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Assessing Adequacy of Collateral Circulation During Balloon Test Occlusion of the Internal Carotid Artery with ^{99m}Tc-HMPAO SPECT

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A balloon test occlusion of the internal carotid artery was performed in 11 patients with internal carotid artery aneurysms. Tolerance by patients was assessed by a combination of clinical examination; angiography; electroencephalography; ^{99m}Tc-hexamethylpropyleneamine oxime (^{99m}Tc-HMPAO) single-photon emission computed tomography (SPECT) with relative quantification; and, in four patients, ^{99m}Tc-HMPAO SPECT with absolute quantification of cerebral blood flow. During test occlusion, angiography showed a patent circle of Willis in all patients. No patient developed new clinical findings or electroencephalographic changes. The SPECT studies of five patients in whom ^{99m}Tc-HMPAO was injected during test occlusion demonstrated changes from their baseline SPECT studies. The internal carotid artery was permanently occluded in two of these patients, neither of whom became symptomatic because of the occlusion. Three patients who demonstrated no changes between baseline and test occlusion SPECT studies underwent permanent occlusion of the internal carotid artery without incident, and postoperative SPECT images were unchanged from baseline.

Our preliminary results suggest that patients who have no changes between baseline and test occlusion ^{99m}Tc-HMPAO SPECT studies should have adequate collateral circulation to sustain cerebral blood flow after occlusion of the internal carotid artery if no thromboembolic episodes occur. In contrast, a patient's tolerance of permanent occlusion cannot be consistently and reliably predicted if there are changes between baseline and test occlusion SPECT studies. In these patients, absolute quantitation of cerebral blood flow is important. Greater numbers of patients are required to confirm these initial results.

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Permanent occlusion of the internal carotid artery (ICA) is a recognized treatment for certain intracranial aneurysms when there is adequate collateral cerebral circulation [1]. As early as 1911, Matas [2] recommended a temporary occlusion test to predict a patient's tolerance of this procedure.

Temporary occlusion can be performed by digital compression [2–6], ligature, clamp [7–12], or balloon catheter [13–24]. In addition to clinical examination, with or without provocative hypotension, several ways of assessing the adequacy of collateral circulation during the test have been recommended. These include angiography [25], electroencephalography (EEG) [26–32], somatosensory evoked potentials (SEPs) [33], stump pressures [12, 32, 34–37], transcranial Doppler [22], xenon-133 with external probes [32, 36, 38, 39], stable xenon with CT [17–19], and ^{99m}Tc-hexamethylpropyleneamine oxime (^{99m}Tc-HMPAO) single-photon emission computed tomography (SPECT) [5, 24] (Monsein et al., Symposium Neuroradiologicum, June 1990). This report describes the use of ^{99m}Tc-HMPAO SPECT with relative and absolute quantification of cerebral blood flow (CBF) in addition to clinical examination, angiography, and EEG in patients undergoing test occlusion of the ICA with a balloon catheter.

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Subjects and Methods

The study population comprised 11 patients with ICA aneurysms who were referred to our institution for ICA occlusion (Table 1). The diagnosis of aneurysm had already been established by CT or MR and angiography.

Balloon Test Occlusion

Sheaths were placed in both common femoral arteries. Diagnostic angiography of the bilateral ICAs and vertebral arteries was performed. The catheter was left in the ICA contralateral to the aneurysm. A 7-French double-lumen balloon occlusion catheter (inflated size, 1 cm) was placed in the ICA below the aneurysm. After baseline EEG recording, the balloon was inflated with 30% contrast medium to completely occlude the artery. After 15 min of inflation, 20 mCi (740 mBq) of ^{99m}Tc-HMPAO was injected IV. The balloon was left inflated for another 5 min, after which it was deflated and removed. During this period, hemodynamic parameters, EEG, limb power, and speech were monitored, and digital subtraction angiography was performed to assess collateral flow via the contralateral ICA and vertebrobasilar system.

SPECT Studies

SPECT imaging was performed in all patients after IV injection of 20 mCi (740 mBq) of ^{99m}Tc-HMPAO (Ceretec, Amersham, England) on three occasions: (1) a baseline study on the day before the balloon test occlusion; (2) after a 15-min balloon test occlusion of the ICA, with the occlusion maintained for an additional 5 min after injection of tracer; and (3) before discharge, if permanent occlusion of the ICA was performed. In two patients (cases 4 and 9), an additional SPECT study was performed the day after test occlusion. The baseline and follow-up injections were made under minimal stimulation conditions (eyes closed, dark quiet room). A thermoplastic face mask and laser alignment were used to ensure reproducible positioning for compari-

TABLE 1: Summary of Patients Undergoing Test Occlusion of Internal Carotid Artery Aneurysms

Aneurysm Site/Case No.	Time of SPECT Study	SPECT Findings	Clinical Follow-up
L carotid-cavernous sinus			
1	Baseline	Normal	Permanent occlusion not yet performed
	Balloon occlusion	Unchanged	
2	Baseline	Normal	Permanent occlusion not yet performed
	Balloon occlusion	Unchanged	
3	Baseline	Bilateral frontal hypoperfusion	Permanent occlusion not yet performed
	Balloon occlusion	Minimal hypoperfusion, L hemisphere	
4	Baseline	Normal	Severe stroke in L middle cerebral artery resulted from premature balloon detachment
	Balloon occlusion	Unchanged	
	Day after test occlusion	Unchanged	
	Follow-up	Stroke, L middle cerebral artery	
5	Baseline	Defect, L inferior frontal lobe	Balloon occlusion performed; no neurlogic sequelae
	Balloon occlusion	Unchanged	
	Follow-up	Unchanged	
R carotid-cavernous sinus			
6	Baseline	Normal	Balloon occlusion performed; no neurologic sequelae
	Balloon occlusion	Unchanged	
	Follow-up	Unchanged	
7	Baseline	Normal	Permanent occlusion not yet performed
	Balloon occlusion	Moderate hypoperfusion, R hemisphere	
8	Baseline	Normal	Balloon occlusion performed; no neurologic sequelae
	Balloon occlusion	Moderate hypoperfusion, R hemisphere	
	Follow-up	Moderate hypoperfusion, R hemisphere	
L ophthalmic artery			
9	Baseline	Normal	Failed clipping, surgical occlusion of L internal carotid artery; small postoperative infarct, L temporal tip; full functional recovery
	Balloon occlusion	Hypoperfusion, L visual cortex	
	Day after test occlusion	Normal	
	Follow-up	Hyperperfusion, L frontotemporal region; infarct, L temporal tip	
10	Baseline	Normal	Balloon occlusion performed; no neurologic sequelae
	Balloon occlusion	Unchanged	
	Follow-up	Unchanged	
L posterior communicating artery			
11	Baseline	Normal	Successful clipping of aneurysm; permanent occlusion not performed
	Balloon occlusion	Marked hypoperfusion, L hemisphere	

son of sequential studies. Imaging was commenced 10 min after injection for the baseline and follow-up studies, and within 2 hr after the balloon test occlusion. A Toshiba 90B rotating-head SPECT camera with a slant hole collimator (six patients) and a Hitachi Neurospect 2000 four-headed camera (five patients) were used. Data were acquired through 360°, and 64 projections were obtained. Each projection was acquired for 30 sec. Data were reconstructed by means of the filtered back projection technique by using a Butterworth filter with a frequency cutoff of 0.3 (Toshiba) or 0.2 (Hitachi), order 14. Slices were obtained in the oblique (parallel to the orbitomeatal line), transverse, sagittal, and coronal planes with a thickness of 12 mm (Toshiba) or 8 mm (Hitachi).

Relative quantification by means of region-of-interest (ROI) analysis was performed in all patients. A total of 14 ROIs were placed on four transverse slices (Fig. 1). The slices were chosen by a single observer and were at the following levels: mid cerebellum, head of the caudate, thalamus, and mid parietal region. The same slices were used for each patient's studies, and strenuous attempts were made to ensure comparative positioning of ROIs. A ratio of counts per pixel within each ROI of the hemisphere on the side of occlusion to counts per pixel in the corresponding ROI of the contralateral hemisphere was calculated. The left/right hemisphere ratio in normal patients has been found to be approximately 1.00 ± 0.10 (2 SD) (Jeffery PJ, unpublished data). Hence, ratios different by more than 10% were considered to be important, particularly if all changes were in the same direction.

In four patients (cases 3 and 7–9), the CBF during test occlusion was calculated in $ml \cdot 100\ g^{-1} \cdot min^{-1}$ by using a new method for absolute quantification of CBF with ^{99m}Tc-HMPAO SPECT data [40]. In one patient, the CBF during the baseline study was also calculated. In order to obtain absolute quantification, ^{99m}Tc-HMPAO was injected into an antecubital vein over 10 sec. A portable scintillation camera was positioned over the vertex of the head. Sixty frames (10 sec each) were acquired with a matrix size of 64 × 64.

An arterial catheter was used for collection of arterial blood. Arterial blood samples were withdrawn continuously at approximately 5-sec intervals for the first 2 min after the injection and every 1–2 min for the next 30 min. Blood samples in 0.5-ml volumes were immediately mixed with 2 ml of octanol and centrifuged for 3 min. Of the resulting supernatant, 0.5 ml was removed. The radioactivities of the total blood samples and of the samples extracted with octanol were measured in a well type scintillation counter.

The arterial input function was obtained by linear interpolation of the measured data points. A numeric integral of the input function was calculated for the first 5 min. The dynamic study was used to

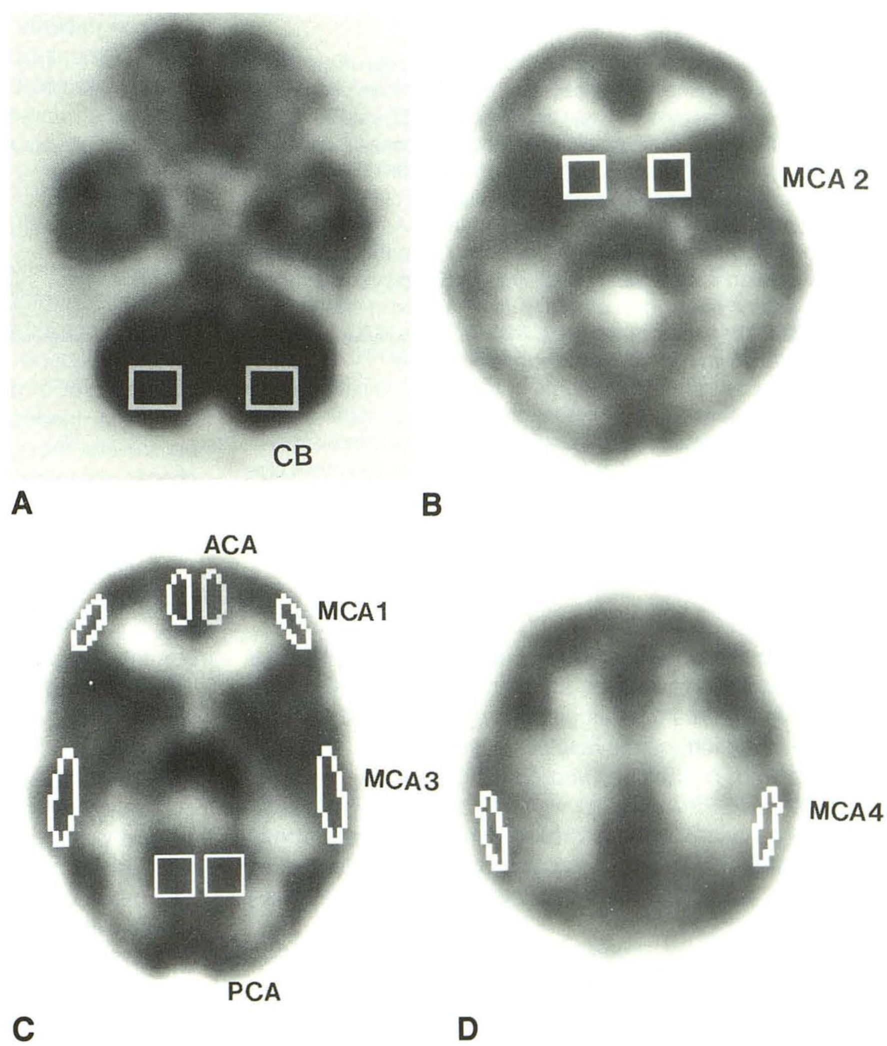

Fig. 1.—Representative cerebral SPECT images illustrating four different levels of axial sections and regions of interest used in analysis.
***A*, Level of mid cerebellum.**
***B*, Level of head of caudate.**
***C*, Level of thalamus.**
***D*, Level of mid parietal lobe.**
CB = cerebellum, MCA2 = middle cerebral artery territory (basal ganglia), ACA = anterior cerebral artery territory (medial frontal), MCA1 = middle cerebral artery territory (lateral frontal), MCA3 = middle cerebral artery (high temporal), PCA = posterior cerebral artery territory (visual cortex), MCA4 = middle cerebral artery territory (parietal).

obtain activity curves from both hemispheres; these were then processed by deconvolutional analysis to obtain the impulse response function. The impulse response function value at 5 min was divided by the maximum of this function to obtain the retention fraction. The CBF was calculated as

$$CBF = FA_{Br'}/A_{Bl'},$$

where F = 1 ml/min, $A_{Br'}$ = brain activity divided by the retention fraction, and $A_{Bl'}$ = lipophilic arterial blood activity integrated over 5 min.

The brain activity was measured with the dedicated four-headed SPECT scanner (NeuroSpect 2000, Hitachi) 45 min after injection of ^{99m}Tc-HMPAO. The system was calibrated with a cylindrical phantom 22 cm in diameter. Attenuation correction was performed after reconstruction with Chang's first-order method by using an attenuation coefficient of 0.11 cm^{-1}. A representative slice including the basal ganglia and thalami was corrected for radioisotope decay and calibrated by using the calibration factor. This slice activity was then divided by the retention fraction, the 5-min integral of the input function, and the brain tissue density of 0.87 g/ml to obtain the mean CBF slice. By using this mean CBF, all the individual pixel values of each brain slice were calculated and displayed in $ml \cdot 100\ g^{-1} \cdot min^{-1}$ tissue.

Permanent Occlusion

Two days to 6 weeks after the balloon test occlusion, permanent occlusion was performed in five patients, three of whom showed no change between baseline and test occlusion SPECT studies (cases 5, 6, and 10) and two of whom did show changes (cases 8 and 9). In four patients, a No. 9 Debrun latex balloon was introduced via the femoral artery and placed above and below the neck of the aneurysm. An additional balloon occluded the stump of the ICA. Balloons were filled with 30% contrast medium and detached from the catheter 15 min after inflation if there were no clinical or EEG changes with the inflated balloon in place. The patients were monitored in the intensive care unit for 24 hr after the procedure. In case 9, the ICA was ligated at surgery during an unsuccessful aneurysm clipping.

Six patients did not have occlusion of the ICA. One patient (case 4) sustained a stroke in the middle cerebral artery territory after premature balloon detachment during attempted endovascular treatment of the aneurysm. Another (case 11) underwent aneurysm clipping without carotid occlusion. In four patients (cases 1–3 and 7), permanent occlusion has not yet been attempted.

Results

Digital subtraction angiography performed during the balloon test occlusion revealed a patent circle of Willis in all patients. No significant changes in any patient were found in clinical examination, cardiovascular status, or EEG monitoring. There were no clinical complications.

The baseline SPECT studies were abnormal in two patients. One patient (case 3) had decreased perfusion in both frontal lobes of unknown origin. Another (case 5) had decreased perfusion in the left frontal lobe consequent to a previously attempted aneurysm surgery.

The SPECT studies of five patients (cases 3, 7–9, and 11), in whom ^{99m}Tc-HMPAO was injected during test occlusion, demonstrated changes from the baseline SPECT studies. In these patients, relatively decreased cerebral perfusion was demonstrated on the side of the occlusion, and the most significant occlusion/nonocclusion cerebral hemisphere (ROI) ratios ranged from 0.81 to 0.86 (Table 2). In four of the patients, the hypoperfusion involved the anterior and middle cerebral artery territories on the side of the occlusion. One patient (case 9) had hypoperfusion in the territory of the left posterior cerebral artery during the balloon occlusion that was not seen on follow-up studies performed the next day or after final occlusion. The reason for this change is unclear. Perhaps it could have been caused by the vertebral artery injection that was done during the test occlusion procedure (i.e., vasospasm or embolus). The results of absolute quantification of CBF in four of these patients (cases 3 and 7–9) revealed the cerebral perfusion in the occluded hemisphere to be greater than 40 $ml \cdot 100\ g^{-1} \cdot min^{-1}$ (normal, 40–60 $ml \cdot 100\ g^{-1} \cdot min^{-1}$) in these patients (Table 3).

Follow-up studies were performed after the permanent occlusion of two patients in whom changes were seen between the baseline and test occlusion SPECT studies. One patient (case 9) developed an infarct in the left anterior temporal lobe after surgical manipulation, and the follow-up study revealed luxury perfusion surrounding the infarct. The follow-up study in case 8 had an appearance similar to that in the test occlusion study, and the patient remained asymptomatic.

Three patients (cases 5, 6, and 10) in whom no changes were demonstrated between baseline and test occlusion SPECT studies underwent permanent occlusion of the ICA and had an unremarkable course. Follow-up SPECT images in these patients were unchanged from baseline.

Discussion

The Cooperative Study of Intracranial Aneurysms and Subarachnoid Hemorrhage demonstrated that occlusion of the common carotid artery or ICA carries a 30% risk of ischemia of the ipsilateral cerebral hemisphere [1]. In 21% of these cases, onset of deficits is delayed for more than 48 hr after occlusion. Inadequate collateral circulation and thromboembolism are thought to be the two mechanisms causing ischemic complications [21]. Many authors have used temporary occlusion of the carotid artery in an attempt to identify those patients who will have inadequate cerebral circulation after permanent occlusion.

We use a balloon catheter for temporary occlusion of the ICA, a procedure well tolerated by patients. It is performed in the angiography suite, which allows imaging of the circle of Willis. That is more effective and reproducible than digital compression, which is recommended by some authors [2–6]. Surgical exposure of the carotid artery with application of a ligature or clamp has also been used but is more invasive. Theoretical advantages of gradual occlusion with ligatures or clamps vs abrupt occlusion with the balloon catheter have not been borne out [8, 41, 42]. CBF flow assessment with xenon-133 and external probes [32, 36, 38, 39] or stable xenon with CT scanning [17–19] appears to improve the sensitivity to test occlusion over assessment with neurologic examination, stump pressure, EEG, SEP, or angiography alone and gives quantitative information. However, the equipment required for CBF determinations with these techniques

TABLE 2: Results of Relative Quantification of Cerebral Blood Flow in Patients Undergoing Test Occlusion of Internal Carotid Artery Aneurysms

Region of Interest/ Time of Measurement	Ratio by Case No.										
	1	2	3	4	5	6	7	8	9	10	11
Anterior cerebral artery territory (medial frontal)											
Baseline	0.99	1.08	1.07	1.00	0.98	0.99	0.98	0.97	1.01	1.00	1.07
Balloon occlusion	1.00	1.08	0.92	1.00	0.97	1.00	0.93	0.89	1.00	0.97	0.99
Day after test occlusion				1.03					1.04		
Follow-up					0.99	1.00		1.01	1.10	0.98	
Middle cerebral artery territory (lateral frontal)											
Baseline	1.01	1.00	1.13	1.05	0.93	1.05	0.94	1.00	1.02	1.00	0.96
Balloon occlusion	0.93	1.03	0.96	0.96	0.86	1.03	0.86	0.84	1.00	0.92	0.88
Day after test occlusion				0.95					1.10		
Follow-up					0.86	1.02		0.78	1.26	1.04	
Middle cerebral artery territory (basal ganglia)											
Baseline	0.97	1.07	0.98	0.99	1.00	1.04	1.03	1.03	0.96	1.02	0.96
Balloon occlusion	1.05	0.99	1.09	0.94	0.95	0.97	0.93	0.96	0.98	0.96	0.86
Day after test occlusion				0.96					0.88		
Follow-up					0.98	1.07		0.93	1.09	0.97	
Middle cerebral artery territory (high temporal)											
Baseline	0.96	0.97	1.06	0.96	0.95	1.06	0.98	1.03	1.06	0.92	0.97
Balloon occlusion	1.00	0.97	1.01	0.97	1.05	1.01	1.02	0.89	1.01	0.97	0.86
Day after test occlusion				0.97					1.04		
Follow-up					0.91	1.10		0.96	1.16	0.99	
Middle cerebral artery territory (parietal)											
Baseline	0.96	1.11	1.03	0.96	0.99	0.96	0.97	0.96	0.95	0.94	0.99
Balloon occlusion	0.90	1.03	1.01	0.96	1.06	0.96	0.87	0.88	0.98	0.99	0.81
Day after test occlusion				1.00					1.01		
Follow-up					1.04	1.04		0.87	1.05	0.98	
Posterior cerebral artery (visual cortex)											
Baseline	0.99	1.00	1.06	0.99	0.95	0.99	0.97	1.02	1.00	1.00	0.97
Balloon occlusion	0.99	0.98	1.08	1.01	1.01	1.03	0.88	0.84	0.82	1.08	0.93
Day after test occlusion				1.00					0.97		
Follow-up					1.02	0.98		0.88	1.04	0.97	

Note.—Ratios are of counts per pixel in region of interest on side of occlusion to counts per pixel in region of interest on contralateral side. Ratios in normal persons are about 1.00 ± 0.10.

TABLE 3: Cerebral Blood Flow Values in Four Patients Whose SPECT Findings Changed Between Baseline and Test Occlusion

Region of Interest/ Study Interval	Cerebral Blood Flow ($ml \cdot 100\ g^{-1} \cdot min^{-1}$)							
	Case 3		Case 7		Case 8		Case 9	
	Left	Right	Left	Right	Left	Right	Left	Right
Anterior cerebral artery (medial frontal)								
Baseline					46	45		
Balloon occlusion	45	48	57	53	53	47	54	54
Middle cerebral artery territory (lateral frontal)								
Baseline					43	43		
Balloon occlusion	46	48	59	53	48	40	52	52
Middle cerebral artery territory (basal ganglia)								
Baseline					48	50		
Balloon occlusion	53	48	66	62	54	52	57	58
Middle cerebral artery territory (high temporal)								
Baseline					46	44		
Balloon occlusion	58	57	59	61	54	48	57	56
Middle cerebral artery territory (parietal)								
Baseline					42	41		
Balloon occlusion	56	55	57	49	49	43	50	51
Posterior cerebral artery territory (visual cortex)								
Baseline					44	44		
Balloon occlusion	46	56	58	53	61	55	53	45
Cerebellum								
Baseline					54	54		
Balloon occlusion	60	63	61	65	61	61	68	66

is not widely available, and there has been some concern about the effect of xenon itself on CBF [43]. External probe measurements with xenon-133 are easy to perform in the angiography suite and offer reproducible quantitative measurements but do not provide information about regional perfusion. Stable xenon with CT gives regional information but is cumbersome and requires transfer of the patient to another room with a carotid catheter in place [17–19].

Matsuda et al. [5] have used ^{99m}Tc-HMPAO SPECT to assess cerebral perfusion during test occlusion of the carotid artery. Their study differed from our study in several aspects. They used manual compression of the common carotid for 5 min and injected ^{99m}Tc-HMPAO after only 30 sec of occlusion. The baseline study was obtained immediately prior to the occlusion, and then digitally subtracted from the second study. Brief occlusion of the carotid artery may not allow enough time for collateral circulation to be established. Compression of the common carotid artery may prevent collateral flow from the external carotid artery, which is of particular importance in elderly persons [37]. This may lead to false-positive results. Temporarily occluding the ICA with a balloon mimics the vascular effects of permanent occlusion, including leaving more time for establishment of collateral flow.

Our technique of assessing tolerance of ICA occlusion with ^{99m}Tc-HMPAO [24] (Monsein et al., Symposium Neuroradiologicum, June 1990) has the advantages of being performed with readily available technology and offers regional information. The images in case 9 demonstrated the exquisite sensitivity of this technique along with its poor predictive value. Decreased perfusion was seen during the test occlusion in the territory of the left posterior cerebral artery, although the patient developed no symptoms and this abnormality was not seen again on subsequent studies.

The major disadvantage at the present time of using ^{99m}Tc-HMPAO SPECT is that absolute quantification of CBF with this technique is difficult and not yet well validated. The importance of absolute quantification is illustrated by case 8, in which a relative decrease in perfusion on the side of the occlusion was noted on both the test occlusion and follow-up SPECT studies that was not present on the baseline study (Fig. 2). However, the absolute CBF as measured by our technique during the test occlusion was well above 20 ml $\cdot$ 100 $g^{-1} \cdot min^{-1}$, which is recognized to be adequate for normal cerebral function. This patient underwent permanent occlusion of the ICA without clinical sequelae.

In the absence of absolute quantification, relative quantification has been attempted, usually with ratios of ROIs to average counts in cerebellum or whole brain. We chose to use occluded/nonoccluded hemisphere ratios rather than cerebrum/cerebellum ratios because of the much larger potential effect of varying environmental conditions between examinations on the cerebrum/cerebellum ratios compared with occluded/nonoccluded cerebrum ratios. This may explain the apparent increase in absolute CBF between the baseline and test occlusion studies in case 8. This increase during the test occlusion may have been due to environmental conditions such as pain or fear, or the effects of sedative drugs rather than to inaccuracies in the quantification methodology. This may also point out the need for quantitative information about the baseline CBF.

There are several means of predicting which patients will not tolerate occlusion because of inadequate collateral circulation. In contrast, no studies are available that can predict which few patients will not tolerate ICA occlusion because of the development of thromboembolic complications. Our preliminary results lead us to believe that patients who do not change between baseline and test occlusion ^{99m}Tc-HMPAO SPECT studies should have adequate collateral circulation to sustain CBF after ICA occlusion if thromboembolic episodes do not occur. In contrast, a patient's tolerance of permanent occlusion cannot be consistently and reliably predicted if there are changes between baseline and test occlusion SPECT studies. In these patients, absolute quantitation of CBF is

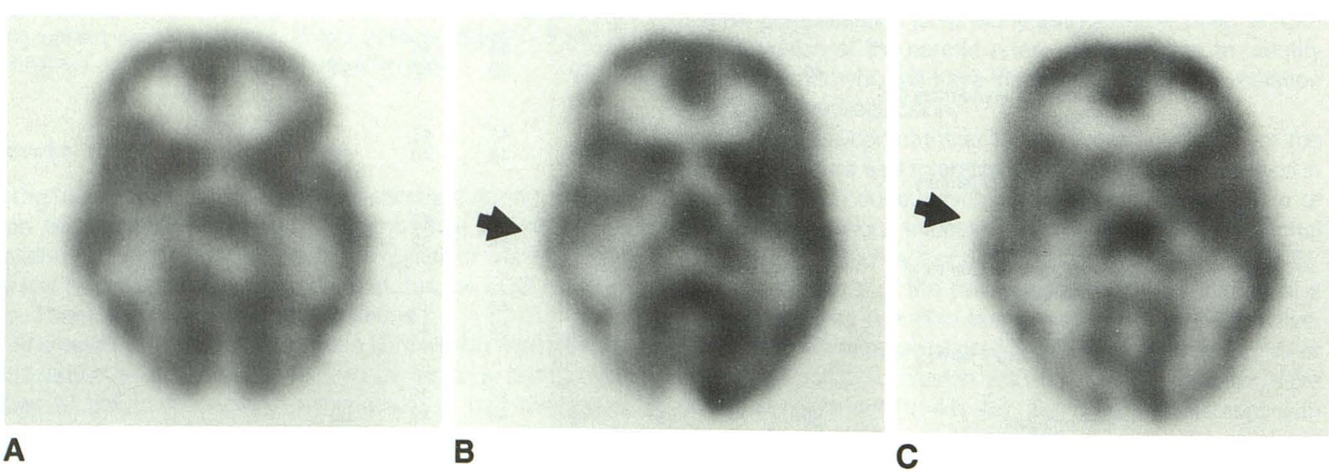

Fig. 2.—SPECT images in case 8. *Arrows* indicate areas of hypoperfusion on side of internal carotid occlusion.
A, Baseline study.
B, Test occlusion study.
C, Follow-up study after permanent occlusion of right internal carotid artery.

important. Greater numbers of patients are required to confirm these initial results.

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The reader's attention is directed to the commentary on this article, which appears on pages 1053–1054.