

Noninvasive Assessment of Intracranial Perfusion in Acute Cerebral Ischemia

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ABSTRACT

Single-photon emission computed tomography (SPECT) and transcranial Doppler sonography (TCD) may help to determine a target group of patients with maximum therapeutic response for tissue rescue after acute stroke. As previously described, the cerebral perfusion index represents a combination of these techniques, and is calculated by multiplying assigned values for TCD and SPECT perfusion patterns. The three grades of cerebral perfusion index (1–5, 6–12, 15–20) may predict short-term outcome if the index is based on SPECT and TCD performed within the first 6 hours after stroke. A total of 30 consecutive patients were studied (18 with middle cerebral artery stroke and 12 with transient ischemic attack or minor stroke). Neurological deficit was scored using the Canadian Neurological Scale. SPECT and TCD were performed 4 ± 2 hours after the onset. Forty-five minutes were required to perform both tests, evaluate the results, and calculate the cerebral perfusion index. The mean score (\pm standard deviation) of the neurological deficit on admission was 84 ± 20 in patients with transient ischemic attack/minor stroke and 54 ± 33 in patients with stroke ($p < 0.009$). The volume of ischemic lesion was measured on computed tomography scans performed more than 3 days after the ictus. Patients with transient ischemic attack/minor stroke had lesion volumes of 8 ± 7 cm³ compared to 72 ± 26 cm³ for those with stroke ($p < 0.0001$). The mean cerebral perfusion index in the transient ischemic attack group was 18 ± 4 , while in the stroke group it was 4 ± 1 ($p < 0.0001$). Clinical examination on admission correctly predicted a reversible neurological deficit in 9 of 12 patients in the transient ischemic attack group and the irreversibility of brain damage in 14 of 18 patients in the stroke group. With the three-grades scale, cerebral perfusion index correctly identified 10 transient ischemic attacks and 17 strokes. Noninvasive diagnosis of intracranial perfusion abnormalities using SPECT and TCD correlates with the clinical outcome and the volume of brain damage, and therefore may improve the accuracy of prognosis in the hyperacute phase of cerebral ischemia. Cerebral perfusion index is a fast and qualitative scoring system that may be used for

early differentiation of transient ischemic attacks, minor strokes, and strokes during the first 6 hours of cerebral ischemia.

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The clinical value of single-photon emission computed tomography (SPECT) and transcranial Doppler sonography (TCD) remains uncertain. The problem is compounded by the lack of methodological standardization: Several quantitative [1] and semiquantitative [2] methods are currently used to evaluate SPECT scans, and there is also no uniformity in quantifying TCD results, although there have been recent attempts to validate well-defined criteria [3]. These powerful methods of exploring cerebral perfusion are effective research tools, but with no apparent impact on the clinical practice of acute stroke [4, 5].

However, since the management of acute stroke patients is based mainly on morphological methods (e.g., computed tomography [CT], angiography), it is unrealistic to expect SPECT and TCD to influence the physicians' decision making immediately. Future studies may determine the role of these functional and noninvasive methods in the treatment of acute stroke patients and stroke prevention. SPECT and TCD potentially may solve several issues such as recoverability [6], etiology [2, 7, 8], and prognosis [2, 9, 10] of cerebral ischemia earlier than CT, and better than clinical assessment. In an initial report the authors [2] suggested that the predictive value of each of these methods may be enhanced by combining the two in a cerebral perfusion index (CPI).

The aim of the present study was to evaluate prospectively the accuracy of CPI in assessing the severity of the neurological deficit in acute stroke and the volume of brain damage during the first hours of cerebral ischemia, with a view to early differentiation of transient ischemic attacks (TIAs), minor strokes, and strokes.

Subjects and Methods

Consecutive patients with symptoms of cerebral ischemia in the middle cerebral artery (MCA) admitted to the emergency

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department within the first 6 hours after onset were studied. Admission tests included clinical examination, CT, SPECT, and TCD. The diagnosis of a reversible neurological deficit (TIA, minor stroke) or stroke was made at the second clinical evaluation performed after the first 24 hours and at 2 weeks after the ictus. Clinical examination was performed by a neurologist who was unaware of SPECT and TCD findings. The scoring of the neurological deficit was performed using the Canadian Neurological Scale (CNS) [11]. This scale is reliable (an agreement of total scores between the observers of 0.924) and valid when compared to a standard neurological examination (0.775, Spearman correlation coefficients); the CNS scores accurately predict outcome and death within 6 months following stroke ($p \leq 0.001$) [11]. Although it may be premature to decide on the outcome of stroke at 2 weeks after the onset, this end point was chosen because early mortality due to brain swelling occurs mostly within this period, and according to the discharge policies, the candidates for rehabilitation and transfer should be determined as early as possible. CT was repeated more than 3 days after

the ictus and a computerized technique ("Sigma Scan," Jandel Scientific, Corte Madera, CA) was used to measure the volume of ischemic lesion. This technique allows reproducible measurements (mean difference between repeated tracings, $3.49 \pm 2.65\%$; median, 3.0%).

SPECT was performed with technetium 99m-labeled hexamethylpropileneamine oxime (^{99m}Tc -HMPAO, Ceretec, Amersham, Amersham, United Kingdom) [2, 12]. A single-headed gamma camera was used. Slice thickness was 5 mm, with a spatial resolution of 1.5-cm full-width, half-maximum. Imaging was performed within 30 minutes after the intravenous injection of the tracer. Images were reconstructed parallel to the orbital-meatal line, correcting for head tilt. Images were flow corrected for nonlinear uptake of HMPAO to improve contrast in high-flow regions. Rapid reconstruction of the images was performed immediately after the test and the scans were interpreted by a neuroradiologist who was unaware of the clinical and CT findings. The following five patterns were evaluated by visual analysis of SPECT images: normal, high, mixed, low, and absent (Fig 1). To test observer

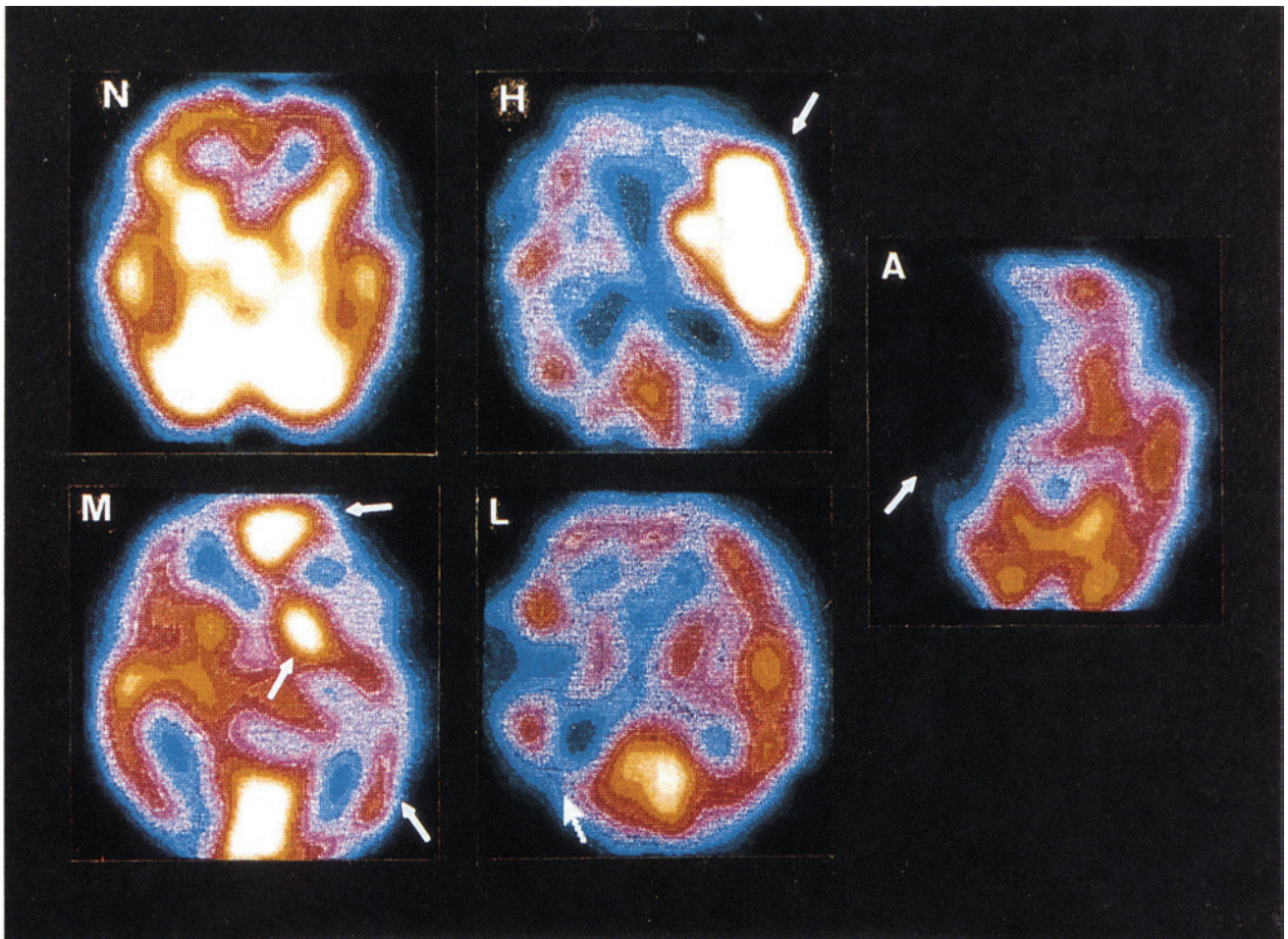


Fig 1. The five patterns of brain hemispheric perfusion are seen in acute stroke by semiquantitative visual analysis of HMPAO SPECT images. N = Normal: a symmetry of the tracer distribution in the brain; H = High: a focal area of the increased HMPAO uptake (arrow) corresponds to the entire involved region; M = Mixed: areas of increased and decreased but not absent (arrows) uptake of the tracer are present within the involved region; L = Low: only a focal decrease of HMPAO uptake (arrow) in the involved area is seen; A = Absent: a focal absence of the tracer's uptake (arrow) is present in the involved region.

bias in SPECT reporting 50 consecutive stroke patients were evaluated previously. Good correlation was demonstrated ($\kappa \geq 0.8$, kappa test) [13]. TCD was performed using a TC-2-64 EME scanner in the emergency room by a sonographer who was unaware of the clinical and CT findings. Four perfusion patterns of the circle of Willis were evaluated with TCD: normal, collateral, stenotic, and occlusive [2, 6]

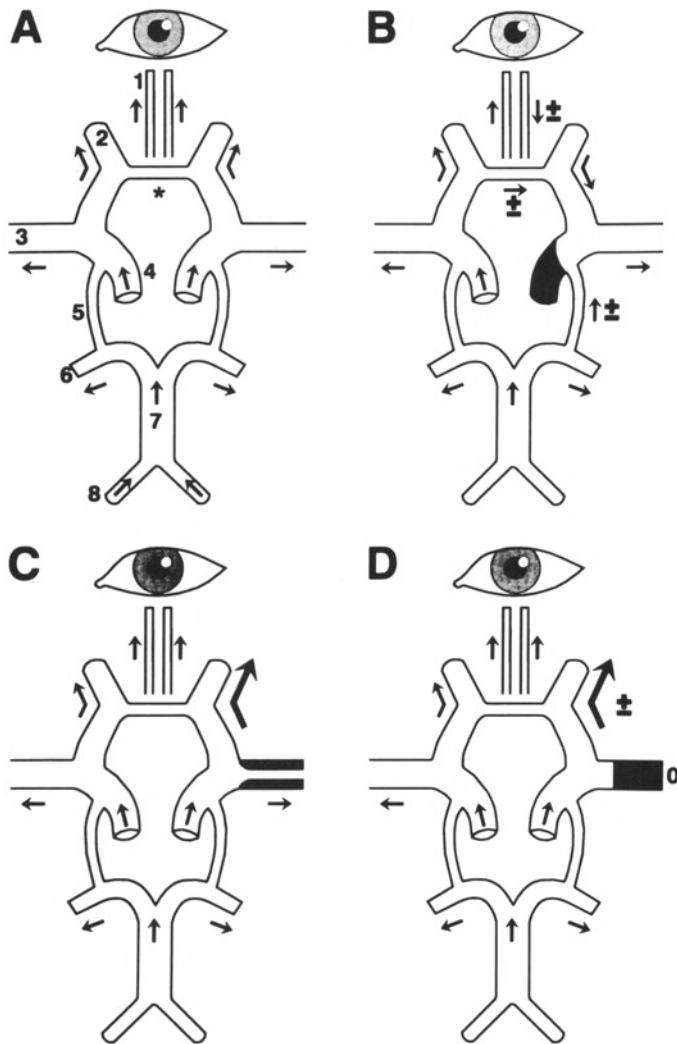


Fig 2. The four patterns of the circle of Willis perfusion in acute stroke seen on TCD. (A) Normal: A symmetry of peak systolic blood flow velocities (BFVs) is present between both sides of the circle of Willis. A normal difference is less than one-third of a smallest peak systolic BFV value, and a normal BFV in the middle cerebral artery (MCA) (3) is presumed to be less than 140 cm/sec. Arteries of the circle of Willis: 1 = ophthalmic; 2 = anterior cerebral and *anterior communicating; 3 = middle cerebral; 4 = terminal internal carotid; 5 = posterior communicating; 6 = posterior cerebral; 7 = basilar; 8 = vertebral. (B) Collateral: Collateral pathways of the circle of Willis (\pm), anterior and posterior communicating arteries, and reversed ophthalmic artery flow. (C) Stenotic: An arterial stenosis is associated with locally increased velocities. Unilateral peak systolic BFVs of at least 140 cm/sec reflect accurately MCA stenosis. Turbulence and diversion of flow (arrow) toward an adjacent artery may also be present. (D) Occlusive: No flow signal is found (0), yet other arteries of the circle of Willis are insonated through the same portal (e.g., temporal bone).

(Fig 2). After TCD examination was completed, the perfusion pattern of the circle of Willis was diagnosed by a neurologist who was unfamiliar with findings on other tests. The diagnostic criteria for the circle of Willis perfusion patterns are based on the peak systolic velocity and the direction of the flow data similar to the authors' previous studies [2, 6] and other studies [3] (see Fig 2). A comparison to cerebral angiography showed these TCD criteria to be accurate in the diagnosis of normal arterial flow as well as MCA stenosis and occlusion [2, 3, 6].

The CPI was then calculated for each patient to qualitatively assess cerebral perfusion abnormalities. For example, from Table 1, if decreased perfusion is seen on SPECT and the patient has MCA stenosis on TCD, the CPI value will be $2 \times 2 = 4$, indicating poor recoverability. If another patient has the same decreased perfusion on SPECT but normal TCD results, the CPI value is $2 \times 4 = 8$, indicating medium recoverability. Those with normal perfusion on SPECT and TCD have a CPI of $5 \times 4 = 20$, associated with good recoverability. Student's *t* test was then used to compare continuous variables in the obtained data correlating CPI with the clinical stroke scores and infarction volumes.

Results

A total of 30 consecutive patients admitted within the first 6 hours after cerebral hemispheric ischemia were studied prospectively. There were 18 patients with MCA stroke and 12 patients with TIA or minor stroke (mean age, 70 ± 10 yr). None of the patients received acute therapeutic intervention or was enrolled into a clinical trial. In 28 patients the initial CT showed no sign of infarction on admission. In all but 4 patients with TIA or minor stroke the neurological deficit had resolved by the time of the initial clinical examination. The mean CNS score for neurological deficit in the TIA group was 84 ± 20 on admission (Table 2). In contrast, the mean score in the stroke patients was 54 ± 33 ($p < 0.009$). Four patients in the stroke group died. Twenty-six patients underwent CT more than 3 days after the onset. The mean volume of infarction was 8 ± 7 cm³ in patients with TIA or minor stroke and 72 ± 26 cm³ in those with stroke ($p < 0.0001$).

Table 1. Cerebral Perfusion Index^a

SPECT Values	TCD Values			
	Normal—4	Col-lateral—3	Ste-notic—2	Occlu-sive—1
Normal—5	20	15	10	5
High—4	16	12	8	4
Mixed—3	12	9	6	3
Low—2	8	6	4	2
Absent—1	4	3	2	1

^aThe cerebral perfusion index is calculated by multiplying the assigned values of SPECT and TCD brain perfusion patterns. There are three grades of the index (20–15, 12–6, 5–1), which correspond to good, medium, and poor recoverability after stroke.

Table 2. Severity of Stroke by Clinical Examination, CT, and Cerebral Perfusion Index (CPI)

Group	TIA/Minor Stroke	Stroke
No. of patients	12	18
CNS	84 ± 20	54 ± 33 ^a
CT	8 ± 7	72 ± 26 ^b
CPI	18 ± 4	4 ± 1 ^b

^a $p < 0.009$.

^b $p < 0.0001$.

CNS = Canadian Neurological Scale (admission); CT = computed tomography (volume of brain damage, cm³); TIA = transient ischemic attack.

TCD and SPECT were performed at a mean of 4 ± 2 hours after the onset of symptoms. There was no failure of insonation on TCD and all patients underwent SPECT successfully. It took 45 minutes to perform both tests, evaluate the results, and calculate the CPI acutely. The mean CPI in the TIA group was 18 ± 4 . In 4 patients, a neurological deficit was present at the time of the TCD and SPECT examination and in 2 of them the perfusion pattern was decreased with one method, but normal with the other one. For example, when a mixed SPECT pattern and a normal TCD pattern were found, the CPI for that particular patient was $3 \times 4 = 12$. In contrast, the mean CPI in patients with stroke was $4 \times 1 = 4$, which is significantly lower than that in the TIA group ($p < 0.0001$).

The three grades of admission CNS scores (115–90, 90–50, 50–0) and CPIs (20–15, 12–6, 5–1) [2] were used to predict the outcome at 2 weeks after the onset. The clinical examination on admission correctly predicted a reversible neurological deficit in 9 of 12 patients in the TIA group and the irreversibility of brain damage in 14 of 18 patients in the stroke group. CPI correctly identified 10 TIAs and 17 strokes. However, no statistical method was applied to compare these positive predictive values of CNS and CPI because of the small numbers of patients in each group.

Case Reports

Patient 1: A 74-year-old woman presented at the emergency room with moderate neurological deficit (CNS score, 80) at 4 hours after the onset of left-sided hemiparesis. The patient did not notice any improvement at the time of clinical and laboratory testing. CT performed on admission showed no sign of infarction. The patient had a high risk of cardiogenic embolism (atrial fibrillation). SPECT showed normal perfusion and TCD showed a normal perfusion pattern (CPI, $5 \times 4 = 20$) and the reversal of the neurological deficit was predicted (Fig 3). The patient made complete recovery 24 hours later (CNS score, 115).

Patient 2: A 70-year-old man was seen $3\frac{1}{2}$ hours after the onset of right-sided hemiplegia and aphasia (CNS score on admission, 30). CT on admission showed no infarction.

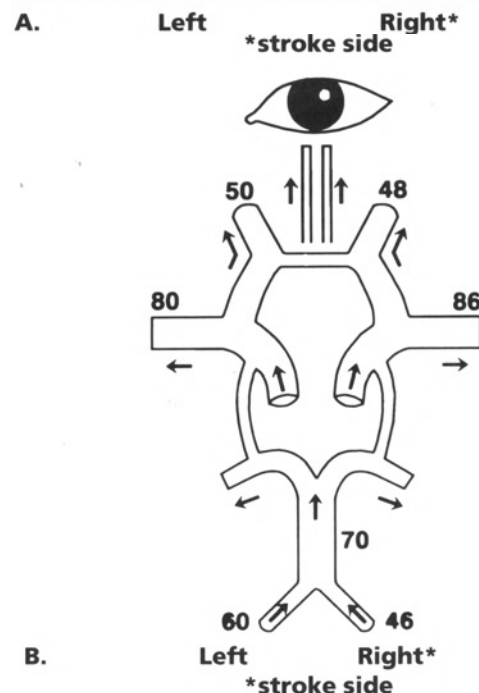


Fig 3. (A, B) Patient 1 (transient ischemic attack). Normal perfusion on SPECT and TCD 4 hours after ictus; cerebral perfusion index (CPI) = $5 \times 4 = 20$, indicating good recoverability.

SPECT and TCD were performed 4 hours after the onset of symptoms. There was decreased uptake of the tracer on SPECT in the left MCA territory (Fig 4). TCD showed a normal perfusion pattern, with a CPI of $2 \times 4 = 8$, indicating medium recoverability. CT showed a small subcortical hypodensity in the left basal ganglia 5 days later. The patient made considerable recovery and reached independence in everyday activities (CNS score, 65; with mild motor aphasia at 2 weeks after the ictus).

Patient 3: A 68-year-old man was admitted to the hospital 5 hours after the onset of left-sided hemiplegia and aphasia

(CNS score on admission, 30). He had a recent myocardial infarction with fresh thrombus detected on transesophageal echocardiogram. CT performed on admission showed mild hypodensity in the right MCA territory. Perfusion pattern was absent on SPECT and an occlusion of the right MCA was detected on TCD at 6 hours after the onset of symptoms (Fig 5). The patient had the lowest CPI, $1 \times 1 = 1$, which indicated the poorest prognosis. Although the patient made some improvement over the next 3 days (CNS score reached 45), he had a cardiac arrest and died on the seventh day of hospital stay.

Discussion

The major finding in this study was that CPI accurately reflects the clinical severity of stroke and so can differentiate reversible brain damage (TIA, minor stroke) during the hyperacute phase of cerebral ischemia (the first 6 hours). CPI is an early marker of ischemic brain damage, and as an early predictor of the short-term outcome, CPI may be better than the clinical examination on admission.

Three grades of CPI (20–15, 12–6, 5–1) correlate with the clinical outcome [2]. In a previous report [2] these criteria indicated good, medium, and poor recoverability after stroke when TCD and SPECT were performed 10 to 48 hours after the onset. In this prospective study patients were assessed during the “therapeutic window” (the first 6 hours after stroke). Patients with TIA or minor stroke had a high CPI (18 ± 4) corresponding to grade 20 to 15, while patients in the stroke group had a low CPI (4 ± 1) corresponding to grade 5 to 1. The difference between perfusion abnormalities (CPI) and lesion volumes (CT) detected in the two groups was significant and the criteria suggest that CPI may be used within the first 6 hours after cerebral ischemia to predict the clinical severity of stroke and the extent of ischemic damage to brain tissue. CPI was developed with a view to simple qualitative evaluation of a variety of perfusion abnormalities in acute stroke patients. So far, after evaluation of more than 100 patients, CPI was found to be applicable in all patients in whom TCD and SPECT can technically be performed.

The combination of SPECT and TCD is superior to each of these methods alone because CPI may allow better prognostication of the outcome: A stenotic TCD pattern often represents early reperfusion and indicates medium recoverability [6]; with SPECT data, the effectiveness of this reperfusion may be demonstrated. Thus, early MCA stenosis and no perfusion on SPECT predict the poorest outcome ($\text{CPI} = 2 \times 1 = 2$), whereas with normal perfusion, this finding will favor a medium outcome ($\text{CPI} = 2 \times 5 = 10$). In this series, the 2 patients with TIA or minor stroke and persisting deficits had decreased perfusion pattern with one method, but normal findings on another. The combination of SPECT and TCD increased the predictive value of non-

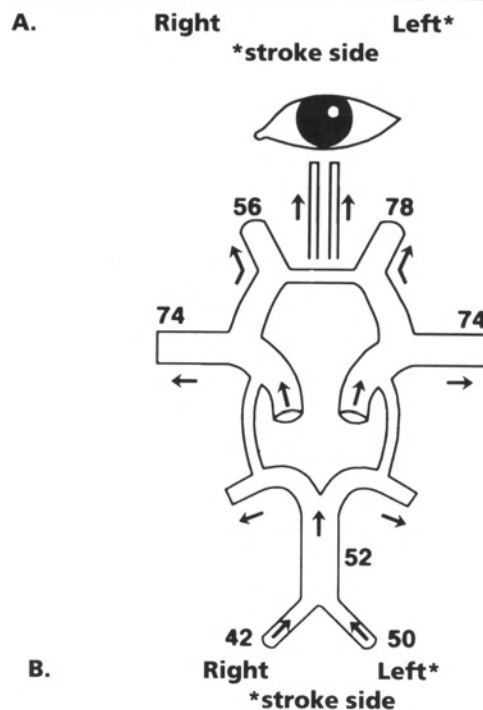
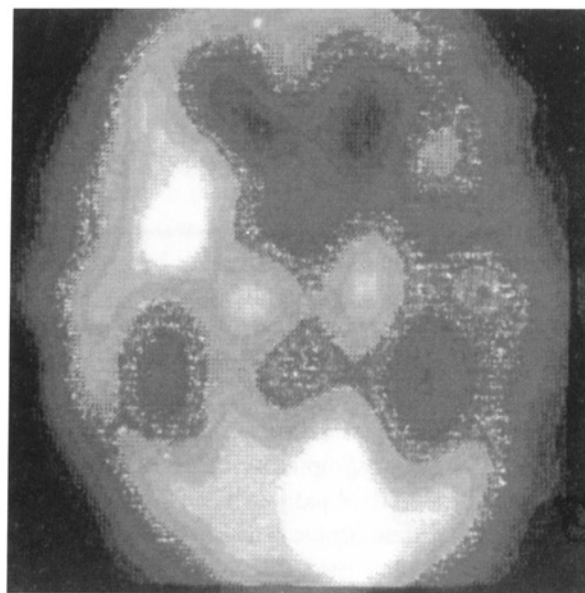
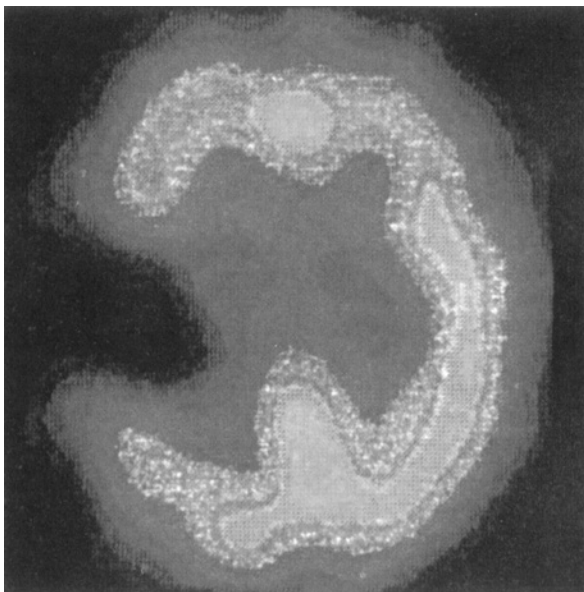


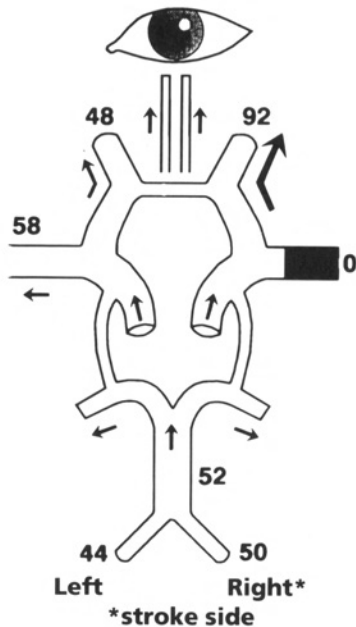
Fig 4. (A, B) Patient 2 (moderate stroke). Low pattern (SPECT) and normal pattern (TCD) at 3½ hours after ictus; $\text{CPI} = 2 \times 4 = 8$, indicating medium recoverability.

invasive assessment of cerebral perfusion in 4 patients, when compared to the neurological examination. Furthermore, repeated tests may demonstrate whether reperfusion occurred in the MCA main stem, or in brain parenchyma, or both.

Several previous attempts have been made to correlate SPECT and TCD data in acute stroke patients [14, 15]. Zannette and colleagues [15] found that the extent of MCA cerebral blood flow impairment (SPECT) may only be classified as nil, moderate, or severe depending on whether the measured flow velocity (TCD) is normal, depressed, or absent. Table 1 illustrates possible combinations of the ar-



A. Right* Left
*stroke side



B. Left Right*
*stroke side

Fig 5. (A, B) Patient 3 (severe stroke). Absent perfusion (SPECT) and middle cerebral artery occlusion (TCD) at 6 hours after ictus; $CPI = 1 \times 1 = 1$, indicating the poorest prognosis.

terial blood flow impairment with parenchymal perfusion patterns. CPI is a marker of relative cerebral perfusion and evaluates a spectrum of perfusion abnormalities seen in acute stroke patients. Also, sophisticated quantitative evaluations of cerebral perfusion have been used but may prove impractical in routine clinical practice and emergency situations. The qualitative approach of the CPI and its quick applicability could play a role in the evaluation of treatment strategies for acute stroke.

Fayad and Brass [16] suggested that SPECT may identify patients at high risk for hemorrhagic transformation following anticoagulation (e.g., severe perfusion deficit on SPECT

when CT shows no infarction acutely). With CPI, an occluded MCA main trunk may also be detected as a risk factor contributing to hemorrhagic conversion and/or edema formation. Hanson and associates [17] suggested that SPECT may assist in making therapeutic decisions if performed within the first 6 hours after cerebral ischemia. CPI may help to determine a target group of patients with a maximum therapeutic response (i.e., grade 12–6, or Patient 2). In a recent study of thrombolysis for stroke [18], only a patient with a small defect on SPECT responded clinically, and those with a severe perfusion defect did not respond to thrombolytic therapy with tissue plasminogen activator. Similar observations were made with other methods of SPECT quantification [10, 17, 19]. Further, serial TCD/SPECT measurements allow ongoing assessment of spontaneous or induced improvement of cerebral perfusion [2, 10, 20, 21].

The timing and degree of recanalization of the occluded intracranial artery are important. In the majority of acute stroke patients, eventually the MCA undergoes spontaneous reperfusion, although in patients with stroke this recanalization is often late and ineffective [2, 6]. Cerebral angiography studies reported similar findings [14, 20], but angiography only shows patency of a major intracranial vessel. Angiography gives no information on the adequacy of capillary perfusion or metabolism of the ischemic region. Serial SPECT and TCD could be used to assess the time threshold of the effectiveness of thrombolysis-induced recanalization of an intracranial artery following stroke [2, 9, 10, 16, 17, 21].

In summary, SPECT and TCD data in acute stroke correlate with the volume of the ischemic lesion on CT [2], with the patency of the intracranial arteries (compared to cerebral angiography) [14, 20, 21], and with the severity of neurological deficit [6, 9, 15, 17, 19]. CPI is applicable in the majority of acute stroke patients and its use during the first 6 hours after cerebral ischemia is feasible. CPI may improve the accuracy of early prognosis in acute stroke patients by differentiating TIA, minor stroke, and stroke. Future trials of treatment strategies in acute stroke should consider the advantages of these methods as noninvasive monitors of cerebral perfusion.

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