Clinical Features, Pathogenesis, and Computed Tomographic Characteristics of Internal Watershed Infarction

Christopher F. Bladin, MBBS, BSc, FRACP; Brian R. Chambers, MBBS, MD, FRACP

Background and Purpose: Infarction in the internal border-zone region has been described radiologically and pathologically. The aim of this study was to define the clinical and pathophysiological correlates of internal watershed infarction.

Methods: Eighteen consecutive stroke patients with evidence of internal watershed infarction on computed tomography (CT) were studied.

Results: Two CT patterns were identified: 6 patients had confluent internal watershed infarction (CIWI), and 12 patients had partial internal watershed infarction (PIWI). Syncopal symptoms and/or documented hypotension were prominent in both groups. Patients with CIWI usually presented with stepwise onset of contralateral hemiplegia and recovered poorly; patients with PIWI usually had discrete episodes of brachiofacial sensorimotor deficit and good recovery. Both groups had evidence of cortical involvement as part of their clinical deficit. Severe carotid occlusive disease was seen in 10 patients, and 12 patients had evidence of transiently impaired cardiac output. Carotid disease \( (P < .001) \), cardiac disease \( (P < .01) \), and diabetes mellitus \( (P < .01) \) were more prevalent in patients with internal watershed infarction compared with our stroke population as a whole.

Conclusions: Distinguishing internal watershed infarction from lacunar and other subcortical infarctions is important because the different pathological mechanisms demand different therapeutic strategies.

(Stroke. 1993;24:1925-1932.)

Key Words: • carotid artery diseases • cerebral infarction • hemodynamics • tomography

Infarction of cerebral watershed areas, the junction between territories of supply of major cerebral arteries, is generally attributed to hemodynamic mechanisms.\(^1\) Prolonged severe hypotension after cardiac arrest sometimes causes bilateral watershed infarction, but unilateral lesions are more common and often occur in association with severe carotid disease. The extent of infarction probably depends on the severity and duration of hypoperfusion, the location and severity of occlusive vascular disease, and the adequacy of collateral blood supply.

Involvement of cortical border-zone regions is the most familiar form of watershed infarction. However, watershed infarction may also occur in internal border-zone regions (Fig 1) between medullary arteries arising from the superficial pial plexus and deep penetrating arteries arising from the basal cerebral arteries.\(^2,7\) These lesions lie in the corona radiata and centrum semiovale adjacent to the lateral ventricles.\(^2,7\)

Although internal watershed infarction (IWI) has been recognized pathologically for at least 30 years\(^\) and radiologically,\(^2,5-7,9\) little is known about incidence, clinical characteristics, computed tomographic (CT) patterns, and pathophysiology. We undertook this prospective study to address these issues.

Subjects and Methods

Between February and November 1988, there were 300 consecutive admissions to the Stroke Unit of Heidelberg Repatriation Hospital, which serves primarily war veterans and their dependents plus some civilians. Eighteen patients were identified with acute stroke and CT evidence of IWI, defined on axial slices as a distinct zone of low attenuation in the internal border zone adjacent to the lateral ventricle in a paraventricular or supraventricular plane.\(^10\)

Thorough neurological assessment was complemented by clinical evaluation for potential hemodynamic disturbances, including pulse and blood pressure measurements in the supine and erect postures. Formal neuropsychological examination for focal cognitive and behavioral dysfunction was performed if patients were well enough to be tested. Neuropsychological tests included the Wechsler Adult Intelligence Scale, Wechsler Memory Scale, Rey Adult Verbal Learning Task, Complex Figure of Rey, Controlled Oral Word Association Test, Nelson Adult Reading Test, and the Austin Maze.

As well as early and delayed CT, all patients had routine pathology tests (full blood examination, blood glucose, biochemical screen), electrocardiogram (ECG),
carotid duplex ultrasound examination, and transcranial Doppler ultrasonography. Digital subtraction angiography, echocardiography, and Holter monitoring were performed when clinically indicated. In some patients, cardiac monitoring was extended to 48 hours or longer in an effort to document suspected arrhythmias.

We compared prevalences of vascular risk factors, namely, heart disease (defined according to accepted clinical and ECG criteria and aided by other investigations as appropriate), carotid disease (>30% stenosis on carotid ultrasound examination), hypertension (systolic blood pressure >160 mm Hg, diastolic blood pressure >90 mm Hg, or current antihypertensive therapy), smoking (past or present), and diabetes (history of diabetes or persistent elevation of blood glucose), for IWI patients and all patients admitted to the Stroke Unit between 1985 and 1988 and used the \( \chi^2 \) test for statistical significance. Outcome at 30 days was determined with respect to disability and recurrent hemodynamic or ischemic events.

**Results**

IWI was identified in 18 (6%) of 300 patients, of whom 16 were men and 2 were women, with a mean age of 72 years. Patients were divided into two groups (Tables 1 and 2) on the basis of distinct CT patterns (see below).

**CT Characteristics**

Six patients had large confluent internal watershed infarcts (CIWI) extending the length of the lateral ventricle (Fig 2). One patient had bilateral infarcts, and 5 patients had unilateral infarcts.

Twelve patients had smaller, nonconfluent or partial internal watershed infarcts (PIWI) in the same subcortical distribution as CIWI. Six patients had solitary PIWI on CT (Fig 3A). Five patients had multiple lesions on CT (Fig 3B); in 3 the infarcts were all unilateral, and in 2 they were bilateral. One patient had a single PIWI and a contralateral occipital infarct.

**Clinical Features**

All 6 patients with CIWI had a history of syncope or near syncope occurring at the time of stroke. Four of the 6 had a stuttering onset to their stroke over hours up to 10 days (patient 3); 2 patients had a single stroke event. Neurological examination revealed hemiparesis, hemisensory loss, and focal cognitive and behavioral dysfunction.

Prodomal syncopal symptoms were present in 6 patients with PIWI. Two others had intraoperative hypotension. Three patients with a prior history of minor stroke leading to carotid endarterectomy presented subsequently with a recurrence of their initial stroke deficit in association with further hemodynamic stress. Neurological examination revealed a brachiofacial sensorimotor deficit in 9 of the 12 patients, of whom 2 also had focal cognitive and behavioral dysfunction. Of the remaining 3 patients, 1 had predominantly leg involvement and 2 had severe hemiplegia and neglect. Those patients with brachiofacial paresis exhibited features of the “dysarthria, clumsy hand” lacunar syndrome but with persisting sensory loss in the upper limb and focal cognitive and behavioral dysfunction on neurological or neuropsychological examination.

**Neuropsychological Deficit**

All 6 patients with CIWI had focal cognitive and behavioral dysfunction (dysphasia, visual/sensory inattention, constructional dyspraxia) on bedside testing consistent with the side of cerebral infarction. More detailed neuropsychological testing was precluded in 5 of 6 patients because of poor clinical condition.

Four of the 12 patients with PIWI had focal cognitive and behavioral dysfunction on bedside examination. Six patients had deficits detectable only on formal neuropsychological evaluation. Left-sided neuropsychological signs included deficits of verbal memory, higher-level naming, and verbal abstract conceptual skills. Right-sided signs included impairment of visual memory and visuospatial, constructional, and planning skills. One left-handed patient with a left hemisphere stroke demonstrated signs of nondominant hemisphere dysfunction. Two patients had no significant neuropsychological abnormalities detected.

**Pathophysiology**

Of the whole group of 18 patients, there were 10 with ipsilateral severe carotid disease and 12 with evidence of temporary impairment of cardiac output. Six patients had carotid disease and hemodynamic insult, 5 had carotid disease without hemodynamic insult, and 7 had hemodynamic insult without carotid disease.

**Carotid disease.** Three patients with CIWI had ipsilateral carotid occlusion, 1 patient had 95% stenosis, and 2 patients had normal carotid arteries. Two of the patients with occlusive disease had bilateral lesions.

Two patients with PIWI had ipsilateral carotid occlusion and 4 had \( \geq 80\% \) stenosis. One patient had moderate carotid stenosis, 1 had minor plaque, and 4 had normal carotid arteries.

**Hemodynamic factors.** Three of the 6 patients with CIWI had identifiable factors capable of producing significant hemodynamic compromise, namely, paroxysmal ventricular tachycardia associated with cardiomyop-
TABLE 1. Patient Details: Confluent Internal Watershed Infarction

<table>
<thead>
<tr>
<th>Patient</th>
<th>Sex/Age</th>
<th>Risk Factors</th>
<th>Clinical Presentation</th>
<th>CT Scan*</th>
<th>Neuropsychology</th>
<th>Other Relevant Investigations</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M/66</td>
<td>IHD, MI, stroke, cardiomyopathy</td>
<td>Headache, dizziness, visual disturbance →L arm/leg paresthesia, visual/sensory inattention</td>
<td>R CIWI</td>
<td>Impaired visuospatial memory, constructional dyspraxia</td>
<td>Duplex/TCD, normal; Holter, recurrent VT; ECG, LBBB</td>
<td>Residual L visual inattention</td>
</tr>
<tr>
<td>2</td>
<td>M/68</td>
<td>DM, stroke, smoker, IHD, HT, PVD</td>
<td>Fluctuating dizziness, dysarthria, L arm &gt;face/leg weakness and numbness, visual/sensory inattention following prazosin for acute HT</td>
<td>R CIWI</td>
<td>Constructional dyspraxia and L hemineglect</td>
<td>Duplex/DSA, 95% stenosis R ICA, mild R &amp; L MCA stenosis; ECG, ischemic changes</td>
<td>Moderately disabled; functionless L arm, mobile with stick</td>
</tr>
<tr>
<td>3</td>
<td>M/75</td>
<td>HT, smoker, PVD, AF</td>
<td>Dizziness, collapse →dysarthria, dysphasia, R face/arm &gt; leg weakness and numbness, visual/sensory inattention</td>
<td>L CIWI</td>
<td>Mixed expressive/receptive dysphasia, R visual/sensory inattention</td>
<td>Duplex/TCD, normal; Echo, LVH; Holter, 2:1 AV block, SVT</td>
<td>Further collapse associated with rapid AF and hypotension →dysphasia, R hemiparesis</td>
</tr>
<tr>
<td>4</td>
<td>F/73</td>
<td>DM, HT, MI</td>
<td>Fluctuating confusion, collapse →dysarthria, quadraparesis R&gt;L</td>
<td>L CIWI</td>
<td>Severe dysphasia precluding further testing</td>
<td>Duplex/TCD, occluded L ICA, ?occluded R ICA, ?occluded L MCA</td>
<td>Vegetative and totally dependent</td>
</tr>
<tr>
<td>5</td>
<td>M/65</td>
<td>DM, HT, smoker, PVD, IHD</td>
<td>Fluctuating dysphasia and R arm/leg weakness →collapse →dysarthria, dysphasia, R face/arm &gt; leg weakness and numbness, visual/sensory inattention</td>
<td>L CIWI</td>
<td>Expressive &gt; receptive dysphasia, R visual/sensory inattention</td>
<td>Duplex/TCD, occluded L ICA, 95% stenosis R ICA, ?stenosis L MCA</td>
<td>Moderately disabled; residual hemiparesis, mobile with stick</td>
</tr>
<tr>
<td>6</td>
<td>M/68</td>
<td>HT, DM, MI</td>
<td>Fluctuating dizziness, L face/arm/leg paresthesia →L hand clumsiness, face/arm &gt; leg numbness, sensory inattention, postural hypotension</td>
<td>R CIWI</td>
<td>Mild constructional dyspraxia, L hemineglect</td>
<td>Duplex/TCD, occluded R ICA; ECG, LBBB</td>
<td>Recurring postural hypotension →&quot;fitting&quot; L arm →dense L hemiparesis, neglect</td>
</tr>
</tbody>
</table>

AF indicates atrial fibrillation; AV, atrioventricular; CIWI, confluent internal watershed infarction; CT, computed tomographic; DM, diabetes mellitus; DSA, digital subtraction angiography; ECG, electrocardiographic; Echo, echocardiography; Holter, Holter monitor; HT, hypertension; ICA, internal carotid artery; IHD, ischemic heart disease; LBBB, left bundle branch block; LVH, left ventricular hypertrophy; MCA, middle cerebral artery; MI, myocardial infarction; PVD, peripheral vascular disease; PIWI, partial internal watershed infarction; SVT, supraventricular tachycardia; TCD, transcranial Doppler; VT, ventricular tachycardia; and →, progressing to.

*Italics indicate most recent infarct.

athy, supraventricular tachycardia, and hypotension induced by acute administration of prazosin. In addition, there were 3 diabetic patients with labile blood pressure, including 1 with refractory postural hypotension, in whom onset of stroke may have been associated with hypotension.

Nine of the 12 patients with PIWI had identifiable factors capable of producing significant hemodynamic compromise: 4 had intermittent arrhythmias, 1 had myocardial infarction with hypotension, 2 had intraoperative hypotension, and 2 had syncope caused by vomiting.

Risk Factors

Cardiac disease, carotid disease, and diabetes were significantly more prevalent among patients with IWI than in our total stroke population (Table 3). Fourteen of the 18 patients had cardiac disease, including either ischemic heart disease, cardiomyopathy, arrhythmias, or a combination of these. Hypertension and smoking were not increased in IWI patients.

Outcome

CIWI was associated with poor outcome, and only 3 of 6 patients achieved independence, including 2 with significant disability. Two patients had ongoing hemodynamic instability and further stroke.

Ten of 12 patients with PIWI regained independence. Patients with multiple unilateral or bilateral PIWI on CT fared no worse than those with single PIWI. Three patients had ongoing hemodynamic instability; 2 patients underwent carotid endarterectomy complicated by perioperative hypotension with transient neurologic deterioration. One patient had ongoing postural hypotension, and repeat CT 8 months later revealed conversion of PIWI to CIWI (Fig 4).

Discussion

Our findings suggest that IWI, which accounted for 6% of our acute stroke admissions, has clinical, CT, and pathophysiological characteristics that distinguish it
### Table 2. Patient Details: Partial Internal Watershed Infarction

<table>
<thead>
<tr>
<th>Patient</th>
<th>Sex/Age</th>
<th>Risk Factors</th>
<th>Clinical Presentation</th>
<th>CT Scan*</th>
<th>Neuropsychology</th>
<th>Other Relevant Investigations</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M/72</td>
<td>HT, MI, AF</td>
<td>Transient sensory disturbance R face/arm→dysarthria, R face/arm weakness and numbness</td>
<td>L PIWI</td>
<td>Verbal specific memory disorder, concreteness of verbal concept formation</td>
<td>Duplex/DSA, 90% L ICA stenosis, 60% R ICA stenosis; Echo, poor LV function; ECG, LBBB; Holter, AF and VT</td>
<td>Hypotension during R CEA→dysphasia, R face/arm→leg weakness. Good recovery</td>
</tr>
<tr>
<td>2</td>
<td>M/72</td>
<td>MI, AF, CCF</td>
<td>Transient confusion, dizziness, dysarthria, R face/hand numbness→dysarthria, R face/hand weakness and numbness</td>
<td>L PIWI</td>
<td>L handed, reversed cerebral dominance, impaired visual memory and planning skills</td>
<td>Duplex/TCD, normal; ECG, old MI, AF; Holter, runs of VT; Echo, poor LV function</td>
<td>Minor disability R hand</td>
</tr>
<tr>
<td>3</td>
<td>M/68</td>
<td>IHD, stroke, L CEA</td>
<td>Dizziness with progressive onset of dysarthria, R arm&gt;leg weakness, numbness, and visual inattention</td>
<td>L PIWI</td>
<td>Impaired verbal memory and verbal abstract reasoning skills</td>
<td>Duplex/TCD, normal; ECG, LVF with strain, bradycardia; Holter, SSS</td>
<td>Minor disability R arm</td>
</tr>
<tr>
<td>4</td>
<td>M/66</td>
<td>Uncontrolled HT, DM, smoker, MI</td>
<td>Severe vomiting→dizziness and dysphasia. Following nifedipine for HT, developed dysphasia, dysarthria, R arm&gt;leg weakness, numbness, and visual inattention</td>
<td>L PIWI</td>
<td>Expressive and receptive dysphasia, R visual inattention</td>
<td>Duplex/TCD, minor bilateral ICA stenosis; ECG, old MI</td>
<td>Minor disability R arm</td>
</tr>
<tr>
<td>5</td>
<td>M/80</td>
<td>PVD, ex-smoker</td>
<td>Dysarthria, L arm weakness and numbness</td>
<td>R PIWI</td>
<td>Normal</td>
<td>Duplex/DSA, 80% stenosis R ICA, bilateral siphon stenosis; ECG, normal</td>
<td>Hypotension during R CEA→transient deterioration. Good recovery</td>
</tr>
<tr>
<td>6</td>
<td>M/73</td>
<td>HT, smoker, IHD</td>
<td>Transient R arm/leg weakness, paresthesia, and visual disturbance→leg&gt;arm weakness</td>
<td>L PIWI</td>
<td>Verbal&gt;visuospatial memory dysfunction, reduced verbal fluency</td>
<td>Duplex/DSA, 90% L ICA stenosis, 50% R ICA stenosis, ECG, LVH, first AV block, bradycardia; Holter, normal</td>
<td>Minor disability: mobile with stick, Later developed L amaurosis fugax→L CEA</td>
</tr>
<tr>
<td>7</td>
<td>M/63</td>
<td>Stroke after R CEA, PVD</td>
<td>Dysarthria, L arm&gt;face weakness and numbness, and sensory inattention</td>
<td>R PIWI×3</td>
<td>Impaired visuospatial memory, constructional dyspraxia, L hemispatial neglect</td>
<td>Duplex/DSA; occluded R ICA 90% stenosis L ICA, L siphon stenosis; ECG, LBBB</td>
<td>Mild disability</td>
</tr>
<tr>
<td>8</td>
<td>M/80</td>
<td>HT, MI, ex-smoker</td>
<td>Headache, collapse, obtunded, dense L hemiparesis, and visual/sensory inattention</td>
<td>R PIWI</td>
<td>Severe L hemispatial neglect</td>
<td>Duplex/TCD, occluded R ICA; ECG, LVH, old MI</td>
<td>Severely disabled: dense hemiparesis and neglect</td>
</tr>
<tr>
<td>9</td>
<td>F/90</td>
<td>HT, IHD</td>
<td>MI→hypotension→obtunded, dense L hemiparesis, and visual/sensory inattention</td>
<td>R PIWI×2</td>
<td>Severe L hemispatial neglect</td>
<td>Duplex/TCD, 80% stenosis R ICA; ECG, subendocardial infarct</td>
<td>Poor recovery. Ongoing postural hypotension. CT after 8 months revealed R CIWI</td>
</tr>
</tbody>
</table>

AAA indicates abdominal aortic aneurysm; AF, atrial fibrillation; AV, atrioventricular; CCF, congestive cardiac failure; CEA, carotid endarterectomy; CIWI, confluent internal watershed infarction; CT, computed tomographic; DM, diabetes mellitus; DSA, digital subtraction angiography; ECG, electrocardiograph; Echo, echocardiography; Holter, Holter monitor; HT, hypertension; ICA, internal carotid artery; IHD, ischemic heart disease; LBBB, left bundle branch block; LVH, left ventricular hypertrophy; MI, myocardial infarction; PVD, peripheral vascular disease; PIWI, partial internal watershed infarction; SSS, sick sinus syndrome; SVT, supraventricular tachycardia; TCD, transtranial Doppler; VT, ventricular tachycardia; and →, progressing to.

*Italics indicate most recent infarct.
from other forms of subcortical infarction. All our cases had associated occlusive vascular disease and/or hemodynamic events resulting in cerebral hypoperfusion. Early recognition of this entity is important to ensure appropriate investigation and treatment.

Cranial CT shows paraventricular or supraventricular low-density lesions in the corona radiata and centrum semiovale. Two subgroups, namely CIWI and PIWI, were recognized. CIWI is demonstrated as a confluent, almost cigar-shaped lesion running parallel to the lateral ventricle and should be distinguished from leukoariosis,12 in which periventricular lucency is bilateral, more extensive, and less distinct. PIWI appears as single or multiple discrete rounded lesions in the same anatomic distribution as CIWI. Multiple lesions form a linear chain of lesions in the internal watershed zone. PIWIIs often have indistinct margins and are distinguished from lacunae, which are smaller (<1.5 cm in diameter) and situated at a lower plane.13,14 Nevertheless, some of our cases were initially reported as “corona radiata lacunae.” There should be no confusion with striatocapsular infarction, which often produces a comma-shaped lesion on CT and occurs at a lower plane with involvement of the internal capsule and striatum.15-17

Although the majority of patients in both subgroups of IWI had syncopal symptoms or other evidence of impaired cardiac output at the onset of cerebral ischemia, clinical as well as radiological differentiation is also possible. Stepwise evolution of neurological deficit is common in CIWI, whereas a single discrete stroke event is more common in PIWI. CIWI produces a major neurological deficit consisting of hemiparesis, hemisensory loss, and focal cortical signs. Focal limb shaking18,19 was seen in one patient. The predominant pattern of neurological deficit with PIWI is brachiofacial motor and sensory deficit with focal cortical signs. Sensory signs tend to be subtle, and cortical signs are often demonstrated only on neuropsychological testing. Many patients with PIWI have a deficit closely resembling the “dysarthria, clumsy hand” syndrome described by Fisher.11 These patients, however, also have sensory impairment and signs of focal cortical dysfunction, often with a history of prodromal syncopal symptoms. Other clinical syndromes have been reported with IWI, including transcortical aphas120 and the opticocephal syndrome.21 Patients with CIWI have a poor prognosis for neurological recovery, whereas those with PIWI recover well. However, both subgroups are prone to further hemodynamic strokes.

Our data, showing a strong association between IWI, severe carotid disease, and hemodynamic events, support the hypothesis that IWI is caused by hypoperfusion of internal border zones. Recognition of the clinical and CT features of IWI should arouse a high level of
TABLE 3. Prevalence of Risk Factors for IWI Patients Compared With Total Stroke Unit Patients

<table>
<thead>
<tr>
<th>Risk Factor</th>
<th>IWI, No. (%)</th>
<th>Stroke Unit, No. (%)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart disease</td>
<td>14 (78%)</td>
<td>364/722 (50%)</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>Carotid disease</td>
<td>10 (56%)</td>
<td>110/491 (22%)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Hypertension</td>
<td>11 (61%)</td>
<td>458/727 (63%)</td>
<td>NS</td>
</tr>
<tr>
<td>Smoking</td>
<td>6 (33%)</td>
<td>276/716 (38%)</td>
<td>NS</td>
</tr>
<tr>
<td>Diabetes</td>
<td>6 (33%)</td>
<td>96/726 (13%)</td>
<td>&lt;.01</td>
</tr>
</tbody>
</table>

Fig 3. A, Computed tomographic scan (partial internal watershed infarction [PIWI] patient 2) showing PIWI involving the left corona radiata. B, Computed tomographic scan (PIWI patient 10) showing multiple PIWIs lying in a chain in the right corona radiata. All lesions lie in the same anatomic plane of the internal watershed region.

Suspicion for hemodynamic problems. Some arrhythmias were detected only after Holter monitoring was performed. Seemingly innocent clinical events such as syncope induced by vomiting or severe postural hypotension may be crucial to establishing causation in some cases. Stroke secondary to coughing or vomiting has been described previously. Coughing reduces carotid flow velocities by 40% or more, and vomiting may induce a vasovagal response, resulting in atrioventricular block and bradycardia.

Other factors may be implicated in the pathogenesis of IWI, including impaired cerebral autoregulation. Cerebral autoregulation is operational within set limits, usually a mean arterial pressure of 60 to 150 mm Hg. Increasing age, hypertension, and diabetes can cause (1) impaired autoregulatory response of cerebral vessels, (2) resetting of the limits of cerebral autoregulation, and (3) small-vessel occlusive disease with reduced luminal diameter and critical closing pressure. Under these conditions, small changes in perfusion pressure (eg, from sudden changes in posture, antihypertensive medications) that would normally be tolerated may produce a marked drop in cerebral blood flow, with vessel collapse and cerebral ischemia.

Embolic occlusion of the distal middle cerebral artery (MCA) trunk has also been implicated as a possible cause of IWI. An Italian group performed angiography within 6 hours in patients with acute embolic stroke and IWI on CT and demonstrated MCA occlusion distal to the lenticulostriate perforating vessels. Some patients also had CT evidence of cortical infarction, supporting an embolic pathogenesis. Embolic MCA occlusion may explain some infarcts in our study, particularly those patients with cardiac arrhythmias and normal or minimally diseased carotid arteries. The recent development of transesophageal echocardiography with its greater ability to detect cardiac thrombus may further clarify this.

Cerebral blood flow studies using inhaled $^{133}$Xe, positron emission tomography, single photon emission computed tomography, and transcranial Doppler ultrasonography in patients with carotid occlusive disease and IWI have demonstrated reduced cerebral blood flow, reduced perfusion reserve (cerebral blood flow/ cerebrovascular reserve), elevated oxygen extraction, and impaired vasomotor reactivity. Cerebral blood flow and perfusion reserve are reduced over an
area far greater than the area of CT abnormality. These techniques could therefore be useful in differentiating IWI from other forms of subcortical stroke, such as lacunar and striatocapsular infarction.

An intriguing aspect of subcortical infarction is the presence of focal cognitive and behavioral dysfunction. The precise pathophysiology is unclear but may represent disruption of cortical projection pathways, impairment of cortical blood flow, or both. Metabolic studies have demonstrated ipsilateral cortical hypometabolism or "diaschisis," particularly with lesions situated in the thalamus and thalamocapsular regions. Cerebral blood flow studies have shown overlying cortical hypoperfusion or an "ischemic penumbra" in which blood flow in the region adjacent to the infarcted tissue is sufficient for tissue viability (and hence a normal CT appearance) but insufficient for adequate neuronal function. At present it is unknown whether these changes are primarily vascular or secondary to cortical deafferentation. Hemodynamic insufficiency seems the most likely basis, and the extent and severity determine whether a subcortical lesion manifests clinically apparent cortical symptoms and signs. Subsequent improvement in regional cerebral blood flow would account for the transient nature of cortical signs on clinical testing.

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