Focal Cerebral Hyperemia in Acute Stroke
Incidence, Pathophysiology and Clinical Significance

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SUMMARY In a consecutive study comprising 41 patients with completed stroke of less than 72 hours duration, cerebral angiography and measurements of the regional cerebral blood flow (rCBF) were performed within 24 hours after admission. The rCBF study was done using the 133-Xenon intracarotid injection method and a 254 multi-detector camera. CT scan was done 24 hours after the rCBF study.

Focal cerebral hyperemia was found in 16 patients. The study revealed 3 different types of hyperemia: Border-zone hyperemia, surrounding ischemic areas, was seen in patients with occluded arteries on angiography, presumably resulting from accumulation of acid metabolites in the border-zone of acute infarcts. Postischemic hyperemia was seen in patients without occlusion, presumably due to recanalization of a prior occluded artery. Remote hyperemia was found distant from the infarcted area, presumably due to local tissue pressure on brain tissue.

Cortical infarcts (10 patients) all had extensive hyperemic areas. Because the 254 detector camera has an excellent resolution in the cortical surface, our findings strongly suggest that all acute cerebral infarcts are, in fact, associated with hyperemic areas. The hyperemic areas are often extensive and vascular reactivity is commonly impaired. It is suggested that treatment aimed at reducing blood flow in hyperemic areas might improve prognosis.

ISCHEMIC LESIONS are responsible for the neurological deficits in most patients with stroke.1 That focal areas of hyperemia may exist in the acute stage of stroke is, however, a relatively new finding first described by Lassen in 1966 as the "luxury perfusion syndrome."2 The phenomenon has now been studied by several investigators4-10 but the clinical significance is still uncertain. It has been associated with a good6,13 as well as a poor prognosis.10,14 The frequency of focal cerebral hyperemia in acute stroke is not known as consecutive studies in the acute stage are not available.

The aim of this study has been to investigate the incidence and the pathophysiological events in areas of focal cerebral hyperemia in a series of consecutive acute patients with stroke, in order to elucidate the clinical significance of hyperemia.

Method

rCBF Study

The rCBF was measured by injecting 133-Xenon into the internal carotid artery and recording clearance of the isotope from the brain using 254 externally placed detectors. The technical details and ability of the 254 multiple detector scintillation camera have recently been described.16 The rCBF investigations were carried out in conjunction with direct carotid angiography. Using the Seldinger technique, a heparinized polyethylene catheter was introduced into the internal carotid artery. About 5-10 mCi 133-Xenon dissolved in 2 ml of isotonic saline was injected as a bolus and the clearance of the isotope was recorded by the 254 detectors. rCBF was calculated using the initial slope index method.16 The flow values calculated are displayed on a TV monitor as a schematic 2-dimensional picture of the hemisphere with 254 colored squares representing absolute flow values on a 16 level color scale.

Vascular Reactivity

Immediately after injection of the isotope a blood sample for Pco2 determination was taken from the internal carotid artery and the clearance of the isotope from the brain using 254 externally placed detectors. The technical details and ability of the 254 multiple detector scintillation camera have recently been described.16 The rCBF investigations were carried out in conjunction with direct carotid angiography. Using the Seldinger technique, a heparinized polyethylene catheter was introduced into the internal carotid artery. About 5-10 mCi 133-Xenon dissolved in 2 ml of isotonic saline was injected as a bolus and the clearance of the isotope was recorded by the 254 detectors. rCBF was calculated using the initial slope index method.16 The flow values calculated are displayed on a TV monitor as a schematic 2-dimensional picture of the hemisphere with 254 colored squares representing absolute flow values on a 16 level color scale.

Material

The present study included 41 patients below the age of 75 with completed stroke, admitted to hospital within 72 hours after onset of symptoms (intra-cerebral hematoma and TIA are not included in this study).

All 41 patients had cerebral angiography, measurement of the regional cerebral blood flow (rCBF), computed tomography (CT scan) and clinical neurological examination. Cerebral angiography and rCBF measurements were carried out within 24 hours after admission and CT scan approximately 24 hours and 14 days after the rCBF measurements.

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12.2% (this is 2.26 times the coefficient of variation seen with this test in 9 normal subjects and hence corresponds to \( p = 0.05 \)).

Autoregulation is considered false if: 1) induced hypertension decreases the blood flow more than 12.2% or if 2) induced hypertension does not change the blood flow more than 12.2% together with impaired CO2 response.\(^{17,18}\)

In case of intact CO2 response the rCBF values obtained during hypertension were corrected to the PaCO2 at rest, implying a correction of 4% flow change for each 1 mm Hg of PCO2.\(^{18}\)

**Definition of Hyperemia**

Larsen et al.\(^{18}\) using the same technique as in the present study, measured resting rCBF repeatedly in a group of 24 normal subjects. Mean CBF was 49 ml/100 g/min in the left hemisphere and 55 ml/100 g/min in the right hemisphere. The random experimental error for the left hemisphere was 3.2 ml/100 g/min and 4.8 ml/100 g/min for the right hemisphere. Expressed as a coefficient of variation the random error for the left hemisphere was 6.5% and for the right hemisphere 8.7%. We, therefore, define focal cerebral hyperemia as areas where rCBF, compared to the mean hemispheric blood flow, is increased more than \( 3 \times 6.5 \approx 20\% (p = 0.01) \) for the left hemisphere and more than \( 3 \times 8.7 \approx 26\% (p = 0.01) \) for the right hemisphere.

Based on the same data we define absolute focal hyperemia as rCBF > 49 + 3 \times 3.2 = 59 ml/100 g/min in the left hemisphere and as rCBF > 55 + 3 \times 4.8 = 69 ml/100 g/min in the right hemisphere (\( p = 0.01 \)).

**Isotope-Angiogram**

In addition to the rCBF measurements, the 254-detector camera is able to monitor the distribution of the injected isotope from the time of injection until the study is finished.

In every second after the bolus injection the total number of counts in each of the 254 detectors is registered and displayed on the TV monitor as a schematic 2-dimensional picture of the hemisphere with 254 color squares, each representing the total number of counts during one second on a 16 level color scale. Such pictures, representing the isotope distribution during the first 5 seconds after the injection, comprise our isotope-angiogram and show the arterial distribution of the isotope before washout of the isotope (fig. 1).

The isotope-angiogram does not show the site of the arterial occlusion but shows the resultant low or non-perfused areas as well as the highly perfused areas in cases with focal hyperemia (fig. 1).

**Results**

The rCBF measurements revealed areas of focal cerebral hyperemia in 16 of the 41 patients, i.e., in 39%. These 16 were investigated from 10 to 84 hours after onset of stroke (table 1). The results of the rCBF studies during rest appear in table 1. Absolute hyperemia was seen in 6 patients in whom the mean flow in the hyperemic areas ranged from 67 to 103 ml/100 g/min. The hyperemias in the remaining 10 patients were only relative and ranged from 28 to 54 ml/100 g/min.

Ischemic areas in the 16 instances of focal cerebral hyperemia were defined as areas of abnormal low isotope filling on the isotope-angiogram 5 seconds after injection of 133-Xenon. Such ischemic areas were seen in 13 patients while 3 did not have ischemic areas.

In all but one of the 16 (patient No. 11) some of the semilogarithmic recorded 2 minutes clearance curves appeared as bending curves irrespective of the magnitude of the hyperemic blood flow.

CT scan showed hypodense areas involving the cortical surface in 10 of the 41 patients and all these 10 had areas of focal cerebral hyperemia (100%).

The CT scan showed hypodense areas without cortical involvement in 25 of the 41 patients. Only 4 of these 25 patients had areas of focal cerebral hyperemia (16%). The CT scan was normal in the remaining 6 patients and 2 of these had areas of focal cerebral hyperemia (33%). According to the findings on the CT scan the hyperemic areas could be separated into 4 different groups:

**Group I:** 7 Patients (Nos. 1-7)

The hyperemic areas were localized adjacent to, and in close topographic relation to low absorption areas.
The hyperemic areas were always relative hyperventilation, rCBF ranging from 28 to 54 ml/100 g/min except in patient 7 where the hyperemia was absolute: 67 ml/100 g/min (table 1).

Autoregulation was tested in all 7 and the results appear in table 2. In the hyperemic areas autoregulation was impaired in 3. In the remaining 4 the blood flow increase did not exceed 12.2% or even decreased during hypertension reflecting normal or “false” autoregulation (patient 7).

Measurements of reactivity to changes in Paco2 were carried out in only 2 patients (3 and 4). The results are shown in table 2. In patient 3, the CO2 response was clearly normal. In patient 4 the blood flow increase did not exceed 12.2% or even decreased during hypertension reflecting normal or “false” autoregulation (patient 7).
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FIGURE 2. Upper panel: Patient 7. Flow map 62 hours after onset of stroke. The blood flow is shown in percent of the hemispheric mean flow. A borderzone hyperemia surrounds an ischemic area involving the left parietal lobe. Lower panel: Flow map 10 hours after onset of stroke. The blood flow is shown in percent of the hemispheric mean flow. A large hyperemic area is seen in the temporal and parietal region. The blood flow in the surrounding tissue is normal (60 ml/100 g/min) and ischemic areas are not seen. The hyperemic area corresponds to a low absorption area on CT scan — therefore a case of post-ischemic hyperemia.

Group II: (Patients 8-9)

Hyperemic areas localized corresponding to the low absorption areas on CT scan.

The low absorption areas in this group also involved the cortical surface. Cerebral angiograms showed no occlusion of significant arteries, and capillary blush and early venous filling in these 2 patients were the only signs of an acute vascular lesion.

The isotope-angiogram did not show any ischemic areas. Both patients showed areas of extremely high and fast isotope-filling areas corresponding to the pronounced hyperemic areas on the flow map. Comparing the CT scan and the flow map, the low absorption areas and the hyperemic areas were in the same place. The localization of the lesions is shown in table 3 and figures 2, 5.

The hyperemias in both cases were absolute hyperemias, the rCBF averaging 75 and 103 ml/100 g/min (table 1).

The tests of autoregulation and CO₂ response in these two patients are shown in table 2. Induced hypertension did not give rise to increased blood flow in the hyperemic area (table 2). CO₂ response was clearly impaired in patient 8 because the blood flow only changed 1% per mm PaCO₂ during hyperventilation. The CO₂ response was probably also impaired in patient 9 as hyperventilation resulted in a blood flow decrease of 5.2% per mm PaCO₂ change. This suggests that the CO₂ response might be considered normal, but the blood flow decreased 8% per mm PaCO₂ during hyperventilation in the surrounding brain. This marked difference in the CO₂ response indicates that it

FIGURE 3. Upper panel: Patient 10. Flow map 18 hours after onset of stroke. The blood flow is shown in percent of the hemispheric mean flow. A large hyperemic area is seen in the upper parietal region. CT scan was apparently normal. Cerebral angiography showed capillary blush and early venous filling in the area, therefore, a post-ischemic hyperemia. Lower panel: Patient 14. Flow map 10 hours after onset of stroke. The blood flow is shown in percent of the hemispheric mean flow. A hyperemic area is seen in the frontal region distant from the ischemic lesion on CT scan, therefore, a remote hyperemia.

FIGURE 4. Patient 7. CT scan 86 hours after onset of stroke. A large low absorption area with cortical involvement in the left hemisphere.
was impaired in the hyperemic area. As the blood flow did not change significantly during hypertension there was probably false autoregulation. The BP decreased 10 mm Hg during hyperventilation and the blood flow decrease in the hyperemic area is therefore most likely the result of this BP decrease.

The CO₂ response was impaired in both the patients and, as the blood flow did not change significantly during induced hypertension, "false" autoregulation was considered present. Recanalization of occluded arteries is believed to be the cause of these hyperemias and they are, therefore, denoted post-ischemic hyperemia.

Group III: (Patients 10-11)

Hyperemic areas present without any low absorption areas on CT scan.

Low absorption areas were not seen and the CT scan appeared completely normal in both patients. Cerebral arterial occlusion was present in patient 11 but not in patient 10. In both a pronounced capillary blush and early venous filling without signs of arterial occlusion were seen in the hyperemic areas.

The isotope-angiogram showed high and fast isotope-filling in the hyperemic areas in both cases. The localization of these lesions are shown in table 3 and figure 3.

The hyperemias in both patients were absolute hyperemias, rCBF averaging 85 and 67 ml/100 g/min (table 1). Autoregulation and CO₂ response were normal in both patients (table 2).

The hyperemic areas in both patients are believed to be of the same origin as in group 2, i.e., recanalization of an occluded artery therefore denoted post-ischemic hyperemia.

Group IV: (Patients 12-16)

Hyperemic areas localized remote from, and without any topographic relation to low absorption areas.

The low absorption areas on CT scan in this group involved the cortical surface in one patient, No. 12. In the remaining 4 (13-16) the low absorption areas were without cortical involvement (deep lesions).

Patient 12. The CT scan was normal in the hy-
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TABLE 3 The Localization of Hyperemic, Ischemic and Low-absorption Areas on Flow Map and CT Scan in 16 Stroke Patients with Focal Cerebral Hyperemia

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Ischemic and low-absorption area  
Hyperemic area

peremic area. Cerebral angiography showed a pronounced capillary blush and early venous filling in the hyperemic area in which the vascular tree was intact without occlusion. A medial branch occlusion was seen in the area corresponding to a low absorption area on CT scan. The isotope-angiogram showed an area of very low isotope-filling corresponding to the low absorption area on CT scan while the isotope distribution to the hyperemic area was extremely fast and high. Comparing the CT scan and flow map, the hyperemic area was localized distant from the low absorption area but it seemed to merge with a borderzone hyperemia surrounding the ischemic lesion as seen in group I.

The localization of the lesions are shown in table 3. The hyperemia was absolute (85 ml/100 g/min). Autoregulation as well as CO₂ response were normal (table 2).

The hyperemia in this case is most likely due to recanalization of an occluded artery as in group II and III, therefore it is classified as post-ischemic hyperemia with persisting occlusion of (another) branch.

**Patients 13-16.** The CT scan was normal in the hyperemic areas in these 4. Cerebral angiography showed occlusions corresponding to the low absorption areas localized deep on CT scan. In the hyperemic areas the vascular tree was intact without occlusions. The isotope-angiogram showed areas of relatively low and delayed isotope-filling in all these patients, but the focal ischaemias were not as pronounced as in group I. The hyperemic areas also showed relatively high and fast isotope-filling but never so prominent as in group I, II and III.

Comparing the CT scan and flow map, the hyperemic areas were localized remote from and without any topographic relation to the low absorption areas. The localization of the lesions are shown in table 3 and figure 3, 6.

Autoregulation and CO₂ response were normal in one patient. “False” autoregulation with impaired CO₂ response was seen in one patient. In the remaining 2 CO₂ response was not tested. Autoregulation was apparently normal in one and “false” in another (table 2).

The pathophysiology in these 4 patients is not clear. They are denoted remote hyperemias.

**Discussion**

In this study initial slope index was used to calculate rCBF. This method of calculation presupposes that the semilogarithmic recorded clearance curves appear monoeXponential during the first minute of recording. In areas of focal cerebral hyperemia several curves showed a downward convex configuration during the first minute of recording. The basis for using the initial slope index is, therefore, no longer present. The steepness of the slope depends on the time interval used in calculation of the slope, i.e., the calculated blood flow will be higher if a shorter time interval is used. For this reason, the blood flow values presented in this study are minimum values of the true blood flow in the hyperemic areas and they should be considered as a semiquantitative manifestation of a high blood flow rather than as absolute figures.

An overabundant cerebral blood flow relative to the metabolic needs of the brain tissue has been denoted "the luxury perfusion syndrome" (Lassen, 1966) and
in several clinical studies this term has been used synonymous with focal cerebral hyperemia. In these studies, as well as in the present study, the existence of luxury perfusion in areas of cerebral hyperemia is not formally proved because reliable measurements of the arterio-venous oxygen deficit from these areas are generally not possible in studies of human stroke.

Luxury perfusion in areas of hyperemia in experimental stroke models is well established as the phenomenon of red veins associated with areas of experimental ischemia and post-ischemic hyperemia. The concept of luxury perfusion in the hyperemic areas has further been supported using positron emission tomography in the study of cerebral metabolism and rCBF in acute stroke. Despite the increased blood flow in the hyperemic areas the oxygen consumption was significantly decreased focally.

The incidence of focal cerebral hyperemia in acute stroke has hitherto been unknown because consecutive series of patients investigated within a well defined period of time have not been available. The incidence of focal cerebral hyperemia in non-consecutive series varies with the time from onset of stroke to the rCBF study. The incidence is high in series investigated early after onset of stroke. In the study of Christensen et al., 33% of patients investigated within 24 hours had hyperemia and in the study of Paulson 1970, 50% of patients investigated within 3 days after stroke had it. Focal cerebral hyperemia was found in only 10% of patients investigated within 2 and 16 months after onset of stroke by Uemura et al., and by Cronquist. Focal cerebral hyperemia must be considered as a common but transient phenomenon most frequently found in the acute phase of stroke. This conclusion from the data in the literature is confirmed in our consecutive early studies of patients in whom focal cerebral hyperemia was seen in 39%. The true incidence of hyperemia in our series is probably considerably higher. Infarcts involving the cortical surface as demonstrated on CT scan were consistently associated with areas of focal cerebral hyperemia — but infarcts localized in the deep grey and white structures were associated with focal cerebral hyperemia in only 4 of 25 patients (16%).

The result of rCBF measurements using the initial slope method are a manifestation of the fast flow component in the brain, i.e., the grey substance, and the absorption of radiation within cerebral tissues means that flow in the outer layers of cortex is recorded with the highest efficiency. The rCBF recorded is, therefore, mainly a manifestation of the blood flow in the lateral cortical mantle of the hemisphere. This is presumably the reason for the finding of focal cerebral hyperemia in all patients with cortical infarction and the much less frequent demonstration of focal cerebral hyperemia in association with infarction deep in the hemisphere.

Focal cerebral hyperemia seems to divide into 3 groups:

Borderzone Hyperemia. Areas of hyperemia surrounding ischemic areas.

Post-Ischemic Hyperemia. Hyperemic areas in brain tissue without arterial occlusion but localized to areas of infarction seen on CT scan, or to areas of marked capillary blush and early venous filling on cerebral angiography.

Remote Hyperemia. Hyperemic areas in apparently normal brain tissue, as revealed by CT scan and cerebral angiography, remote from an ischemic lesion.

Borderzone Hyperemia. Hyperemic areas adjacent to areas of ischemia are common findings in experimental models of acute focal cerebral ischemia. Such hyperemic areas have been examined histopathologically by Yamaguchi et al. Morphological changes were either absent or mild in the hyperemic areas indicating that areas of slightly impaired, as well as unimpaired, tissue can be found in the areas with borderzone hyperemia. This is presumably also the case in the borderzone hyperemic areas in our study as indicated by the varying degree of impaired vascular reactivity in these patients, ranging from areas of normal autoregulation to areas of impaired CO2 response and "false" autoregulation. These results suggest that borderzone hyperemic areas are threatened areas with a potential for survival.

Borderzone hyperemia is probably caused by a combination of several mechanisms. One is spread of acid metabolites from an ischemic region, suggested by Lassen and supported in experimental stroke models. The accumulation of acid metabolites results in vasodilatation and varying degree of vasomotor paresis depending on the degree of pH decrease. Another mechanism is the clearance of aggregates of blood elements formed earlier in small blood vessels, as demonstrated by Yamaguchi and Waltz 1971.

Borderzone hyperemia was found in all patients with areas of low absorption involving the cortical surface areas on CT scan. These are areas where borderzone hyperemia is detectible with the 254-detector
Remote Hyperemia. It is well known that there is a
global decrease of blood flow in brains suffering from
acute apoplexy. The finding of focal cerebral
hyperemia remote from the infarcted areas in 5
patients (Nos. 6, 13–16) is surprising and has to our
knowledge not been described previously in patients
with acute stroke.

Similar findings of remote hyperemias have been
reported in rCBF studies in patients with intracranial
tumors. The cause of remote hyperemia is difficult to
assess. The phenomenon was seen in only 5 of 35 patients
with low absorption areas on CT scan (14%). A great
deal of the brain is not seen with our equipment, par-
ticularly brain tissue near the skull and foramen
magnum and the opposite hemisphere. Remote
hyperemia could be transient and, perhaps, intermit-
tent, and its occurrence could be more common than
indicated in this study.

Mass displacement due to pressure gradients could
be responsible for the hyperemia in these patients.
Permanent or intermittent compression against un-
yielding anatomical structures might produce local
ischemia and hyperemia or in adjacent tissues because
of focal spread of acid metabolites. A mass effect
manifested by ventricular compression was present in
all the patients with remote hyperemia but it was also
found in several patients without remote hyperemia.

Possible Therapeutic Implications

The concept of the borderzone as a threatened area
with a potential to survive means that treatment of
brain infarcts should not be directed exclusively
toward ischemia, but toward the areas of hyperemia
as well.

Cerebral infarcts of more than 24 hours duration
are made up of 2 essentially different parts: one is
ischemic, the other hyperemic.

In stroke models, treatment (induced hypertension,
hyperventilation, barbituates, etc.) directed at the
ischemic part of the infarct is subject to strong
vasodilator stimuli (acid metabolites). Vasodilating
agents would be without much direct positive effect on
the infarcted areas. Indirectly vasodilatating agents
might, nevertheless, be of some benefit in 2 ways: 1)
The vasodilatation could produce a slight hypoten-
sion, reducing flow and edema production in the
hyperemic areas. 2) Vasodilatation in the surround-
ing normal brain tissue could further reduce the blood
flow in the hyperemia (and therefore also edema and
blood engorgement) because of “steal” from the
hyperemic to the surrounding normal brain tissue.
Therapy with vasoconstrictive agents might be harmful, as autoregulation is commonly impaired in the hyperemic areas. These agents would produce vasoconstriction only outside the hyperemic area resulting in "inverse steal" from the surrounding brain to the hyperemic area. An "inverse steal" might increase blood flow, blood engorgement and, therefore, also edema in the area of hyperemia.

References

Cerebral Extraction of N-13 Ammonia: Its Dependence on Cerebral Blood Flow and Capillary Permeability — Surface Area Product

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AND DAVID E. KUHL, M.D.

SUMMARY 'N-labeled ammonia was used to investigate 1) the cerebral extraction and clearance of ammonia, 2) the mechanism by which capillaries accommodate changes in cerebral blood flow (CBF) and 3) its use for the measurement of CBF. The unidirectional extraction of 'NH₃ in rhesus monkeys was measured during Paco₂-induced changes in CBF and dog studies were performed using in vitro tissue counting techniques to examine 'NH₃ extraction in gray and white matter, mixed tissue and cerebellum during variations in CBF produced by combinations of embolization, local brain compression, and changes in Paco₂. The single pass extraction fraction of 'NH₃ varied from about 70 to 20% over a CBF range of 12 to 140 cc/min/100 g. Capillary permeability-surface area product (PS) estimates with a Renkin/Crone model show PS increasing with CBF. The magnitude and rate of increase in PS with CBF was highest in gray matter > mixed tissue > white matter. Tissue extraction of 'NH₃ vs CBF relationship was best described by a unidirectional transport model in which CBF increases by both recruitment of capillaries and by increases of blood velocity in open capillaries. This saturable-recruitment model provides a possible explanation for the mechanism of flow changes at the capillary level. The net 'NH₃ extraction subsequent to an i.v. injection increases non-linearly with CBF. Doubling or halving basal CBF produced from 35 to 50% changes in the 'N tissue concentrations with further increases in CBF associated with progressively smaller changes in 'N concentrations.

Since it was originally proposed by Hunter et al.1-3 and Harper et al.'(N-13) ammonia (15NH₃) has been used as an imaging agent for the heart and brain with very little information available regarding what factors determine its tissue distribution. The rapid diffusion of 15NH₃ through cerebral 4 and myocardial5 capillaries and its rapid incorporation and trapping in the slowly turning over amino acid pools can potentially allow the use of this labeled substrate for imaging capillary perfusion, the study of the capillary flow mechanisms, or the study of ammonia and amino acid metabolism. However, due to the complexities involved in the extraction and retention of 15NH₃ in these organs, more extensive studies are required to better understand the potential uses of this tracer.

Phelps et al., using positron computed tomography (PCT) with normal volunteers, showed that the relative 15N concentrations in structures of the brain were in good agreement with the relative capillary densities and/or cerebral blood flow (CBF). Subsequently, Phelps et al.6 demonstrated in the monkey that the unidirectional extraction fraction of 15NH₃ by the brain was 1) less than 100% at normal values of CBF, 2) inversely related to CBF, 3) unaffected by blood ammonia concentrations from 80 to 1400 μg% and insensitive to changes in arterial blood pH over the range of 7.2 and 7.7, 4) decreased by about 24% during hypoglycemic coma and 5) was limited by capillary permeability. Intravenously injected 15NH₃ was proposed for estimation of capillary perfusion in brain and heart in analogy to the microsphere model with capillary occlusion by microspheres replaced by metabolic trapping of 15NH₄. *

Cooper et al.7 found that the brain ammonia pool

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