PET Studies of Changes in Cerebral Blood Flow and Oxygen Metabolism After Unilateral Microembolization of the Brain in Anesthetized Dogs

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Cerebral blood flow and oxygen metabolism have been measured with the steady-state oxygen-15 technique and positron emission tomography in anesthetized dogs. Regional microembolization was induced by infusing Sephadex particles (diameter, 40 μm) into one of the common carotid arteries. In the first series of experiments, 2.5 mg Sephadex was infused, and the dogs were examined within 3–4 hours after embolization. In a second series 0.55 mg Sephadex was infused, and the dogs were examined either in the first 3–4 hours or 24–48 hours after embolization. Cerebral blood flow, oxygen extraction ratio, and cerebral oxygen utilization were measured at 3 Pco2 levels. In the acute experiments, cerebral oxygen utilization in the embolized hemisphere was 6 (0.55 mg Sephadex) and 25% (2.5 mg Sephadex) lower than on the contralateral side. While cerebral blood flow was symmetrically distributed in normocapnia and hypocapnia, it was 9 (0.55 mg Sephadex) and 35% (2.5 mg Sephadex) lower in the embolized hemisphere during hypercapnia. In normocapnia and hypocapnia the lower oxygen utilization in the embolized hemisphere was characterized by a lower oxygen extraction ratio, and in hypercapnia by an unchanged (0.55 mg Sephadex) or by a higher (2.5 mg Sephadex) extraction ratio. The different effect on oxygen extraction ratio in the control and embolized hemispheres resulted in images of uncoupling between perfusion and oxygen demand that varied according to the Pco2. The experiments also showed a fall in cerebral blood flow in the embolized hemisphere after 3–4 hours, indicating delayed hypoperfusion. After 24–48 hours, blood flow was about 10% higher in the embolized hemisphere, and this was observed at the 3 Pco2 levels, while the oxygen extraction ratio was systematically lower. Oxygen utilization in the embolized hemisphere was depressed to practically the same extent as in acute experiments. It can be concluded that between 4 and 24 hours after microembolization the cerebral microcirculation shows important changes, with installation of luxury perfusion in the face of an unchanged decreased oxygen metabolism. (Stroke 1987;18:128-137)
FIGURE 1. Experimental procedures. There were 2 series of experiments: "severe" (Series I) and "mild" (Series II) embolization. In Series I there were control groups with sham-embolization and in Series II embolization was performed either acutely or 24-48 hours before the measurements.

As depicted in Figure 1, 4 groups of experiments were performed, each consisting of 6 dogs — 2 groups with sham embolization and 2 other groups with microsphere embolization. The first CBF measurement \( N_1 \) was made 30 minutes after \( P_{CO_2} \) had returned to normal following embolization, and the final CBF measurement \( N_2 \) also was performed in normocapnia about 3 hours later. In the time between those 2 normocapnic CBF measurements, \( P_{CO_2} \) was either increased to about 55 mm Hg (by substitution of 6% \( CO_2 \) for \( O_2 \) in the gas mixture and adjusting tidal volume) or decreased to about 25 mm Hg (by adjusting tidal volume). CBF was measured at the beginning \( H_1 \) and at the end \( H_2 \) of the hypercapnic or hypocapnic period. The \( H_1 \) measurement was followed by a \(^{15}O_2\) scan to assess oxidative metabolism in hyper- or hypocapnia. At the end of the experiment, the animals were sacrificed by i.v. injection of saturated KCl solution.

**Series II: Mild Embolization**

**GROUP I: ACUTE EXPERIMENTS.** Eight dogs were instrumentally prepared as described above except that regional cerebral infarction was produced by infusing 0.55 mg Sephadex particles. After embolization, repetitive \(^{13}C\)O and \(^{15}O_2\) scans were obtained at 3 differ-
ent PCO₂ levels, each level being maintained for 60–70 minutes as illustrated in the lower part of Figure 1.

Group 2: 24–48 Hour Experiments. The experiments were performed on 8 dogs that had been embolized 24 or 48 hours previously. After anesthesia and installing artificial ventilation similar to that in the other experiments, polyethylene tubing was inserted into the left thyroid artery and 0.55 mg Sephadex particles was infused. Surgical wounds were closed and antibiotics given. The procedure lasted 45–60 minutes. After recovery from anesthesia, all dogs were conscious but had neurological deficits. Most frequently we observed tonic deviation of the head and circling movements. Of the 8 dogs showed paresis of the lower extremities. After 24 hours (4 dogs) or 48 hours (4 dogs), anesthesia was again induced with xylazine and pentobarbital (xylazine was reduced to 1.0 mg/kg). Further procedures were as described for the acute experiments.

Measurement of CBF, OER, and CMRO₂

The procedures were essentially similar to those described by Frackowiak et al., with some modifications. All measurements were made using a Neuro-Ecat PET scanner (EG&G Ortec, Oak Ridge, Tenn.) equipped with 2 rings of detectors and with lateral and axial resolution of 8.1 mm and 14.0 mm respectively. Distance between the centers of the 2 detector rings is 32 mm. The scanner was previously calibrated to accurately measure in vivo concentrations of positron-emitting isotopes. Phantom studies on a dog skull with a radioactivity concentration varying between 40 and 0.5 μCi/ml at the time of the measurement proved good calibration and excellent recovery in each slice when the skull was positioned as in the actual experiments. The sensitivity was linear up to an activity concentration of 12 μCi/ml, which is well above that encountered during actual experiments.

The head was positioned to allow the accumulation of data from 2 coronal slices, with their centers 3 and 35 mm anterior to the intermeatal line and which were perpendicular to the orbito–meatal line. Thereafter, a transmission scan was performed with an external germanium-68 ring source to measure photon attenuation and to correct the subsequent emission scans.

C₁⁵O₂ scan. To measure CBF, C₁⁵O₂ was added to the inhalation gas mixture at the inlet of the ventilation pump at a rate of 30 μCi/min. After 9 minutes of equilibration, the radioactivity in the head was scanned during 250 seconds. Two arterial blood samples were obtained anaerobically at the beginning and at the end of the scan. To measure radioactivity concentration, 8–10 drops of blood were transferred into tared tubes containing liquid paraffin. The volume of blood added was calculated by difference in weight, assuming a density of 1.05 mg/ml blood. Radioactivity was measured in a well-type 3-inch Nal-Tl crystal coupled to a rate counter (Canberra, Meridon, Conn.) that was cross-calibrated with the PET scanner. The difference in radioactivity concentration between the 2 blood samples was usually <4%; if it was >8% the scan was repeated. In our experimental conditions—adapted for studies in laboratory animals—radioactivity concentration in arterial blood in vivo was about 8.5 μCi/ml, and usually 3 million true coincidence counts were obtained in each slice. Blood flow was computed pixel-by-pixel according to the formula

\[
\text{CBF (ml/100 ml/min)} = \frac{100 \lambda}{(C_f/C_p) - A}
\]

where \(C_f = \) arterial radioactivity concentration (mean of 2 samples), \(C_t = \) tissue radioactivity concentration in a particular pixel (pixel size was 2.77 mm), \(\lambda = \) radioactive decay constant for oxygen-15 (0.338/min). Measurement of CBF with \(^{13}\text{O}_2\) requires knowledge of the extraction of \(^{15}\text{O}_2\) and its partition coefficient between brain tissue and blood. In this formula a partition coefficient of 1 ml/ml is assumed as well as complete extraction of water (see "Discussion").

From these "pixel blood flows," CBF was calculated in 4 elliptical regions of interest, 2 in each plane, that were essentially hemispheric (surface 3.93 and 2.39 cm² in posterior and anterior plane respectively). Since they were not systematically different from each other, CBF values in the 2 planes were combined.

\(^{15}\text{O}_2\) scan. To measure OER, \(^{15}\text{O}_2\) was inhaled at a rate of 45 μCi/min, and similar procedures were used as described above except that scan time was extended to 400 seconds and plasma was obtained by centrifugation at 9,000g for 2 minutes. To measure radioactivity, about 0.5 ml plasma was transferred into tared tubes with paraffin, and the volume was calculated by assuming a density of 1.03 mg/ml plasma. Radioactivity concentrations in blood and plasma were about 4.0 and 0.8 μCi/ml respectively, and usually ca. 1.5 million true coincidence counts were collected per slice. OER was computed pixel-by-pixel according to the formula

\[
\text{OER} = \frac{(C_f/C_p) - A}{(C_f/C_p) - A}
\]

where \(C_f = \) activity concentration in blood during \(^{14}\text{O}_2\), \(C_t = \) activity concentration in brain during \(^{14}\text{O}_2\), \(C_p = \) activity concentration in blood during \(^{15}\text{O}_2\), \(C_p = \) activity concentration in plasma during \(^{15}\text{O}_2\), \(A = \) activity concentration in blood to that in plasma during \(^{14}\text{O}_2\) inhalation. The value for A for human blood can be calculated from the hematocrit (Hct) according to the formula A = 1 – 0.245 Hct. In dogs we found excellent agreement between directly measured and calculated values for A. In 16 experiments where A was measured and calculated the greatest difference was 2.66%, and in 12 of these the difference was <1%.

Measurement of OER requires knowledge of intravascular radioactivity within each pixel. In this formula, however, the contribution of intravascular radioactivity is neglected (see "Discussion"). From
these "pixel OER's," mean hemispheric OER was calculated.

CMRO$_2$. Hemispheric CMRO$_2$ (ml/100 ml/min) was calculated according to the equation CMRO$_2$ = CBF x OER x CaO$_2$ where CaO$_2$ = arterial oxygen content. Because in our experiments PaO$_2$ varied between 120 and 170 mm Hg, oxygen saturation should be almost 100%, and CaO$_2$ is approximated by the equation CaO$_2$ = 1.34 x Hb, where Hb is the hemoglobin concentration.

Chemical Analysis

pH, Po$_2$, and PcO$_2$ were measured in arterial blood samples with specific electrodes (Radiometer, Copenhagen, Denmark). Hct was measured by centrifugation of blood for 5 minutes at 11,000g in capillary tubes. Hb was measured with the cyanohemoglobin method.

Statistical Analysis

Significance was determined by $t$ test for paired (within each group) or unpaired (between different groups) values. Probability ($p$) values <0.05 were considered significant.

Results

Series I — Severe Embolization

Results in sham-embolized animals (Groups 1 and 2) are represented in Figure 2. In these animals hemispheric blood flow never showed a left-right (L-R) difference. In Group 1 (Figure 2 A) hemispheric blood flow was 23.2 ml/100 ml/min in normocapnia (mean of L and R values) and increased ($p<0.001$) to 45.9 (H$_1$) and 39.5 (H$_2$) in hypercapnia. The difference between H$_1$ and H$_2$ is significant ($p<0.01$). The hypercapnic response between N$_1$ and H$_1$ was 0.98 ml/100 ml/min/mm Hg. On return to normocapnia, CBF decreased to 23.7, which is statistically not different from the initial value. OER and CMRO$_2$ were also symmetrical, with values in hypercapnia of 33.0% and 2.98 ml/100 ml/min respectively (Figure 2 C and D).

In Group 2, normocapnic CBF was 22.7 ml/100 ml/min, decreased ($p<0.001$) to 19.1 (H$_1$) and 17.0 (H$_2$) in hypocapnia, and again increased to 19.9 on return to normocapnia. Although the H$_1$ and N$_1$ values are both about 2 ml/100 ml/min lower than their corresponding preceding value, the differences are not significant (Figure 2 B). In hypoxemia OER and CMRO$_2$...
were 72.6\% and 2.93 ml/100 ml/min respectively (Figure 2 C and D).

The results in embolized animals (Groups 3 and 4) are represented in Figure 3.

In spite of unilateral embolization there was no L–R difference in hemispheric blood flow at N\(_1\) during normocapnia. In Group 3 CBF was 24.5 ml/100 ml/min. The effect of hypercapnia was very different in the 2 hemispheres (Figure 3 A). In the control hemisphere\(^*\) CBF increased \((p<0.001)\) to 44.7 (H\(_1\)) and 43.6 (H\(_2\)) ml/100 ml/min (difference not significant). The hypercapnic response between N\(_1\) and H\(_1\) was 0.88 ml/100 ml/min/mm Hg. These values were practically identical to the corresponding values in sham-embolized animals. In the embolized hemisphere CBF increased \((p<0.01)\) only to 29.1 (H\(_3\)) and 26.6 (H\(_4\)) ml/100 ml/min (difference not significant). The hypercapnic response between N\(_1\) and H\(_1\) was only 0.19 ml/100 ml/min/mm Hg. The difference in CBF between the 2 hemispheres during hypercapnia is significant \((p<0.001)\), with ratios of 0.65 (H\(_1\)) and 0.62 (H\(_2\)). On return to normocapnia, CBF in the control hemisphere decreased \((p<0.001)\) to 23.2 ml/100 ml/min, which was similar to the N\(_1\) value. In the embolized hemisphere, CBF decreased \((p<0.001)\) to 19.9 ml/100 ml/min. The L–R difference (ratio 0.86) is significant \((p<0.001)\). This asymmetrical blood flow at N\(_1\) and the decrease in ratio between H\(_1\) and H\(_2\) \((p<0.05)\) indicate delayed hypoperfusion in the embolized hemisphere.

Marked L–R differences were also observed in CMRO\(_2\) and OER (Figure 3 C and D). In hypercapnia OER was 16\% higher in the embolized than in the control hemisphere \((p<0.001)\). The higher OER, however, only partially compensated for the lower CBF, and CMR\(_O_2\) was 26\% lower in the embolized than in the control hemisphere.

In Group 4 CBF in normocapnia (N\(_4\)) was 31.6 ml/100 ml/min (Figure 3 B). We have no explanation for the higher CBF's in this group, where subsequent values in hypocapnia were also somewhat higher than in Group 2. Hypocapnia, in contrast to hypercapnia, had practically the same effect in the 2 hemispheres. CBF decreased \((p<0.001)\) to about 21 (H\(_4\)) and 19 (H\(_4\)) ml/100 ml/min (difference not significant). At both times there was no significant L–R difference, but the slight decrease in ratio (from 1.03 to 0.97) was

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*Author's Note: In this paper "control hemisphere" refers to the right hemisphere. Although the Sephadex particles were injected into the left CCA the right hemisphere is not necessarily normal. Due to the unusual arterial anastomotic arrangement in dogs, some particles probably are going to this hemisphere. However, because the values for CBF and CMRO\(_2\) in this hemisphere are very similar to those in nonembolized animals its degree of embolization is probably small.
Results of Series II, acute experiments (Group I).

A: Hemispheric CBF. B: Hemispheric OER. C: Hemispheric CMRO₂.

(L = left, embolized hemisphere; R = right, control hemisphere). Left, middle, and right pair of columns in each panel refer to values obtained in normocapnia, hypercapnia, and hypocapnia with respective P_CO₂'s of 36 ± 1.0, 63 ± 1.9, and 22 ± 0.9 mm Hg. The hemispheric ratio (L/R) is indicated below each pair of columns. All values are mean ± SEM.

significant (p < 0.05). On return to normocapnia, CBF in the control hemisphere increased (p < 0.001) to 22.5 ml/100 ml/min. In the embolized hemisphere it merely increased (not significantly) to 20.0 ml/100 ml/min. The L-R difference was significant (p < 0.01). The fall in ratio between H₁ and H₂, the asymmetrical blood flow at N₂, and the failure of CBF to increase on transition from hypo- to normocapnia again indicate delayed hypoperfusion in the embolized hemisphere.

Cerebral OER and CMRO₂ also showed marked L-R differences (Figure 3 C and D). In hypocapnia, when CBF was practically identical in both hemispheres, CMRO₂ and OER were respectively 21 and 22% lower in the embolized than in the control hemisphere.

Series II — Mild Embolization

In general, CBF shows the classical P_CO₂ response, and CMRO₂ is practically independent of P_CO₂. As a result, OER decreases in hypercapnia and increases in hypocapnia. In normocapnia and in hypocapnia there were no significant L-R differences in hemispheric blood flow, with levels at about 19 and 16 ml/100 ml/min respectively. In hypercapnia CBF was 9% lower in the embolized than in the control hemisphere (p < 0.01). The CBF responses to hypercapnia in the control and in the infarcted hemisphere were 1.41 ± 0.245 and 1.37 ± 0.153 ml/100 ml/min/mm Hg respectively (mean ± SD, p < 0.01) (Figure 4 A). In general, CBF and CMRO₂ values were somewhat higher in the acute experiments, but the differences in CMRO₂ were not significant. At each of the 3 P_CO₂ levels, CBF was between 7 and 12% higher in the embolized hemisphere than in the control hemisphere (p at least < 0.01). On the other hand, OER (p < 0.001) and CMRO₂ (p at least < 0.05) were lower in the embolized hemisphere, the differences being between 11 and 19 and between 5 and 9%, respectively (Figure 5 B and C).

Discussion

In the above-described experiments we measured CBF, OER, and CMRO₂ in dogs with acute regional microembolization of the brain. Two doses of microembolization were used; with mild microembolization the mortality rate was 0, and the animals were also studied 1 or 2 days after embolization.

The experiments indicate that microembolization 1) immediately induces relative luxury perfusion, which in the course of 3 hours is followed by a delayed hypoperfusion; 2) decreases hemodynamic reserve in acute hypercapnia; 3) does not affect the hypocapnic CBF response; 4) causes a dose-dependent decrease in the CMRO₂; and 5) produces luxury perfusion after 24—48 hours with restoration of the hemodynamic reserve. However, before discussing the pathophysiological aspects of the experiments, the method and procedures used need comment.

Comments on Methods and Experimental Model

The theoretical principles of the steady-state oxygen-15 technique as well as its potential inaccura-
ties are well documented. Using this technique we found a CBF value in nonembolized animals of 23 ml/100 ml/min (Paco₂ = 33 mm Hg) with an increase to 46 ml/100 ml/min in hypercapnia (Paco₂ = 56 mm Hg) and a decrease to 19 ml/100 ml/min in hypocapnia (Paco₂ = 27 mm Hg). CMRO₂ was independent of Paco₂ and amounted to 2.95 ml/100 ml/min. As a result, OER was inversely related to Paco₂ with a value of 73% in hypocapnia and 33% in hypercapnia. We have no normocapnic OER measurement in nonembolized animals, but with mild embolization OER is about 70% in the control hemisphere.

The absolute values thus obtained suffer to a certain degree from a number of instrument- and model-related limitations.

1. The CBF measurement requires knowledge of the extraction of H₂¹⁵O and its partition coefficient between brain and blood. By assuming unlimited diffusion of H₂¹⁵O, as we did, true CBF is underestimated, although for practical use the effect is usually ignored. The C¹⁵O₂ technique also is sensitive to error in the partition coefficient, especially at higher flow rates. The correct value of the partition coefficient is a matter of debate, and although individual variations occur in the function of Hct, a standard value is usually accepted. We accepted a value of 1 ml blood/ml brain.

2. The C¹⁵O₂ model itself predicts a systematic CBF underestimation in areas with mixed gray and white matter because blood flow varies as a nonlinear, in fact a concave, function of the radioactivity concentration in the brain. In view of the size of the dog's brain, e.g., the thickness of its cortex (approx 2.5 mm) and the resolution of the Neuro-Ecat PET scanner, most of the pixel values will actually represent a weighted average of radioactivities in purely white and purely gray matter, which does not correspond to a weighted average of flow. It has been argued that the ensuing underestimation of CBF is at maximum 20% for the affected pixels.

3. We did not correct the ¹⁵O scan for cerebral blood volume, which would require an additional CO scan for each Paco₂ level and would strongly interfere with our experimental setup. Omitting such correction leads to a systematic overestimation of OER. In normal humans corrected OER is about 10% less than uncorrected OER. That difference increases with increasing cerebral blood volume and with arterial hyperoxia, and therefore in our experiments may exceed 10%.

It can be concluded that we probably underestimated CBF and overestimated OER. It should be noted, however, that the main aim of our study was to investigate differential changes. The degree of CBF underestimation was assessed in a series of 7 dogs by simultaneously measuring CBF with the C¹⁵O₂ inhalation technique and with the labelled microspheres technique. Using microspheres with a mean diameter of 15 μm (New England Nuclear, Boston, Mass.), CBF was 34.0 ± 15.1 ml/100 g/min compared with 25.6 ± 3.9 ml/100 ml/min with the C¹⁵O₂ method (mean ± SD). In baboons, however, comparable values were reported with both methods. Our divergent results can perhaps be attributed to species differences or to the difference in technique, since in the baboon experiments the microspheres in the brain were not measured according to the standard technique but with a PET technique.

In a recent study in which CBF and oxygen metabolism in dogs were measured with the oxygen-15 technique, normocapnic values for CBF and OER were 40 ml/100 ml/min and 50% respectively. Using microspheres with a mean diameter of 15 μm, CBF was 34.0 ± 15.1 ml/100 g/min compared with 25.6 ± 3.9 ml/100 ml/min with the C¹⁵O₂ method (mean ± SD). In baboons, however, comparable values were reported with both methods. Our divergent results can perhaps be attributed to species differences or to the difference in technique, since in the baboon experiments the microspheres in the brain were not measured according to the standard technique but with a PET technique.
which illustrates the reliability of the oxygen-15 method for studying the effect of ischemia in experimental animals. In our comparative study mentioned above, the oxygen-15 technique for CBF measurement appeared to have an even greater precision than the microsphere technique (coefficients of variation of 15 and 44%, respectively).

In our experiments ischemia was induced by means of regional microembolization, the pathophysiology of which differs fundamentally from that of other forms of ischemia, and therefore is perhaps less relevant to the clinical condition.19 The number of particles entering the brain was increased by raising PCO₂ during the embolization. Orientation experiments in which radioactive particles (carbonized plastic, mean diameter 15 μm, New England Nuclear, Boston, Mass.) were infused into the CCA have indeed indicated that the ratio of microsphere distribution between the ipsilateral hemisphere and the ipsilateral masseter muscle was 20–30 times higher in hypercapnia than in normocapnia. Using this procedure the effects of microembolization on CBF and OER were very reproducible; indeed, the scatter of the results is comparable in the embolized and in the control hemisphere. Such reproducibility is in contrast to most other experimental models of ischemia and is an advantage when different groups are compared.

**Effects on CBF**

The 2 series of experiments clearly indicate that in the acute phase after microembolization, CBF in the infarcted hemisphere remains practically unchanged in comparison with the control hemisphere, unless hypercapnia is induced. This finding suggests that this form of microembolization immediately induces dilation of nonoccluded vessels. This reactive dilation was also observed in cats that were embolized with plastic microspheres (diameter, 15 μm) — even in amounts that caused brain death within a few hours.20 Although dilation of nonoccluded vessels allows for a normal overall blood flow in normocapnia and in hypocapnia, it no longer allows a complete adaptation in hypercapnia, which indicates decreased hemodynamic reserve after embolization. The decrease is dose-dependent and amounts to 35 (ratio 0.65) and 9% (ratio 0.91) with severe and mild embolization, respectively. Unilateral occlusion of the CCA in rats also does not affect hemispheric CBF in normocapnia but has a profound effect in hypercapnia.21

In the different groups of animals of Series I, CBF decreased somewhat with time, and the N₂ and H₂ values were usually lower than their corresponding previous values. In the embolized animals, however, the decrease with time is more marked in the embolized than in the control hemisphere. In both groups with microembolization, CBF at the end of the experiment and in normocapnia (N₂) was 12–14% lower in the embolized hemisphere than in the control hemisphere. This asymmetrical blood flow was at variance with the situation at the onset of the experiments and does not occur in the sham-embolized animals. In the embolized animals there is a slight decrease in hemispheric ratio between H₂ and H₄ that is not observed in the nonembolized animals and that also indicates decrease of CBF in the embolized hemisphere with time. This delayed hypoperfusion can result from ischemic brain edema developing around the occluded vessels or from further metabolic depression as a result of ischemic neuronal damage.

The experiments of Series II indicate that 1 and 2 days after embolization, the hemispheric CBF was significantly higher in the embolized than in the control hemisphere, indicating hyperperfusion in the embolized hemisphere. The fact that the hypercapnic response of CBF, which was depressed in the acute phase, now attains the same value in both hemispheres is also remarkable. Concerning the mechanism of the hyperperfusion and restoration of hemodynamic reserve we can merely speculate. Obviously there must be a compensation for the intravascular obstruction leading to a decrease of the vascular resistance and to an increase of the local perfusion pressure, e.g., by dilation of collateral channels.

**Effects on CMRO₂**

As expected and also observed by Rhodes et al8 CMRO₂ in nonembolized dogs is practically independent of acute changes in PCO₂, and a rise in CBF is characterized by a fall in OER. The present work extends this observation to infarcted brain tissue.

In our experiments unilateral embolization induced a dose-related interhemispheric difference in CMRO₂. In the acute experiments with mild embolization, CMRO₂ is 6% lower in the infarcted than in the control hemisphere, and with severe embolization this difference increases to 15%. The experiments falsely suggest that a 6% decrease in CMRO₂ produces neurological deficits, which were indeed observed when the animals recovered from anesthesia. In clinical studies with stroke patients, CMRO₂ in the infarcted region is usually >30% lower than on the contralateral side.22,23

The smaller figure in the present experiments, which might suggest a lower CMRO₂ threshold to induce necrosis, is probably due to the special nature of embolization (which in contrast to clinical stroke induces multifocal small infarcts) and/or to the effect of anesthesia (which decreases the difference in CMRO₂ between normal and infarcted brain tissue). A decrease of CMRO₂ in the other hemisphere due to contralateral embolization is another possibility, although less probable, since CMRO₂ in the contralateral hemisphere attains practically the same value as in nonembolized animals. On the other hand, the true difference in CMRO₂ could be underestimated due to methodological limitations. Because of the small size of the dog's brain relative to the resolution of the scanner, the region examined was essentially hemispheric and therefore hardly limited to the infarct. Moreover, we accepted a similar value in normal and infarcted brain for the extraction of water, its partition coefficient, and for the regional blood volume (which in both conditions was accepted to be 0). In this regard it has been demon-
strated that the overestimation of OER increases with decreasing OER\textsuperscript{10}; therefore in our experiments the true difference in OER between the 2 hemispheres was certainly greater than the measured difference. Although the importance of such factors is difficult to quantify, it can be concluded that the decrease of CMRO\textsubscript{2} in the infarcted region is probably more important than indicated by the measured hemispheric values, and that the CMRO\textsubscript{2} threshold is thus greater than 6%.

In the second series of experiments, the mean values for CMRO\textsubscript{2} are somewhat higher in Group 2 (24–48 hours) than in Group 1 with acute embolization. The difference is not significant, and we concluded that CMRO\textsubscript{2} remained unchanged.

**Effects on OER and Coupling Between CBF and Metabolism**

The experiments indicate that OER decreases in hypercapnia and increases in hypocapnia in the infarcted as well as in the contralateral hemisphere although with a L–R difference. This difference is not constant and varies according to the experimental conditions, especially PCO\textsubscript{2} and time, indicating changes in the coupling between CBF and metabolism.

In the early phase after embolization and in normocapnia, OER is lower in the infarcted than in the control hemisphere — with mild embolization the measured difference amounts to 8%. The lower OER goes hand-in-hand with the lower CMRO\textsubscript{2} because CBF is the same in the 2 hemispheres. Although we have not measured OER in normocapnia after severe embolization, there is indirect evidence that the interhemispheric difference was between 20 and 25%. Indeed, CBF was the same in both hemispheres, and the difference in CMRO\textsubscript{2} as it was measured in hypocapnia and in hypercapnia was between 20 and 25%. The lower OER in the infarcted hemisphere is in agreement with the experiments of Vise et al\textsuperscript{20} who described cerebrovenous hyperoxia upon microembolization in normocapnic cats. Both our study and that of Vise et al indicate relative luxury perfusion in the embolized hemisphere, which is in contrast to usual clinical findings. Results of PET studies with oxygen-15 in cerebral ischemia in man were recently reviewed by Frackowiak.\textsuperscript{21} From these clinical studies, it appears that "misery perfusion"\textsuperscript{22} with low CBF and high OER is the usual finding in the first hours after clinical stroke.\textsuperscript{23,24} Thereafter, relative luxury perfusion with low OER and CBF becomes the usual finding,\textsuperscript{22} and on rare occasions a focal increase of OER persists beyond the first hours after stroke.\textsuperscript{25} In our experimental conditions we did not observe a lower CBF in the infarcted hemisphere. The differential effects of clinical stroke and microembolization have been previously stressed by Hossmann.\textsuperscript{19}

On transition from normocapnia to hypocapnia, CBF decreased to the same extent in both hemispheres with severe as well as with mild embolization. As a result, the condition of relative luxury perfusion with lower OER in the infarcted hemisphere was main-
tained. The measured difference was 22 and 8% in severe and mild embolization respectively. On transition from normocapnia to hypercapnia, the increase in CBF in the infarcted hemisphere was markedly attenuated, which resulted in an important interhemispheric flow difference. With mild embolization this interhemispheric difference in CBF practically matches the difference in CMRO\textsubscript{2}. Thus the interhemispheric difference in OER during hypercapnia was not significant (ratio 1.04). However, with severe embolization there was practically no rise of CBF in the infarcted hemisphere, so that the interhemispheric difference in CBF largely exceeded that in CMRO\textsubscript{2}. There was therefore a higher OER in the infarcted hemisphere, with a hemispheric ratio of 1.16. It can be concluded that with an increase in PCO\textsubscript{2} the relative OER in the embolized hemisphere increases from a value of <1 in normocapnia to about 1 after mild embolization, and to a value of >1 after severe embolization. In the clinical literature the condition of such focally higher OER concomitant with a lower CBF has been defined as the "misery-perfusion syndrome."\textsuperscript{23} In our experiments (according to this concept) there exists a "misery perfusion" pattern during hypercapnia in the embolized hemisphere after severe embolization. We should stress, however, the limited significance of this concept in our conditions because in hypercapnia CBF in the infarcted hemisphere is higher than in normocapnia.

In accordance with the different effects on CBF, the effects on OER 24 and 48 hours after embolization also were very different from those in the first hours. Since at each PCO\textsubscript{2} level CBF was about 10% higher in the embolized hemisphere, OER was systematically lower in the hemispheres than in the control hemisphere. The relative luxury perfusion in the infarcted hemisphere in normocapnic dogs thus progressively shifts into an absolute luxury perfusion within the first 24 hours after microembolization.

In conclusion: The experiments show that the effects of microembolization on cerebral blood flow and metabolism, as realized with the methods described, are very reproducible and dose-dependent. When PCO\textsubscript{2} is changed, there are marked differences in CBF and OER responses between the control and the embolized hemisphere, giving varying images for uncoupling between perfusion and oxygen demand. The chronic experiments indicate that when measured 24 hours after microembolization, CBF was higher than immediately following microembolization, but that CMRO\textsubscript{2} remained practically unchanged.

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