Regional Cerebral Blood Volume During Acute Transient Rises of the Intracranial Pressure (Plateau Waves)*

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It is a well-known fact that progressive intracranial hypertension during one stage of its development is characterized by intermittent, sometimes paroxysmal symptoms. Continuous recording of the ventricular fluid pressure (VFP) in patients with expanding intracranial lesions has shown that such intermittent symptoms coincide with acute temporary rises of the VFP level. The corresponding VFP curve usually follows a specific pattern, characterized by a steep rise to a high level (60–100 mm Hg) and, following some minutes, an often equally steep fall. This gives the curve a plateau-like appearance (Figs. 1–3).

The plateau waves have been subjected to extensive clinical studies. Variations of the VFP curve similar to plateau waves could be provoked by increasing the pressure in the ventricles at ventriculography or by exerting pressure on the region of a skull defect. It was inferred that an induced or spontaneous increase of the intracranial pressure may cause dilatation of cerebral vessels which in turn causes the intracranial pressure to rise further. By means of simultaneous recording of the cerebral blood flow and the ventricular fluid pressure combined with cerebral angiography, it was shown that the plateau waves are accompanied by dilatation of cerebral arteries and, at the same time, a decrease of the cerebral blood flow. These findings indicate that during the plateau waves there is an increase of the intracranial blood volume. In general, the studies quoted suggest that the plateau waves may appear independently of systemic circulatory events and that they are related to cerebral vasomotor changes and to a failure of mechanisms compensating intracranial volume and pressure variations.

The observation of Langfitt and his group in animal experiments should be recalled in this connection. They produced a rise in intracranial pressure by expanding a subdural balloon. This initial rise was followed by a “secondary rise” which these investigators ascribed to a reactive dilatation of cerebral vessels.

In the present investigation we have measured the regional cerebral blood volume (rCBV) in patients with plateau waves. The rCBV measurements have been carried out by means of a new, continuous, and relatively atraumatic method. Since this method is continuous, it has been possible to record the intracranial pressure simultaneously and to compare the VFP and rCBV events in detail. It will be shown that rCBV augmentations always took place during the plateau waves. Furthermore, the tracings we obtained show that the interrelations of the VFP and rCBV followed a well-defined pattern, with maximal blood volume values during the minutes preceding the rapid fall of the intracranial pressure at the end of the plateau wave.

Material

The rCBV was measured in two patients in whom the VFP was continuously recorded for other purposes consistent with established principles practised in our neurosurgical department.

Case 1. Intracranial Hypertension of Unknown Origin. A 42-year-old woman had a history of legal abortion because of rubeola, following which she complained of impaired
Fig. 1. Case 2. Simultaneous recordings of regional cerebral blood volume (rCBV) and ventricular fluid pressure (VFP) during a spontaneous plateau wave. The rCBV was measured in eight regions over the right hemisphere. The mean changes in the eight regions (m 1–8) are shown in the uppermost curve of the rCBV diagram.

vision, tinnitus, unsteadiness of gait, and paresthesias in the limbs. Ophthalmoscopy revealed bilateral papilledema with a protrusion of 5 to 6 diopters. On admission, neurological examination, including air studies and cerebral angiography, revealed no abnormalities besides the papilledema. A ventricular catheter was inserted into the frontal horn of the right lateral ventricle for continuous recording and control of the VFP. There was a basic pressure of 10 to 30 mm Hg and intermittent, regular, and rhythmic plateau waves (height 70 to 90 mm Hg, duration 10 to 15 min). The plateau waves were accompanied by headache, facial flush, blurred vision, numbness in the fingers, and a feeling of unreality and confusion. Following a Spitz-Holter shunt operation, the pressure level remained low, between 5 and 10 mm Hg without any gross variations. The
Case 1. Simultaneous recordings of regional cerebral blood volume (rCBV) and ventricular fluid pressure (VFP) during a spontaneous plateau wave. The rCBV was measured in eight regions over the left hemisphere. The mean changes in the eight regions (m 1–8) are shown in the uppermost curve of the rCBV diagram.

The patient's condition improved rapidly, and the papilledema eventually subsided.

Case 2. Non-Verified Central Glioma in the Left Cerebral Hemisphere. A woman, aged 28, had had headaches for 2 months before admission. Papilledema was discovered, and she was admitted to the Department of Neurosurgery where a protrusion of four diopters was confirmed bilaterally. Otherwise the neurological examination showed no abnormality. A catheter was inserted into the frontal horn of the right lateral ventricle for ventriculography and pressure control. The records showed a basic pressure of 15 to 30 mm Hg. About once an hour, this level was interrupted by plateau waves (height 60 to 80 mm Hg, duration 15 to 30 min). During these waves the patient suffered from headache, but there were no additional complaints. Ventriculography and angiography showed a central glioma in the left hemisphere which had invaded the corpus callosum and the right hemisphere. A subtemporal decompression was performed before the patient was sent back to her local hospital.

Methods

Recording of VFP. In brief, this technique implies the insertion into the lateral ventricle of a cannula made of flexible, thin-walled polyethylene tubing, connected to the recording equipment. The cannula is anchored to the skull by a rubber plug tightly fitting into a burr-hole. The recording equipment consists of a strain gauge transducer, amplifier, and an inkwriting recorder.
Measurement of Regional Cerebral Blood Volume (rCBV). A description of the rCBV technique has recently been presented elsewhere.\textsuperscript{24,26} A non-diffusible, gamma-emitting indicator, 400 \( \mu \)Ci of \(^{13}1\)iodine-labelled human serum albumin (RISA), is injected intravenously, and, after equilibration, a continuous measure of relative changes in rCBV is obtained by external recording of the radiation from different parts of the brain. Gamma-radiation was recorded by means of eight scintillation detectors (1 \( \times \) 1 inch NaI(Tl) crystals) mounted in cylindrical parallel holes (diameter 3.5 cm) in a block of lead, placed at a right angle to the lateral surface of the patient's head. In Case 1 the left hemisphere was close to the lead block, and in Case 2 the right hemisphere. The position of the detectors in relation to the brain is shown in Figs. 1-3. Each detector recorded the radiation from a slightly conical part of the brain (diameters 4 to 5 cm). Calculations showed that about 75\% of the counts registered came from the hemisphere closest to the detectors.\textsuperscript{22}

The eight detectors were coupled via amplifiers to pulse height analyzers (windows set at 180 to 450 KeV) and to storage and playback systems, which yielded the absolute number of counts during 1-minute periods of recording. The data were plotted either manually or by means of a fast X-Y writing unit. Counting rates of about 1500 to 2500 cpm were recorded from each detector. In Case 1 rCBV was measured for 5 hours and 35 minutes (five plateau waves registered) and in Case 2 for 1 hour and 30 minutes (one plateau wave). Stable levels of rCBV at a relatively low VFP level (15 to 30 mm Hg) were chosen as the reference (100\%) counting rate. In Fig. 1, the first 5 minutes of recording were used as reference; in Fig. 2, the first 10 minutes; and in Fig. 3, the 14 to 28 minutes level.

Results
Simultaneous recordings of VFP and rCBV were made during a total of six plateau waves. Figures 1–3 show the findings in five of the six waves studied. The results
Plateau Waves and Cerebral Blood Volume

were, as seen, very consistent. All the waves were accompanied by an increase of rCBV, which reached a maximum of about 20% and which was clearly visible in all eight regions measured in both patients.

There were, however, important differences between the VFP and the rCBV curves. In most instances, the VFP curves showed a fast rise up to the maximal pressure of the plateau wave, and this was followed by a slow fall which ended in a very rapid sudden fall, marking the end of the wave. The rCBV curves, on the other hand, showed a slow increase during the initial phase of the wave, with the maximal rCBV value during the minutes preceding the rapid fall at the end of the wave. During the intervals between the plateau waves, there was also an obvious discrepancy between the two curves. The fall in pressure at the end of the plateau wave usually did not stop until the pressure was below the pre-wave level. It is especially evident in Fig. 3 that an increase of rCBV persisted at the low VFP level following the plateau wave. From this low level the VFP curves then showed a steady increase of the pressure up to a point when the next wave began. It is evident from Fig. 3 that the total rise of the VFP between two plateau waves amounted to about 20 mm Hg. During this slow rise of the pressure, there was no change of the rCBV.

When the rCBV recordings from the different regional detectors were compared, it was not possible to find consistent differences between them. Only over “central” parts of the brain, which include ventricles and the choroid plexuses, did the augmentations in rCBV appear somewhat larger than in the other regions.

Discussion

The rCBV Method. It is a prerequisite for the rCBV method that the major part of the radioactive tracer, RISA, remains in the blood stream and does not penetrate extravasally. The present and previous results indicate that tracer penetration cannot have taken place to any significant extent. As shown by Fig. 3, the baseline level between the three plateau waves was very stable for about 3 hours, and the rCBV changes recorded during the plateau waves were almost identical. This is strong evidence for the view that no considerable amount of RISA became immobile during the measurements. It is therefore possible to conclude that the regional variations in radiation recorded with the present technique must have represented changes in rCBV.

No observations made during the measurements indicated that respiratory or systemic circulatory changes might have influenced the rCBV recordings significantly.

Main Result. The main result of this study was the consistent finding of an increase of rCBV during the plateau waves. This proves that these waves are accompanied by an increased intracranial blood volume, most likely due to a dilatation of cerebral vessels.

In all figures, the tracings show a slow increase of the VFP to about 30 mm Hg before the pressure suddenly starts to rise rapidly. At this moment the rCBV also starts to augment. This observation should be related to the findings of one of us in man and of Langfitt, et al., in experimental animals that a limited induced rise of the intracranial pressure may produce a secondary rise of this pressure. The investigations by Woolf and Forbes, by Fog, and by Noell and Schneider who showed that an increase of the intracranial pressure produces a dilatation of cerebral vessels are pertinent.

Taken together these investigations favor the view that “intrinsic” vasomotor reactions which maintain cerebral circulatory homeostasis during intracranial pressure variations are involved in the mechanism behind the plateau waves. Animal experiments suggest that the pressor response (the Cushing phenomenon) also participates. In man, plateau waves may be accompanied by a rise of the systemic blood pressure, but they may also occur without any changes of this pressure at all. Thus, the plateau waves seem to be closely related to the autoregulation of the cerebrovascular resistance to variations of the perfusion pressure.

Normally there is a positive linear correlation between the cerebral blood flow and the cerebral blood volume. However, during plateau waves a decrease of cerebral blood flow has been demonstrated independently by means of isotope clearance and by a thermo-electric technique. This apparent discrepancy can only be explained by the occurrence of an increased resistance some-
where within the cerebral vascular system. Here it might be recalled that animal experiments have shown that an increase of the intracranial pressure to levels close to the arterial pressure gives rise to a decrease of the sagittal sinus pressure. During induced intracranial hypertension, it has been observed in animals that veins on the hemisphere convexities remain filled.8,20 These observations suggest that an increase in intracranial pressure may cause an obstruction of the venous outlets from the cranial cavity, probably due to compression of cerebral veins in the subarachnoid space or the dural sinuses.9,28,30 In serial angiograms taken in patients during spontaneous plateau waves, filled convexity veins were clearly visible.19 The studies quoted indicate that during a plateau wave the locus for the main pressure fall shifts from the arteries, which normally determine the cerebral vascular resistance, to the draining cerebral veins and even into the venous sinuses. It seems probable that the obstruction of the venous outlets is a purely mechanical effect of the brain swelling. The details of venous obstruction during plateau waves will, however, require further studies.

The lack of parallelism between the rCBV and VFP tracings (Figs. 1–3) indicates that apart from the intracranial blood volume at least one more variable is involved. It is known that, dependent upon the CSF pressure, water may pass from the CSF to the blood, and vice versa, with considerable rapidity.8 Under normal conditions, the CSF may thus act as a mechanical buffer for intracranial pressure variations and compensate variations of the intracranial blood volume. If the CSF spaces become permanently reduced by an expanding lesion, the capacity for such damping and for spatial compensation is diminished correspondingly.5,16,27,28 It appears that the course of the two curves is determined by interrelated variations of the volumes (and pressures) of the intracranial blood and CSF pools respectively.

To summarize, we suggest the following interpretation of our findings. Between the plateau waves, the slow rise of VFP is due to a refilling of the CSF spaces. During this period, the rCBV does not change. When the intracranial pressure reaches a certain critical level, a dilatation of cerebral arteries takes place and probably also an obstruction of draining veins. The blood pressure within the cerebral vascular bed increases, and the intracranial blood volume augments. Though initially small, the increase of the intracranial blood volume cannot be immediately compensated for and, consequently, the intracranial pressure rises rapidly. However, during the following period of high pressure, a compensatory outflow of CSF causes a slow fall in VFP, in spite of the fact that rCBV still increases. When the intracranial pressure has fallen to another critical level, the tone of the resistance vessels (arteries) is restored (spontaneous effect13). Hypercapnia, causing arterial hypocapnia, may contribute to this and the venous flow becomes normal. This gives rise to a sudden fall of both the VFP and the rCBV. Since the CSF spaces have been emptied at this point, the VFP falls to a level which is considerably lower than that at the onset of the plateau wave, in spite of the fact that the rCBV is still somewhat increased.

It should be added, however, that plateau waves sometimes appear unpredictably and irregularly without any preceding slow increase of the VFP. In such cases, it appears likely that the plateau wave is provoked by an initial vasodilatation and not by a refilling of CSF spaces. Clinical observations suggest that hypercapnia, emotional reactions, painful stimulation, bodily and mental activity, or sleep may be the causative agent in these situations.1,3,4,10,11,12,18

There is good clinical and experimental evidence that plateau waves appear in an intermediary stage during the gradual development of intracranial hypertension.15,18 This stage lies between that when full compensation for volume and pressure variations can take place and the stage of lasting compensation when the perfusion pressure is jeopardized and cerebral hypoxia with vasoparalysis and brain edema ensues. The present study indicates that the plateau waves signal the beginning of a failure of the compensating mechanisms. Hence plateau waves are of diagnostic importance, besides being the cause of acute incidents during the later stages of intracranial hypertension.

Summary
With an isotope method, variations in the
regional cerebral blood volume (rCBV) were continuously recorded simultaneously with the ventricular fluid pressure (VFP) in two patients with intracranial hypertension and acute, reversible rises of the intracranial pressure (plateau waves). It was shown that every plateau wave was accompanied by an increase of the cerebral blood volume.

Analysis of the curves revealed that the variations of the rCBV and VFP followed a well-defined pattern, clearly visible during and between all plateau waves recorded. There were two kinds of VFP variations: 1) rapid changes simultaneous with and in the same direction as the changes of the rCBV; and 2) slower shifts independent of the rCBV variations and partly in the opposite direction. The latter variations of the VFP are assumed to reflect shifts of the intracranial CSF volume too slow to compensate effectively for the volume variations of the intracranial blood pool.

The results indicate that the plateau waves are caused by cerebral vasodilatation elicited by an initial limited increase of the intracranial pressure and that they then develop due to a defective compensation of volume variations of the intracranial blood pool.

References
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