Assessment of cerebral haemodynamic reserve: correlation between PET parameters and CO\textsubscript{2} reactivity measured by the intravenous $^{133}$ xenon injection technique

SIGRID HEROLD,* MARTIN M BROWN,† R S J FRACKOWIAK,*† A O MANSFIELD,‡ D J THOMAS,*‡ J MARSHALL†

From the MRC Cyclotron Unit, Hammersmith Hospital,* National Hospital for Nervous Diseases, Queen Square,† and St. Mary’s Hospital,‡ London, UK

SUMMARY Regional cerebral blood flow (CBF), oxygen utilisation, fractional oxygen extraction (OER) and cerebral blood volume (CBV) were measured by positron emission tomography (PET) in 21 patients with occlusive carotid artery disease. In the same patients, measurements of cerebral CO\textsubscript{2} reactivity were performed using the intravenous xenon-133 technique. A significant correlation was found in symptomatic hemispheres between the CBF/CBV ratio and CO\textsubscript{2} reactivity. Four patients had significant increases in OER and this was associated with a reduction in CBF/CBV ratio implying exhaustion of haemodynamic reserve. CO\textsubscript{2} reactivity was reduced below 1.5% mm Hg in all four cases with raised OER but only in two cases with normal OER. In patients with CO\textsubscript{2} reactivities above 1.5% mm Hg, OER was normal in all cases. It is concluded that measurements of CO\textsubscript{2} reactivity provide a satisfactory method for assessing cerebral haemodynamic reserve.

The international EC-IC bypass study recently showed that EC-IC bypass does not reduce the subsequent risk of stroke in patients with carotid artery occlusion. The results of this well designed and conducted trial appear to provide convincing evidence against the further use of this procedure. Patients were selected for the study on the basis of clinical criteria and a description of the anatomy of the carotid arteries obtained by angiography. However, some commentators have pointed out that there remains a possibility that the operation might be successful in preventing stroke if a subgroup of patients with impaired cerebral haemodynamics could be identified.

A quantitative assessment of the haemodynamic compensatory responses to a fall in perfusion pressure can be obtained by the combined measurement of regional cerebral blood flow (CBF), cerebral blood volume (CBV) and fractional oxygen extraction (OER) with positron emission tomography (PET). There is an increase in CBV (as autoregulatory vasodilatation occurs) and a subsequent decline in CBF (when the limit of autoregulation is reached), consequently the relationship between the two physiological parameters expressed by the CBF/CBV ratio is a sensitive index of haemodynamic reserve. This reasoning is supported by observations on the relationship between the CBF/CBV ratio and the OER. The latter increases when the CBF/CBV ratio falls below a critical threshold value which appears to indicate the limit of autoregulation and haemodynamic reserve. These measurements allow quantification of the degree of haemodynamic compromise in patients with occlusive carotid artery disease but their routine application is limited by the scarcity and expense of PET facilities.

An alternative approach to assessing the degree of compensatory vasodilatation demonstrated as a low CBF/CBV ratio with PET rests on the observation that some patients with carotid occlusion have a reduced capacity to increase CBF in response to hypercapnia. This reduced CO\textsubscript{2} reactivity is explained by maximal or near maximal resting or base-
line vasodilatation in response to reduced perfusion pressure. CBF can be measured by more readily available single photon techniques, particularly the xenon-133 clearance method. Because of the fast elimination of xenon-133 from the tissues, the method easily allows the sequential measurements of CBF during normocapnia and hypercapnia necessary for the determination of CO₂ reactivity.

We have compared these two ways of assessing haemodynamic reserve by performing both PET studies and measurements of CO₂ reactivity with the xenon-133 clearance method on the same day in a group of patients with occlusive carotid artery disease. Our aim was to establish whether a readily available clinical test could be calibrated and validated against direct measurements of haemodynamic reserve with PET.

Patients and methods

Patients
Twenty-one patients with artherosclerotic carotid artery disease were studied. Mean age was 61.9 years (SD 11.0 years). The extent of carotid artery disease was demonstrated by angiography in 19 patients. Two patients underwent Doppler examination only. Sixteen patients had unilateral occlusion of the internal or common carotid artery, six with significant contralateral stenosis (>50%). Three subjects had bilateral occlusion of the internal carotid artery; of those three, two had previously undergone EC-IC bypass surgery on one side. One patient had unilateral and one bilateral high grade stenosis of the internal carotid artery. Clinically, six patients presented with a history of previous stroke and two patients with a history of previous transient ischaemic attacks (TIAs) but all had not had any symptoms for at least 2 months. Six patients who had had TIAs with symptoms appropriate to the carotid circulation on the side of the occlusion within 2 months prior to the study were classified as having continuing symptoms. Three patients had experienced symptoms consistent with ischaemia in the verteobasilar territory. Four patients were asymptomatic. In these patients, carotid artery disease had been established during the course of investigations for cardiac or peripheral vascular disease. One patient with continuing symptoms showed a clinical feature suggesting reduced perfusion pressure. He suffered from focal seizures associated with change of posture.

The study was approved by the Research Ethics Committee of the Royal Postgraduate Medical School, Hammersmith Hospital and the National Hospital, Queen Square. Permission for the use of radioisotopes was given by the UK Administration of Radioactive Substances Advisory Committee. Patients' informed consent was obtained prior to each study.

Methods

1) Positron emission tomography Regional cerebral blood flow (CBF), oxygen extraction ratio (OER), oxygen utilisation (CMRO₂) and cerebral blood volume (CBV) were measured by positron emission tomography, using the oxygen-15 steady state inhalation technique and the carbon-11 carboxy-haemoglobin technique. Two separate emission scans were carried out during continuous inhalation of oxygen-15 labelled carbon dioxide and molecular oxygen respectively for the measurement of CBF and OER. A third emission scan was performed after bolus inhalation of carbon-11 labelled carbon monoxide for the measurement of CBV. During the scans, serial blood samples were taken via a fine gauge radial artery canula to measure arterial isotope activity, arterial oxygen content (O₂C) and arterial pCO₂. Oxygen utilisation was calculated from the relationship CMRO₂ = CBF × OER × O₂C. The CBV provided physiological information and was also used to correct the OER measurement for the signal arising from non-extracted haemoglobin-bound oxygen.

The scans were performed using an ECAT-II (EG & G Ortec) PET scanner with a spatial resolution of 16.7 x 16.7 x 16 mm at full width half maximum. Emission scans were corrected for the effects of tissue attenuation by corresponding transmission scans obtained with an external 68Ge/68Ga ring source. Data were collected from two transaxial planes 4.5 and 6.5 cm above and parallel to the orbitomeatal line in which apart from the posterior regions the cortical blood supply arises from the carotid arteries.

Data analysis from the cerebral images was performed using an objective cortical plot technique previously described for the analysis of data from patients with acute and chronic cerebrovascular disease. Values were obtained from a strip of 12 contiguous rectangular blocks of tissue of size 7.5 x 15 mm, corresponding to the superficial distribution of the middle cerebral artery in each hemisphere. The reported values were obtained by calculating the mean from both tomographic planes in each patient. Areas of grossly infarcted tissue, clearly delineated on PET-images and CT-scans, were present in 11 of the patients and were excluded from the regions of analysis.

2) Measurement of CO₂ reactivity CBF measurements for the determination of CO₂ reactivity were performed using a noninvasive intravenous xenon-133 clearance technique. A bolus of approximately 7 mCi of xenon-133 dissolved in saline was injected intravenously and the clearance of the isotope from the brain monitored by six external 25 mm diameter scintillation detectors. The concentration of xenon-133 in the expired air was monitored with a seventh detector and the end-tidal levels were used to estimate recirculating arterial xenon-133 concentrations. Regional CBF values for each detector were derived from a one minute initial slope analysis of the clearance curves. Arterial pCO₂ was estimated from the mean end tidal concentration of CO₂ in expired air, monitored throughout the procedure by a Datex CD300 infrared capnograph.

Each patient had two CBF measurements within 2 hours. Measurements were separated by at least 45 minutes to allow for complete elimination of the first dose of xenon-133. The first CBF measurement was performed with the patient breathing room air (normocapnia), the second with the patient breathing 5% CO₂ in air (hypercapnia). Inhalation of CO₂ was started at least 2 minutes prior to the beginning of the second CBF measurement to allow for equilibration and it was continued at the same concentration throughout the measurement. This led to an average increase in pCO₂ of 11 SD 2 mm Hg (range 9–16 mm Hg) between the two mea-
Assessment of cerebral haemodynamic reserve: correlation between PET parameters and CO\textsubscript{2} reactivity

Hemispheric CBF values were calculated as the mean of the initial flow values from the three detectors on each side placed over frontal, fronto-parietal and temporo-parietal regions. Hemispheric CO\textsubscript{2} reactivity was calculated as the percentage rise in CBF above normocapnic values per mm Hg increase in pCO\textsubscript{2}.

PET studies and measurements of CO\textsubscript{2} reactivity were usually performed on the same day except in two patients where technical failures delayed the second investigation for 1 and 2 days. There was no significant difference in blood pressure between the two studies (paired t tests). Arterial pCO\textsubscript{2} levels during the baseline xenon measurement (37.5 SD 2.6 mm Hg) were significantly lower than during the PET study (39.5, SD 3.3 mm Hg; p < 0.01).

Because the two cerebral hemispheres are not haemodynamically independent, statistical analysis (using Student’s t test) was confined to the hemisphere from which the patients’ clinical symptoms had arisen or, in the case of the asymptomatic patients and the patients with symptoms of vertebrobasilar ischaemia, to the hemisphere with the greater degree of occlusive disease.

Results

Figure 1 shows the relationship between CBF/CBV ratio (measured with PET) and CO\textsubscript{2} reactivity (measured with the xenon-133 intravenous injection method) for the symptomatic hemispheres of the 21 patients. There is a significant linear relationship between the two variables (r = 0.573; p < 0.01).

Figure 2 gives a plot of the CBF/CBV ratio against the oxygen extraction ratio and fig 3 shows the corresponding plot of CO\textsubscript{2} reactivity against OER. These data can be looked at in two different ways. Linear relationships are apparent to the eye and are statistically significant (r = 0.573, p < 0.01 in fig 2; r = 0.573, p < 0.01 in fig 3). However, there also seems to be a stepwise response, CBF/CBV ratios and CO\textsubscript{2} reactivities below a critical value being associated with abnormal OERs (age-matched normal OER range in patients' age group in our laboratory 0.29–0.48). Four of the 21 patients had mildly raised OERs between 0.50 and 0.56 which suggests an exhausted hae-
modynamic reserve and a decreased oxygen carriage reserve. CBF/CBV values in these four cases were below 7.0 (range 2.9–6.9). A stepwise increase in OER with diminishing CBF/CBV ratio was more strikingly demonstrated in a previous study from our laboratory which also included normal controls though recalculation of the data also shows a significant linear relationship ($r = 0.559$, $p < 0.001$). The apparent linearity results from the relatively small number of patients with elevated OERs in both the current and the previous data set. Also, increases in OER are only slight to moderate, since major rises mainly occur in situations of acute ischaemia.

For CO$_2$ reactivity, a cut-off point of 1.5%/mm Hg appeared to separate the severely compromised cases: of the six patients with CO$_2$ reactivities below 1.5%/mm Hg, four had elevated OERs. All patients with CO$_2$ reactivities above 1.5%/mm Hg had normal OERs. Error estimation using the “leaving-one-out method” gives a misclassification rate of 14% for this threshold value in relation to definitely abnormal OERs. The point furthest on the left (CO$_2$ reactivity $-0.7%$/mm Hg) represents a patient with a difference in OER of 0.04 between the two hemispheres (0.48 on occluded side, 0.44 on contralateral stenosed side). Such an asymmetry is very suggestive of impairment of oxygen carriage reserve on the occluded side, although the absolute value of OER still lay in the range found in normal subjects.

The six patients with CO$_2$ reactivities below 1.5%/mm Hg were amongst those with the most severe occlusive disease demonstrated angiographically; four had unilateral occlusion with a contralateral stenosis of more than 50%, one was the patient with bilateral occlusions and no previous EC-IC bypass surgery. None of the six patients was asymptomatic. Three had had previous stroke or TIA, two belonged to the group of patients with continuing symptoms and one had presented with symptoms of vertebrobasilar ischaemia. One of the patients with continuing symptoms and reduced CO$_2$ reactivity was the patient with clinical features of a critical haemodynamic state.

**Discussion**

Previous studies of cerebral haemodynamics and oxygen metabolism using PET have shown that only a proportion of patients with occlusive carotid artery disease is haemodynamically compromised; in the majority of patients, cerebral blood flow is adequate for the tissue’s metabolic demands though it may be reduced in absolute terms. In this study, almost 20% of patients had increased cerebral oxygen extraction fractions compensating for an inappropriately reduced blood supply. In agreement with a previous study, low CBF/CBV ratios in these patients suggested an exhausted cerebral circulatory reserve. Theoretically, patients with haemodynamic compromise who cannot be reliably distinguished clinically, should be identifiable. They may constitute a pathophysiological homogeneous group of patients in which the effects of revascularising surgery could be assessed.

The measurement of regional OER can only be achieved by PET and hence is restricted to small numbers of patients. CBF/CBV ratios can be determined with single photon emitting isotopes and gamma scanning but quantification of these methods is difficult. The studies published to date have reported hemispheric ratios of radioactivity rather than absolute values of the physiological variables an approach which will overlook bilaterally compromised hemispheres.

Assessment of the capacity to increase cerebral blood flow in response to vasodilators such as carbon dioxide or acetazolamide is an alternative way of measuring cerebral circulatory reserve. Such a “physiological stress test” has several advantages. The two separate measurements are made with one technique. The relevant information is a change of flow following an intervention, thus patients serve as their own controls. Problems inherent in the regional quantification of resting flow levels, such as “cross-talk” from the opposite hemisphere and “look through” of low flow areas, with the xenon washout methods, have relatively little effect on the measurement of CO$_2$ reactivity.

Another approach for assessing cerebral vascular reserve uses transcranial Doppler to measure middle cerebral artery blood flow velocity and its response to hypercapnia. CO$_2$ reactivity was found to be significantly lower in middle cerebral arteries above a carotid occlusion than in those above a patent carotid artery. A good correlation between CO$_2$ reactivity measured by xenon-133 flow measurements and doppler middle cerebral artery flow velocity changes was shown.

Our study validates and confirms the usefulness of measuring CO$_2$ reactivity to assess cerebral haemodynamic reserve. As expected from basic pathophysiological considerations, the capacity to vasodilate in response to inhaled CO$_2$ decreased as blood volume rose in relation to the prevailing cerebral blood flow and a significant correlation was obtained between CO$_2$ reactivity and CBF/CBV ratio. The scatter around the line can be attributed to the use of three tracer techniques ($C^{13}O_2$, $^{11}$CO and $^{133}$Xe), four measurements and two different ways of analysis. However, more important seems the demonstration of a clear association between reduced CO$_2$ reactivity and raised OER. All patients with impaired oxygen
carriage reserve had a CO₂ reactivity below a threshold value of 1.5%/mm Hg. Only one patient with clearly normal OER had a CO₂ reactivity below this threshold and all those with values above had appropriately normal OER. This is consistent with the finding of a previous study that the majority of patients with apparently haemodynamically transient ischaemic attacks had reactivity values of less than 1.5%/mm Hg.⁹

PET studies following extracranial-intracranial bypass surgery have demonstrated an increase in blood flow and a fall of preoperatively raised oxygen extraction ratios to normal levels in a small number of patients.¹⁸ 24–26 In one of these studies, the more frequent finding was that of a postoperative reduction in one of these studies, the more frequent finding was that of a postoperative reduction in blood flow and an increase in haemodynamic reserve. Anal-

frequent finding was that of a postoperative reduction in blood flow and an increase in haemodynamic reserve. Anal-

References


Assessment of cerebral haemodynamic reserve: correlation between PET parameters and CO2 reactivity measured by the intravenous 133 xenon injection technique.

S Herold, M M Brown, R S Frackowiak, A O Mansfield, D J Thomas and J Marshall

*J Neurol Neurosurg Psychiatry* 1988 51: 1045-1050
doi: 10.1136/jnnp.51.8.1045