</td>
<td>Fall. Multiple contusions. Left hemisphere, small extradural haematoma. Right parietal. Delayed deterioration. Partial left temporal lobeotmy. Disabled.</td>
</tr>
<tr>
<td>17</td>
<td>44</td>
<td>5 days</td>
<td>Hydrocephalic with shunts. Fell out of bed → bifrontal contusions. Delayed coma. ICP high. Right frontal contusion evacuated. Disabled.</td>
</tr>
<tr>
<td>18</td>
<td>72</td>
<td>11 days</td>
<td>Fall. Persistently confused. Right frontal subacute subdural, small temporal contusion. (Burst lobe at surgery). Disabled.</td>
</tr>
</tbody>
</table>

Specimens were then fixed in 2% osmium tetroxide in phosphate buffer, and the slices were critical-point dried, mounted on scanning electron microscopy stubs with silver paint and sputter-coated before viewing in a JEOL 300 TS scanning electron microscope. Blood vessels were selected for particular study and micrographs were taken at a magnification of 7000 and 1500 times to allow demonstration of endothelial surface structure and measure vessel size. After scanning electron microscopy specimens were carefully removed from the SEM stubs and washed three times in 100% acetone to remove the silver paint. The material was then embedded in araldite resin and cut into semi-thin sections stained with toluidine blue and areas of interest selected for transmission electron microscopy. Thin sections were cut for the transmission EM and routinely stained with lead citrate and uranyl acetate and examined in a JEOL 100 S transmission electron microscope.

Results

Biopsies were obtained at time points ranging from three hours to 11 days after injury. In all the specimens the quality of fixation as judged by preservation of intracellular organelles was acceptable.

Control patients

Normal glial, neuronal and vascular ultrastructure was present in all control patients, and the neuropil and white matter density was normal (fig 1). Scanning electronmicroscopy demonstrated pit-vesicle activity on the endothelial surface of the lumen of all vessels in the control patients (table 2).

Transmission EM findings in patients with cerebral contusion

A) GROSS DISRUPTION OF TISSUE

In five specimens taken from three patients the architecture of the cortical neuropil was disrupted by red blood cells and plasma. Whenever this was seen, the adjacent neuropil was grossly abnormal, demonstrating marked vacuolation and lycency of astrocyte cytoplasm (fig 2).

B) GLIAL CELL SWELLING

The most consistent finding in both grey and white matter in patients with cerebral contusions was severe swelling affecting particularly astrocytes. This was associated with "loosening" and apparent pseudo-vacuolation of the neuropil to produce a "Swiss cheese" appearance, particularly striking on SEM. This appearance developed rapidly (figs 3, 4a) within three hours of injury but was still present in specimens taken three days after

Figure 1 Thin section of cortical neuropil from control patient KW. Preservation of intracytoplasmic organelles is satisfactory and vacuolation of neuropil is absent. (Magnification: x 2973).
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Figure 2 Thin section through cortical neuropil 16 hours after injury. Note gross swelling of astrocytic cytoplasm (lower right) and vacuolation of neuropil caused by swelling astrocytic process. Note mitochondria apparently lying free within the cytoplasm of swollen astrocytes (arrow). (Magnification: x 5250).

Figure 3 Scanning EM of a section through cortical neuropil to show vacuolation surrounding a blood vessel (arrow) ("Swiss cheese" appearance). (Magnification: x 1000).

injury. In the worst affected astrocytes, cytoplasmic disruption was present with complete rupture of the cell membrane (fig 5). Organelles such as mitochondria were, however, still recognisable. In the specimens taken five days after injury, astrocytic swelling was less marked although still apparent (fig 6a, b) and the astrocytes now contained deposits of glycogen, typical of the "sheet reaction" described by Torvick (fig 6).^9^ Comparison between the changes seen in cortex (fig 4a, b) and those in white matter (figs 4, 5, 6) should, however, be made with caution.

D) VASCULAR CHANGES (TRANSMISSION ELECTRONMICROSCOPY)

In the majority of vessels seen within con-
tused tissue, endothelial cell morphology was grossly normal and in those vessels where adjacent astrocytic swelling was not noticed, vessel lumina were not disrupted or occluded. No disruption of inter-endothelial tight junctions was noted, and in the majority of vessels studied, the morphology of the perivascular basement membrane was also normal.

An increased number of cytoplasmic folds and processes on the luminal aspects of endothelium were seen within vessels and thin transmission sections showed a very irregular luminal profile to the endothelium at two days (fig 7). Inter-endothelial junctions were not disrupted despite gross disruption of the adjacent neuropil. This irregular endothelial profile was also seen at five days when the astrocytic sheet reaction had become well established (fig 8). Counts of endothelial pinocytic vesicles in the vessels from contusion specimens taken at different times after injury, showed a decline with time and the highest numbers of vesicles were seen in the control and acute patients (table 3).

**Early white matter changes on transmission EM**

Twelve specimens of white matter from contused tissue were studied. Preservation of myelin was remarkably good. In some patients, swelling of axoplasm was noted, but this was never severe. Cytoplasmic swelling of glial cells within white matter was present but was less marked than that seen in the grey matter. Accumulation of interstitial fluid within white matter was marked (fig 5).

**Delayed changes**

**A pyknosis and shrinkage**

Pyknosis and shrinkage of both neurons and glia was noted when biopsies were taken at three or more days after injury (fig 9). Pyknotic neurons were frequently surrounded by microglia which appeared to be carrying out phagocytosis of damaged neuropil and cells. In specimens from the two patients who were studied five and 11 days after injury, extensive leucocyte and microglial phagocytosis was seen and deposition of collagen fibres was prominent.

**Table 3 Microvillus counts (SEM) and pinocytic vesicle activity (TEM) after contusion.**

<table>
<thead>
<tr>
<th>Time interval after injury</th>
<th>Endothelial pinocytic vesicle count per µ² mean (SD)</th>
<th>Luminal microvillus counts per 25 µ² mean (SD)</th>
<th>Capillaries (&lt;10 µ)</th>
<th>(&lt;10 µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controls</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contusion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-6 hours</td>
<td>6105 (351)</td>
<td>12916 (381)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13-23 hours</td>
<td>6125 (299)</td>
<td>12916 (381)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24-48 hours</td>
<td>472 (301)</td>
<td>5434 (244)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-5 days</td>
<td>472 (301)</td>
<td>5434 (244)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 days</td>
<td>472 (301)</td>
<td>5434 (244)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6 (A) Thin section of white matter taken five days after contusion—the swelling of astrocytic foot processes (a) is less marked with glycogen accumulation. The sheet reaction is apparent. (Magnification: x 8200); (B) Thin section of cortical neuropil in a different patient, operated upon five days after head injury. Swollen astrocyte processes and accumulation of glycogen granules therein are seen. (The so-called "sheet reaction"). (Magnification: x 8750).

Figure 7 High magnification thin section of part of a vessel wall two days after injury to show a thickened irregular profile of the endothelium. Microvilli are present. Note that the interendothelial tight junctions are intact (arrow). Astrocytic foot processes on the abluminal surface of the basal lamina are grossly swollen. (Magnification: x 20000).
the neuropil in tissue adjacent to cerebral contusions was particularly noticeable on scanning EM in comparison with the control patients (fig 3).

**B VASCULAR AND PERIVASCULAR CHANGES**

Vessel morphology was remarkably normal in all specimens studied. Tears in vessel walls were not seen. Blood clots occluding the lumen of vessels were seen only occasionally, although this may relate to the vibration and ultrasonication process which was used to visualise the lumina. In many vessels, however, adherent red cells and leucocytes were found suggesting an abnormality of endothelial adhesion characteristics. Red cells were seen moving through fenestrations in the endothelial membrane to leave the vessel lumen, by a process of diapedesis (fig 11a, b).

Perivascular accumulations of red blood cells were a frequent finding and in several specimens, these caused streak-like disruption of tissue architecture.

**Pin-vesicle activity**

Pin-vesicle activity was present in both control and contusion specimens, but was less extensive in the patients with contusions. In some areas, the endothelial luminal membrane was disrupted by coalescent vesicles to form irregular holes in the vessel walls, and in two specimens, red cells were seen passing through these (fig 11a, b). Pin-vesicle activity in the endothelium was always accompanied by parallel development of microvillus formation, but the proportion of pin-vesicle and microvillus activity was variable from specimen to specimen, and no clear relationship was seen, either to time after injury, or to other microscopic changes. When the number of luminal microvilli per 25 μm² were counted using SEM, and correlated with the number of vacuoles within the endothelial cytoplasm seen on transmission electronmicroscopy, (table 3) no relationship was seen in either the contusion or control material.

The mean number of endothelial micropinocytotic vesicles in control patients was 6.105 μm² and 6.125 μm² in contusion patients at three hours after injury, 4.72 μm² at 24–48 hours after injury, and 1.5 μm² at five days after injury. Thus there was a slight (but not statistically significant) decline over time in the number of endothelial pinocytotic vesicles in damaged tissue.

Marked changes in luminal microvillus activity were seen in the contusion material, at various times after injury (table 3). In capillaries, microvilli numbers dropped to their lowest levels when astrocytic and foot process swelling was most marked, at 13–24 hours and slowly rose to near control values by 11 days. By contrast, in larger vessels microvillus activity rapidly rose to almost twice control levels in the first six hours after injury, then dropped to nearly a third of control levels at 24–48 hours, and were approaching control levels by 11 days.
Discussion

Cerebral contusion has been studied extensively by light microscopy in humans and by light and electron microscopy in animal models, but the ultrastructural changes in humans have not been reported.1-5,10-12 The majority of histopathological studies were largely descriptive, but Lindenberg and Freytag have also speculated on the mechanisms of neuronal damage. It is postulated that the streaky form of neuronal ischaemic necrosis which is seen surrounding contusion differs from the conventional changes of ischaemia,4,13 and postulated that impact injury propagates waves of shear stress through brain substance which damage neurons by tearing axons and dendritic processes.5 However, neither in the present ultrastructural study nor in that of Hekmatpanah in a rat model could shearing of dendritic processes or axons be demonstrated.14 Moreover, the neuropathological studies of Adams and Graham carried out in 635 patients dying after severe head injury have not documented an association between either retraction balls or microglial stars, the hallmarks of diffuse axonal injury, and cerebral contusion.14

In this study, neurons demonstrating the features of the ischaemic cell process were not seen in the specimens taken at three and six hours, but were clearly apparent in the specimens taken at one day; by the third day, pyknosis and nuclear lysis were obvious (fig 9). This suggests that the neuronal degeneration which occurs after contusion in humans may be a secondary, delayed process. This is in contrast to the findings in the rat model of cerebral contusion described by Hekmatpanah, in which neuronal changes were well established by three hours after injury, both on light and electron microscopy.11

Measurement of rCBF in patients after cerebral contusion, has shown zones of profoundly reduced CBF (around 15-20 ml/100 gm/min), at the site of the contusion, using SPECT mapping and PET techniques.8,15 These have been shown as early as within 24 hours of injury and up to three weeks after injury. Local microcirculatory vascular factors may therefore be important in the pathogenesis of neuronal degeneration adjacent to cerebral contusions. This study demonstrates four major microvascular changes, which have also been seen in a variety of animal models: 1) marked perivascular astrocytic process swelling—sometimes sufficient to cause apparent compression of the vessel lumen (fig 4); 2) reduced luminal pit-vesicle and microvillus activity, (table 3; figs 7 and 8); 3) decreased endothelial cytoplasmic vacuole formation (table 3), and 4) transvascular red cell diapedesis (fig 11).

Our study suggests that the major structural feature associated with reduced local tissue perfusion is microvascular collapse and compression due to astrocytic perivascular podocytic process swelling together with some compromise of cerebral circulation mediated by the development of endothelial microvilli (figs 4, 11). This accords with our previous ultrastructural findings, those of Dietrich et al, and the pattern of profound perfidocclusion in rCBF seen in a model of intracerebral haematoma.8,12,16,17 Perivascular astrocytic podocytic swelling was also prominent in the ultrastructural studies of Allen—performed in a primate model of high velocity missile injury, and Hekmatpanah, in the rat contusion model.10,11 We have not, however, seen the vessel tears and thrombosis described by Hekmatpanah in the rat model, and we have not demonstrated disruption of inter-endothelial tight junctions (fig 7).

Although the specimens studied five days after injury showed less marked astrocyte cell body and foot process swelling than those
Glial swelling following human cerebral contusion: an ultrastructural study

Glial following human cerebral contusion: through are seen to "pure" microvillus formation form ragged pinocytotic ble (table 3). of number delayed post-contusional fluid percussion demonstrated that these experimental processes passed rapidly through after intravascular beneath the basement injury, netate, were development performed at various time intervals.8

In an animal process. This agrees with the results of studies in microgravimetric authors. Povlishock, using a fluid percussion model of head injury, demonstrated that Horseradish peroxidase (HRP) passed rapidly through intact endothelial cells after intravascular injection, and accumulated beneath the basement membrane, and within endothelial vesicles.9 HRP was found chiefly within endothelial cytoplasmic vesicles and the number of vesicles increased rapidly within 15 to 30 minutes after trauma. In contrast to these experimental observations, we have demonstrated that after a contusion micropinocytic vesicles decline in number with time (table 3). Therefore, it is unlikely that micropinocytosis is an important mechanism in delayed post-contusional oedema.

The role of pit-vesicle activity and microvillus formation after head injury is not understood. Its presence within hours of injury after "pure" diffuse axonal injury suggests that it may be a non-specific response to the invariable hypertensive surge which occurs within seconds after severe head injury.2, 22-25

We have observed coalescence of vesicles to form ragged holes in the endothelial luminal membrane, through which intact erythrocytes are seen to pass (fig 11). This partly accords with other studies,22 and may provide a mechanism for the peri-vascular accumulation of erythrocytes, which is a frequent histological feature after contusion but which has not been previously explained.14-15 Vessel tears may therefore not be necessary for perivascular "haemorrhage".

Although we and other authors have shown that astrocytic swelling is well established after cerebral contusion as early as three hours after injury, both in this study and in animal models, the cause for this swelling remains uncertain.10-12 20 22

When cerebral blood flow falls sufficiently low to cause failure of neuronal energy metabolism, and membrane depolarisation (around 14–15 ml/100 gm/min) due to global or focal ischaemia, massive astrocytic swelling occurs as a buffering mechanism; astrocytes absorb free K+ ions in an attempt to maintain extracellular fluid homeostasis.26-27 Global ischaemia is, however, unlikely to occur as a very early event after focal human contusion and, moreover, some animal studies have shown blood pressure and CBF to be transiently elevated after head injury.23-25

Faden et al and Becker et al have demonstrated massive release of excitatory amino acids after fluid percussion injury, in tissues immediately beneath the impact point, but not distant from it.28-29 Excitatory neuronal mem- brane depolarisation may result from this glutamate release, to cause subsequent K+ ion flooding of the extracellular space, and this may cause astrocytic swelling, which itself may jeopardise focal tissue perfusion adjacent to a cerebral contusion, and induce further ischaemic damage.24 A pathological "vicious cycle" such as that shown in fig 12, may thus be postulated, as a cause for neuronal death in cerebral contusion.

Vasoconstrictor substances such as K+, serotonin, or prostaglandins may also be released into the contused tissue, inducing the profound fall in regional blood flow, which we have demonstrated on SPECT (8).

Further studies are needed to clarify the causes of astrocytic swelling, and to explore the possibilities of therapy for preventing or attenuating this astrocytic response, which may be detrimental to neuronal survival.

We are grateful to the neurosurgeons at the Institute of Neurological Sciences, Glasgow who assisted with obtaining cerebral contusion and control specimens, and to Anne Semple for preparing the manuscript.


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