Ischemic Core and Penumbra in Human Stroke

Anthony M. Kaufmann, MD, MSc, FRCSC; Andrew D. Firlik, MD; Melanie B. Fukui, MD; Lawrence R. Wechsler, MD; Charles A. Jungrties, MD; Howard Yonas, MD

Background and Purpose—The ischemic core and penumbra have not been thoroughly characterized after acute cerebral thromboembolic occlusion in humans. Differentiation between areas of potentially viable and irreversibly injured ischemic tissue may facilitate assessment and treatment of stroke patients.

Methods—Cerebral blood flow (CBF) was measured in 20 patients with acute middle cerebral artery (MCA) occlusion between 60 and 360 minutes after stroke onset, with the stable xenon computerized tomography (CT) technique. Threshold displays were generated at a single level, and the percentages of hemisphere with CBF $\leq 6$, $\leq 10$, 11 to 20, 21 to 30, and $>30$ cm$^3$·100 g$^{-1}$·min$^{-1}$ were measured. The corresponding images on 12 available follow-up CT scans were similarly assessed to determine the area of final infarct. Comparisons were analyzed with a paired Student’s $t$ test and Pearson’s correlation coefficient.

Results—Discrete and confluent areas of CBF $\leq 20$ cm$^3$·100 g$^{-1}$·min$^{-1}$ were identified in all patients, ipsilateral to the symptomatic MCA territory. The average area of CBF $\leq 20$ cm$^3$·100 g$^{-1}$·min$^{-1}$ within the ipsilateral hemisphere was $66\pm17\%$ compared with $36\pm12\%$ contralaterally ($P<0.001$). A difference in the extent of low CBF was due primarily to areas with CBF $\leq 10$ cm$^3$·100 g$^{-1}$·min$^{-1}$ (48$\pm18\%$ versus 16$\pm7\%$, $P<0.001$). The area of most severe ipsilateral ischemia ($\geq 6$ cm$^3$·100 g$^{-1}$·min$^{-1}$) best corresponded to the final area of infarction ($37\pm18\%$ versus 40$\pm24\%$; correlation coefficient, 0.866; $P<0.01$). The acute ischemic core destined to infarction was not surrounded by a widened rim of moderate ischemia because the area with CBF 11 to 20 cm$^3$·100 g$^{-1}$·min$^{-1}$ was similar bilaterally (19$\pm4\%$ versus 20$\pm7\%$, $P=0.792$, thus not significant).

Conclusions—Our study in acute human stroke involving MCA occlusion indicates that a severely ischemic core (CBF $\leq 6$ cm$^3$·100 g$^{-1}$·min$^{-1}$), observed between 1 to 6 hours after stroke onset, corresponds to the cerebral tissue destined to infarction. The ischemic penumbra with flow values between 7 and 20 cm$^3$·100 g$^{-1}$·min$^{-1}$ surrounding the ischemic core is very narrow. Therefore, strategies to improve the outcome of many patients with acute MCA occlusion must either include interventions to reverse the ischemic process within a few minutes of onset or increase the cerebral tolerance of ischemia and thereby prolong the potential therapeutic window. (Stroke. 1999;30:93-99.)

Key Words: cerebral blood flow ▪ cerebral infarction ▪ cerebral ischemia ▪ penumbra ▪ tomography, emission computed

The current goal of acute stroke therapy is to protect cerebral tissue before development of irreversible injury. A transition from reversible to irreversible injury is dependent primarily on the severity and duration of ischemia. Efforts to reestablish tissue perfusion in a timely fashion are therefore expected to be beneficial. Indeed, human studies of thrombolysis have shown improved outcome for carefully selected patients compared with placebo-treated control subjects. However, these studies have not identified a reduction in size of infarction because there has been no pretreatment delineation of the tissue at risk. Furthermore, clinical and computerized tomographic (CT) findings do not reflect the extent or severity of acute cerebral ischemia. To better evaluate acute stroke interventions, it is necessary to establish imaging techniques that demonstrate the therapeutic target and differentiate this from areas of already established infarction.

Experimental data have demonstrated a gradual progression of a reversible degree of ischemia toward infarction. A central core with severely compromised cerebral blood flow (CBF) is thought to be surrounded by a rim of moderate ischemic tissue with impaired electrical activity but preserved cellular metabolism and viability. This “penumbra” has a variable outcome, and tissue salvage may be achieved when reperfusion is established within a 6- to 8-hour period. Positron emission tomography (PET) studies have also demonstrated a gradual reduction in cerebral metabolic activity within regions of acute focal ischemia. Retained cerebral metabolism has been demonstrated for $\leq 17$ hours in severely ischemic areas that subsequently progress to infarc-

Received July 7, 1998; final revision received September 30, 1998; accepted October 14, 1998.
From the University of Calgary, Calgary, Alberta, Canada (A.M.K.), and the University of Pittsburgh, Pittsburgh, Pa (A.D.F., M.B.F., L.R.W., C.A.J., H.Y.). Correspondence to Anthony M. Kaufmann, MD, MSc, FRCSC, Assistant Professor, Division of Neurosurgery, Department of Clinical Neurosciences, University of Calgary, 12th Floor, Foothills Hospital, 1403 29th St NW, Calgary, Alberta, Canada T2N 2T9. E-mail anthony.kaufmann@crha-health.ab.ca
© 1999 American Heart Association, Inc.
Stroke is available at http://www.strokeaha.org

93
tion. However, such cellular activity does not necessarily indicate functional viability. Indeed, tissue injury in the severely ischemic core may progress to infarction within 1 to 2 hours. Although PET imaging has greatly increased our understanding of the stroke process, its availability and practicality in acute clinical settings are limited. There is a need to establish readily available imaging techniques that may delineate the extent and severity of cerebral ischemia during the first minutes and hours after stroke onset. Such data may define the areas of brain destined to infarction and distinguish potentially viable tissue at risk (ie, therapeutic target). Deletion of this tissue will facilitate evaluation of future treatments. Management decisions may then be individualized among the inhomogeneous group of acute stroke victims.

In the present study, we examine quantitative measurements of CBF in the first 6 hours after middle cerebral artery (MCA) territory stroke onset in humans. The extent and severity of ischemia were determined and compared with the final area of infarction. These data characterize the ischemic core and penumbra and support the concept of an ischemic threshold in human stroke.

### Subjects and Methods

We retrospectively reviewed a consecutive series of patients with MCA ischemic stroke who underwent quantitative CBF measurements within 6 hours of stroke onset. A precise onset time was necessary for patient inclusion; therefore, individuals who awoke with stroke symptoms were excluded. Patients were also excluded if preliminary conventional CT scans demonstrated intracranial hemorrhage, mass lesion, or early CT evidence of infarction over one third of the affected MCA territory. Therefore, all these patients were potential candidates for thrombolytic interventions. Although none received intravenous thrombolytic therapy, all were initially assessed as potential candidates for an institutional intra-arterial thrombolysis (IATL) protocol with urokinase within the first 6 hours of acute MCA stroke presentation. However, therapeutic decisions regarding the use of IATL in the present series of patients were made at the discretion of the attending stroke neurologist or neurosurgeon independently of the acute CBF imaging results (Table 1).

### Xenon-Enhanced CT CBF Technique

Xenon-enhanced CT (XeCT) is a quantitative CBF imaging technique with a high degree of sensitivity and spatial resolution. Its accuracy has been validated against other quantitative CBF techniques, including radiolabeled microspheres, $^{133}$Xe, and iodoantipyrine CBF techniques. Previous investigations have determined that the normal CBF in human mixed cortical tissue is $50 \pm 20$...
TABLE 2. Stable XeCT CBF Measurements in 12 Patients With Acute MCA Occlusion and Final CT Scan-Defined Infarct

<table>
<thead>
<tr>
<th>Patient</th>
<th>Acute CBF Ranges</th>
<th>Follow-Up CT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;30,† cm³ 100 g⁻¹ min⁻¹</td>
<td>0–6,† cm³ 100 g⁻¹ min⁻¹</td>
</tr>
<tr>
<td>1</td>
<td>41 20 7</td>
<td>0 3</td>
</tr>
<tr>
<td>2</td>
<td>38 25 12</td>
<td>10 6</td>
</tr>
<tr>
<td>3</td>
<td>28 24 10</td>
<td>14 4</td>
</tr>
<tr>
<td>4</td>
<td>24 16 13</td>
<td>30 65 2</td>
</tr>
<tr>
<td>5</td>
<td>23 20 11</td>
<td>36 43 14</td>
</tr>
<tr>
<td>6</td>
<td>7 19 7</td>
<td>40 31 20</td>
</tr>
<tr>
<td>7</td>
<td>17 18 11</td>
<td>43 43 4</td>
</tr>
<tr>
<td>8</td>
<td>19 15 9</td>
<td>49 47 41</td>
</tr>
<tr>
<td>9</td>
<td>7 15 15</td>
<td>50 45 7</td>
</tr>
<tr>
<td>10</td>
<td>14 20 13</td>
<td>53 68 4</td>
</tr>
<tr>
<td>11</td>
<td>11 12 7</td>
<td>63 69 8</td>
</tr>
<tr>
<td>12</td>
<td>6 16 8</td>
<td>64 61 6</td>
</tr>
<tr>
<td>Average</td>
<td>19 18 10</td>
<td>37 40 11</td>
</tr>
<tr>
<td>SD</td>
<td>11 4 2</td>
<td>18 24 11</td>
</tr>
</tbody>
</table>

*Areas given as percent of hemisphere.
†Interval between stroke presentation and follow-up CT scan.

Acute CBF Versus Infarct Area

The extent of infarction was measured in patients 1 through 12 from CT scans obtained between 2 and 41 days after initial presentation (Figure 2). In these patients, significant correlations were found between the extent of severe cerebral ischemia of ≤6 cm³ 100 g⁻¹ min⁻¹ and the final area of infarction, with Pearson correlation coefficients of 0.866 and 0.867 for ipsilateral and contralateral hemispheres, respectively.

Kaufmann et al January 1999

Interpretation of XeCT Scans and Late Infarct

The CBF data obtained at 60 to 360 minutes after stroke onset and before any therapeutic interventions were analyzed by means of the XeCT computerized program. Analysis was limited to the middle scan level, which allowed maximal representation of the MCA territory and provided the potential to coregister with follow-up CT images. Several CBF ranges were selected, including 0 to 6, 0 to 10, 11 to 20, 21 to 30, and >30 cm³ 100 g⁻¹ min⁻¹. The areas of cerebral tissue with these specified values were superimposed on accompanying CT scan images. These highlighted areas were then measured with a 2-dimensional computer tracing plot apparatus and recorded as a percentage of cerebral hemisphere area. The lateral ventricles were excluded from all measurements, and no areas of preexisting infarction were encountered.

Available follow-up CT scans were reviewed, and the 1-cm slice image most closely corresponding to the XeCT middle level was selected. Infarction on CT was defined as a distinct area of brain lucency. These areas were measured by the same 2-dimensional tracing technique, without reference to the previous XeCT CBF area measurements. Comparisons were analyzed with a paired Student’s t test and Pearson’s correlation coefficient. Patient numbers are maintained throughout all figures and tables.

Results

Acute XeCT Measurements

The CBF ranges were determined in all 20 patients and recorded as a percentage of hemisphere area on a single image level (Table 2). The extent of severe ipsilateral ischemia (ie, ≤10 cm³ 100 g⁻¹ min⁻¹) varied between individuals, ranging between 14% and 72% of the ipsilateral hemisphere, reflecting differences in naturally occurring collateral circulation. Side-to-side asymmetries of CBF were also variable and dependent on the extent of this severe ischemia (48±18% ipsilaterally versus 16±7% contralaterally, P<0.001). There was a homogeneous distribution of CBF 11 to 20 cm³ 100 g⁻¹ min⁻¹ that corresponded to the sulcal and hemispheric deep white matter, and this area was similar bilaterally in all 20 patients (19±4% versus 20±7%, P=0.792). There was, however, no widened rim of such “moderate ischemia” surrounding the ischemic core (Figure 1).
and 0.901, respectively ($P<0.01$). The area of infarction was not measured in patients 13 through 15, who developed post-IATL hemorrhages, and no follow-up CT scans were available for patients 16 through 20. However, the distribution of severe ischemia and surrounding moderate CBF reductions did not differ between these groups.

The ischemic core $\leq 6 \text{ cm}^3 \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1}$ most closely correlated to the area of final infarction and never overestimated the infarct by $>10\%$ (Figure 3). In patient 4, the final infarct was significantly more extensive than the initial CBF measurements would have predicted, which may have resulted from secondary ischemic insults after the initial XeCT. Initial CT scans free of early lucency or swelling did not correspond to the duration of symptoms or extent of final infarction. The extent of final infarction was also not appreciably influenced by the IATL interventions (Figure 3).

![Figure 2. Acute stable XeCT images and follow-up CT scans from patients with right MCA occlusive stroke. Extent of severe ischemia (CBF $\leq 6$ or $10 \text{ cm}^3 \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1}$) corresponded to area of subsequent infarction. However, ischemic core was surrounded by relatively narrow rim of moderate cerebral ischemia (CBF $\leq 20 \text{ cm}^3 \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1}$).](http://stroke.ahajournals.org/)

**Discussion**

Development of cerebral infarction depends primarily on the duration and severity of ischemia. Although there are few data on the acute quantitative CBF in human stroke, experimental studies have shown that severe ischemia produces infarction within 1 hour. Yonas et al demonstrated that selective occlusion of the lenticulostriate arteries in baboons reduced CBF to $<8 \text{ cm}^3 \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1}$, which consistently produced infarction of the involved territory after 60 minutes. Others have also demonstrated that a CBF threshold in the first hour of cerebral ischemia is predictive of infarction. A threshold for cerebral viability has also been suggested by the results of PET studies that demonstrate infarction of all tissue with cerebral metabolic rate $<1.5 \text{ cm}^3 \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1}$. Recently, Touho and Karasawa showed with XeCT in humans that CBF $<9 \text{ cm}^3 \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1}$ at 2 hours...
after stroke onset was associated with infarction. However, the extent of severe ischemia was not compared with follow-up CT scan–defined infarction. Our findings indicated that the extent of severe ischemia corresponds to the final infarct. The present study has some limitations, including the retrospective nature, variable intervals between follow-up CT scans, and analysis at a single level. However, the statistically significant correlations between areas with CBF &lt;= 6 cm³/100 g⁻¹/min measured between 140 and 360 minutes and the final infarct suggest that quantitative XeCT may be a powerful tool to delineate the ischemic core in acute human stroke.

Astrup et al described the ischemic penumbra as an area of moderate cerebral ischemia with reduced electrical activity that still maintained a membrane function and therefore was potentially viable. Neurological deficits may be reversed in penumbral tissue when normal CBF is reestablished within 6 to 8 hours. Although medical diagrams often depict a substantial rim of penumbral cerebral tissue surrounding the ischemic core, the extent of such potentially reversible cerebral ischemia has not been well characterized in human stroke. Our quantitative CBF measurements between 60 and 360 minutes demonstrated no widened rim of moderate ischemia (7 to 20 cm³/100 g⁻¹/min) around the well-delineated ischemic core at risk for infarction. These observations were consistent at 60 and 360 minutes, suggesting that the core of irreversible ischemic injury may be determined very early in the course of acute stroke.

It is not surprising that attempted IATL did not beneficially influence the relationship between the acute ischemic core and final infarct (Figure 3). Although these interventions were usually initiated &gt;2 hours after stroke onset, the acute CBF measurement results suggest that the early extent of severe ischemia defines the final extent of infarction. Therefore, the actual therapeutic window probably is &lt;1 to 2 hours, and hyperacute interventions are needed to reduce infarct volume. Such treatments may include agents to facilitate reperfusion and increase cerebral tolerance to ische-
Conclusions

Acute measurements of CBF are necessary to delineate the extent and severity of cerebral ischemia in human stroke patients. Quantitative techniques such as XeCT have the capacity to accurately predict the area of irreversible ischemic injury at risk for infarction and facilitate the evaluation of stroke interventions. The preliminary results provided in this report suggest that the severely ischemic core established in the first hours after acute MCA occlusion in humans is destined to infarct. Furthermore, the surrounding ischemic penumbra is narrow. Therefore, hyperacute interventions to facilitate reperfusion or neural protection are necessary to limit the extent of infarction.

Acknowledgments

Dr Yonas’ work is partially sponsored by a grant from Praxair Inc. We thank Tara Lye, BSc, CMMS/Zool, for her assistance in the preparation and editing of this manuscript.

References


Ischemic Core and Penumbra in Human Stroke
Anthony M. Kaufmann, Andrew D. Firlik, Melanie B. Fukui, Lawrence R. Wechsler, Charles A. Jungrics and Howard Yonas

doi: 10.1161/01.STR.30.1.93

Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1999 American Heart Association, Inc. All rights reserved.
Print ISSN: 0039-2499. Online ISSN: 1524-4628

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://stroke.ahajournals.org/content/30/1/93

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Stroke can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Stroke is online at:
http://stroke.ahajournals.org//subscriptions/