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)

IN ACUTE stroke disease, measurements of changes in cerebral blood flow (CBF) alone have only a limited prognostic value; their clinical significance increases when they are analyzed in the context of metabolic alterations.1,2 The introduction of positron emission tomography (PET) represents a significant methodological advance because it allows accurate measurement of tissue radioisotope distribution in vivo, analogous to postmortem autoradiography in animals. Several radiopharmaceuticals are proposed to study CBF and cerebral energy metabolism with PET.3 Among those, the steady-state oxygen-15 inhalation technique elaborated by Frackowiak et al4 (following early work by Jones et al5) has the dual advantage of being relatively simple and allowing assessment of both CBF and oxygen extraction ratio (OER) with practically the same procedure.

Clinical studies show a high variability in changes of CBF and cerebral metabolism in ischemia. Most experimental models also suffer from a considerable variability in the severity of ischemia.6 In the present study we have measured CBF and cerebral oxygen metabolism with the steady-state oxygen-15 technique in experimental animals after cerebral microembolization, which induced very reproducible and dose-dependent effects. Our aim therefore was 1) to assess the possibilities of the steady-state oxygen-15 technique in animals with standardized experimental cerebral ischemia; 2) to investigate the early changes in CBF and cerebral metabolic rate of oxygen (CMRO2) in this particular type of ischemia; 3) to study the influence of changes in Pco2 on these parameters; and 4) to compare the acute effects with the situation 24–48 hours later.

Materials and Methods

The experiments were performed on anesthetized and artificially ventilated mongrel dogs of both sexes with body weights between 16 and 29 kg. There were 2 series of experiments, the experimental designs of which are depicted in Figure 1.

Series I: Acute Experiments with Severe Embolization

Anesthesia was induced with i.m. injection of xylazine (Rompun, 1.5 mg/kg) followed by i.v. injection of pentobarbital (10 mg/kg) 15 minutes later. After
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**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 (N₁) was made 30 minutes after Pco₂ had returned to normal following embolization, and the final CBF measurement (N₂) also was performed in normocapnia about 3 hours later. In the time between those 2 normocapnic CBF measurements, Paco₂ was either increased to about 55 mm Hg (by substitution of 6% CO₂ for O₂ 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 (H₁) and at the end (H₂) of the hypercapnic or hypocapnic period. The H₁ measurement was followed by a ¹⁵ O₂ scan to assess oxidative metabolism in hyper- or hypocapnia.

The experimental procedures involved the induction of cerebral ischemia in both series. In Series I, the ischemia was induced by infusing 2.5 mg Sephadex G 25 particles into the left CCA. In Series II, regional cerebral ischemia was induced by infusing 0.55 mg Sephadex particles into the left CCA. After embolization, repetitive C¹⁵O₂ and ¹⁵O₂ 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 embo-
223 lized 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. Three 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 the cranial cavity filled with Na14CO3 solutions 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 NaI-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

\[
\text{CBF (ml/100 ml/min)} = \frac{100 \cdot \lambda}{(C'_c/C'_p) - 1} \]

where \(C'_c\) = arterial radioactivity concentration (mean of 2 samples), \(C'_t\) = tissue radioactivity concentration in a particular pixel (pixel size was 2.77 mm), \(\lambda\) = radiative decay constant for oxygen-15 (0.338/min). Measurement of CBF with H218O requires knowledge of the extraction of H218O and its partition coefficient between brain tissue and blood. In this formula a partition coefficient of 1.0 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.

**18O SCAN.** To measure OER, C15O2 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

\[
\text{OER} = \left(\frac{C'_c}{C'_p}\right) \times \left(\frac{C'_c}{C'_p} - A\right) \left(\frac{C'_c}{C'_p} - A\right) \]

where \(C'_c\) = activity concentration in blood during C15O2, \(C'_c\) = activity concentration in brain during C15O2, \(C'_c\) = activity concentration in blood during H218O, \(C'_c\) = activity concentration in plasma during H218O, \(C'_c\) = activity concentration in brain during H218O, \(A\) = ratio of activity concentration in blood to that in plasma during C15O2 inhalation. The value for A for human blood can be calculated from the hematocrit (Hct) according to the formula A = 1 – 0.245 Hct.1 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.5–10 In this formula, however, the contribution of intravascular radioactivity is neglected (see “Discussion”). From
these "pixel OER's," mean hemispheric OER was calculated.

CMRO2. Hemispheric CMRO2 (ml/100 ml/min) was calculated according to the equation CMRO2 = CBF x OER x CaO2, where CaO2 = arterial oxygen content. Because in our experiments PaO2 varied between 120 and 170 mm Hg, oxygen saturation should be almost 100%, and CaO2 is approximated by the equation CaO2 = 1.34 x Hb, where Hb is the hemoglobin concentration.

Chemical Analysis
pH, Po2, and Pco2 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 (H1) and 39.5 (H2) in hypercapnia. The difference between H1 and H2 is significant (p<0.01). The hypercapnic response between N, and H, 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 CMRO2 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 (H1) and 17.0 (H2) in hypocapnia, and again increased to 19.9 on return to normocapnia. Although the H2 and N2 values are both about 2 ml/100 ml/min lower than their corresponding preceding value, the differences are not significant (Figure 2 B). In hypocapnia OER and CMRO2 were also symmetrical, with values in hypercapnia of 33.0% and 2.98 ml/100 ml/min respectively (Figure 2 C and D).

FIGURE 2. Results of Series I, sham-embolized dogs (Groups 1 and 2). A and B: Hemispheric blood flow in Group 1 (A) and 2 (B). (——) left (L) hemisphere; (-----) right (R) hemisphere. N1 and N2 are values obtained in normocapnia (Paco2: 33 ± 0.9 mm Hg); H1 and H2 were obtained in hypercapnia (A, Paco2: 56 ± 1.9 mm Hg) or hypocapnia (B, Paco2: 27 ± 1.0 mm Hg). Values for the hemispheric ratio of blood flow (CBF L/CBF R) at the 4 points in time are also indicated. C: OER in the L and R hemispheres. Values for the hemispheric ratio (L/R) of OER are also given. D: CMRO2 in the L and R hemispheres. Values for the hemispheric ratio (L/R) of CMRO2 are also given. All values are mean ± SEM.
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 N1 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 (H1) and 43.6 (H2) ml/100 ml/min (difference not significant). The hypercapnic response between N1 and H1 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 (H1) and 26.6 (H2) ml/100 ml/min (difference not significant). The hypercapnic response between N1 and H1 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 (H1) and 0.62 (H2). 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 N1 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 N2 and the decrease in ratio between H1 and H2 (p < 0.05) indicate delayed hypoperfusion in the embolized hemisphere.

Marked L–R differences were also observed in CMRO2 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 CMRO2 was 26% lower in the embolized than in the control hemisphere.

In Group 4 CBF in normocapnia (N1) 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 (H1) and 19 (H2) 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
FIGURE 4. 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 Pacos 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.

**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 CMR02; and 5) produces luxury perfusion after 24–48 hours with restoration of the hemodynamic reserve. However, before discussing the pathophysiologic 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-
FIGURE 5. Results of Series II, 24-48 hour experiments (Group 2). See legend to Figure 4, except the respective Paco2's were 34 ± 1.8, 60 ± 3.1, and 21 ± 1.1 mm Hg.

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.4 The C15O2 technique also is sensitive to error in the partition coefficient, especially at higher flow rates.13 The correct value of the partition coefficient is a matter of debate, and although individual variations occur in the function of Hct, it is usually accepted. We accepted a value of 1 ml blood/ml brain.4

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.13 In view of the size of the dog's brain, e.g., the thickness of its cortex (approx 2.5 mm)13 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.13

3. We did not correct the 15O2 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 volume6,10 and with arterial hyperoxia,10 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.16 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 ± 3.91 ml/100 ml/min with the C15O2 method (mean ± SD). In baboons, however, comparable values were reported with both methods.17 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 technique16 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.18 The fact that our experiments showed a higher CBF and a lower OER is probably related to the use of a different anesthetic. Indeed, since the completion of the present experiments, we induce anesthesia with thiopental instead of xylazine-pentobarbital, which gives normocapnic values for CBF and OER of 40.4 ± 5.31 ml/100 ml/min and 41.8 ± 6.45% respectively (mean ± SD). In spite of these limitations, we found a high reproducibility in the measurements of CBF and OER,
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.\(^9\) The number of particles entering the brain was increased by raising P\(_{\text{CO}_2}\) during the embolization. Orientation experiments in which radioactive particles (carbonized plastic, mean diameter 15 \(\mu\text{m}\), 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\(^a\) 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 \(\mu\text{m}\)) — even in amounts that caused brain death within a few hours.\(^2\) 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.\(^2\)

In the different groups of animals of Series I, CBF decreased somewhat with time, and the \(N_2\) and \(H_2\) 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 \((N_2)\) 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 \(H_2\) and \(H_2\) that is not observed in the nonembolized animals and that also indicates decrease of CBF in the embolized hemisphere with time. This delayed hyperperfusion 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 \(\text{CMRO}_2\)

As expected and also observed by Rhodes et al\(^8\), \(\text{CMRO}_2\) in nonembolized dogs is practically independent of acute changes in P\(_{\text{CO}_2}\), 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 \(\text{CMRO}_2\). In the acute experiments with mild embolization, \(\text{CMRO}_2\) 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 \(\text{CMRO}_2\) produces neurological deficits, which were indeed observed when the animals recovered from anesthesia. In clinical studies with stroke patients, \(\text{CMRO}_2\) in the infarcted region is usually > 30% lower than on the contralateral side.\(^22\)

The smaller figure in the present experiments, which might suggest a lower \(\text{CMRO}_2\) 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 \(\text{CMRO}_2\) between normal and infarcted brain tissue). A decrease of \(\text{CMRO}_2\) in the other hemisphere due to contralateral embolization is another possibility, although less probable, since \(\text{CMRO}_2\) in the contralateral hemisphere attains practically the same value as in nonembolized animals. On the other hand, the true difference in \(\text{CMRO}_2\) 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; 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 CMRO2 in the infarcted region is probably more important than indicated by the measured hemispheric values, and that the CMRO2 threshold is thus greater than 6%.

In the second series of experiments, the mean values for CMRO2 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 CMRO2 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 Pco2 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 CMRO2 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 CMRO2 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 al21 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.24 From these clinical studies, it appears that "misery perfusion"25 with low CBF and high OER is the usual finding in the first hours after clinical stroke.24 Thereafter, relative luxury perfusion with low OER and CBF becomes the usual finding,22 23 26 27 and on rare occasions a focal increase of OER persists beyond the first hours after stroke.25 26 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.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-

References

1. Ackerman RH, Alpert NM, Correia JA, Finklestein S, Buonanno F, Davis SM, Chang JY, Brownell GL, Taveras JM: Importance of monitoring metabolic function in assessing the
26. Wise JS, Bernardi S, Frackowiak RSJ, Legg NJ, Jones T: Serial observations on the pathophysiology of acute stroke. The transition from ischemia to infarction as reflected in regional oxygen extraction. Brain 1983;106:197-222

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PET studies of changes in cerebral blood flow and oxygen metabolism after unilateral microembolization of the brain in anesthetized dogs.
J Weyne, G De Ley, G Demeester, C Vandecasteele, F L Vermeulen, H Donche and J Deman

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