Cerebral Neutrophil Recruitment, Histology, and Outcome in Acute Ischemic Stroke
An Imaging-Based Study

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Background and Purpose—Evidence now exists for a pathogenic role for neutrophils in acute cerebral ischemia. We have studied the patterns and temporal profile of cerebral neutrophil recruitment to areas of acute ischemic stroke (IS) and have attempted to correlate this with neurological status and outcome.

Methods—Patients with cortical middle cerebral artery (MCA) IS were recruited within 24 hours of clinical onset. Neutrophil recruitment was studied using indium-111 (111 In) troponolate-labeled neutrophils, planar imaging, and single-photon emission computed tomography (SPECT). Volume of brain infarction was calculated from concurrent computed tomography (CT). Hematoxylin and eosin sections were obtained postmortem (n=2). Outcome was measured using Barthel, Rankin, and National Institute of Health Stroke (NIHSS) scales.

Results—Fifteen patients were studied. Significant 111 In–neutrophil recruitment to ipsilateral hemisphere, as measured by asymmetry index (AI), was demonstrated within 24 hours of onset in 9 patients; this response was heterogeneous between patients and on repeated measurement attenuated over time. Histologically, recruitment was confirmed within intravascular, intramural, and intraparenchymal compartments. Interindividual heterogeneity in neutrophil response did not correlate with infarct volume or outcome. In an exploratory analysis, neutrophil accumulation appeared to correlate significantly with infarct expansion (Spearman rho=0.66; P=0.03, n=12).

Conclusions—Neutrophils recruit to areas of ischemic brain within 24 hours of symptom onset. This recruitment attenuates over time and is confirmed histologically. While neutrophil accumulation may be associated with either the magnitude or the rate of infarct growth, these results require confirmation in future studies. (Stroke. 2004;35:1659-1664.)

Key Words: stroke ■ ischemia ■ neutrophils ■ SPECT ■ histology

Despite decreases in mortality, ischemic stroke (IS) remains a leading cause of death and disability, and the need for novel effective therapies remains imperative. Evidence from experimental studies suggests a direct role of leukocytes in the pathogenesis of ischemic injury. This evidence goes beyond histological accumulation to a more direct role in ischemic pathophysiology. Neutrophils have been implicated in the development of the “no-reflow” phenomenon in a primate model, whereas selective experimental interventional studies have strengthened the case for a causative role. Despite such studies, this remains a controversial area.

In the clinical arena, evidence for such processes is less robust. The failure of clinical trials has prompted a need for precise definition of human pathophysiology and this has partly been addressed by imaging studies. Single-photon emission computed tomography (SPECT) studies have localized mixed populations of leukocytes to ischemic hemisphere using indium-111 (111 In) and technetium-99m (99mTc). While the use of mixed cells offers limited pathological insights, such studies are confounded because 99mTc-hexamethylpropyleneamine oxide (HMPAO) elutes from leukocytes in hydrophilic-form that may undergo reuptake in the brain as a result of blood-brain barrier (BBB) disruption. Furthermore, they provide little information about acute pathophysiology or outcome. Regions of cerebral infarction do attract selective populations of 99mTc-HMPAO–labeled leukocytes, but such studies may offer only limited insights into recovery measured on a single scale. None of these studies has provided histological evidence to support the imaging data.
TABLE 1. Inclusion and Exclusion Criteria

<table>
<thead>
<tr>
<th>Inclusion</th>
<th>Exclusion</th>
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<tbody>
<tr>
<td>Cortical IS attributable to the MCA</td>
<td>Premorbid cognitive impairment</td>
</tr>
<tr>
<td>Male or females, aged 50 – 85 y</td>
<td>Previous stroke</td>
</tr>
<tr>
<td>Informed consent</td>
<td>Malignant disease</td>
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<tr>
<td>Patients are able to undergo neutrophil labeling and injection within 24 h of onset</td>
<td>Other ongoing organ failure</td>
</tr>
<tr>
<td>CT has excluded hemorrhage or other intracranial pathology</td>
<td>Myocardial infarction within 2 mo</td>
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Subjects and Methods

Patients

After informed consent, patients with a clear time of onset and ischemic cortical middle cerebral artery (MCA) territory syndromes fitting appropriate criteria (Table 1) were recruited. The Local Regional Ethics Committee (LREC) and the Administration of Radioactive Substances Advisory Committee (ARSAC) of the United Kingdom approved the study.

Cell Labeling

Separation and labeling of neutrophils was performed with the assistance of the Nuclear Medicine Department using a standard protocol as previously described. Briefly, venous blood is mixed with acid citrate dextrose (ACD) (NIH Formula A) before centrifugation and resuspension of cells in cell free plasma (CFP). Neutrophils were separated using an iso-osmotic discontinuous gradient of Percoll (Pharmacia) and labeled with In tropanolate. Autologous-labeled neutrophils were returned to the patient within 24 hours and thereafter at follow-up studies for 4 to 7 and 8 to 15 days. Administered radiation dose aimed for a target of 16 MBq equating to 7.2 mSv effective dose equivalent (ED). Cell recovery was calculated from previous studies are 10%. Achieving convergence was not apparently problematic, nor did varying the previous distribution of a parameter, Lambda, where A = ipsilateral and B = contralateral summed count rates. AI values from the 3 imaging studies were referred to as AI1, AI2, and AI3.

Imaging

Planar gamma camera and SPECT imaging were performed on an Elscint dual-headed gamma camera fitted with medium energy collimators. The targeted interval between injection of labeled cells and onset of clinical symptoms for these 3 time points were 24 hours, 4 to 7 days, and 8 to 15 days. Planar images (anterior and posterior) and SPECT were performed within 24 hours after injection. All quantitative studies were performed on regions of interest (ROI) defined manually from the planar hemispheric images and outside the head as a background region. Counts were measured from ipsilateral and contralateral hemispheres anteriorly and posteriorly, and decay corrected and adjusted for administered dose to give counts 10 minutes’ MBq. Baseline images were acquired before each follow-up study when decay-corrected counts were subtracted. SPECT data were acquired to give a slice thickness of \( \approx 8 \) mm. Data were reconstructed into transaxial, coronal, and sagittal planes using filtered back projection.

Consent was obtained for brain postmortem. Brains were fixed in buffered 10% formal saline before sectioning. Sections were taken from peri-infarct areas in transaxial or coronal planes, stained with hematoxylin and eosin (H&E), and examined by an independent neuropathologist blinded to the imaging studies.

Histology

Asymmetry indices (AI) were calculated for each SPECT study as previously described. Al = (A – B)/(A + B), where A = ipsilateral and B = contralateral summed count rates. AI values from the 3 imaging studies were referred to as Al1, Al2, and Al3. A and B were modeled as being Poisson variables with a common parameter, Lambda (\( \lambda \)), and the posterior distribution (having observed A and B) of (A – B)/(A + B) was used to generate a 95% confidence interval for the Al. A and B were observed for all patients. If the observation of AI was not within the confidence interval, then this was deemed significant evidence that the assumption of a common parameter, ie, the assumption of symmetry, did not hold. This analysis was conducted with WinBUGS version 1.4 (MRC Biostatistics Unit). Because of the simplicity of the model, achieving convergence was not apparently problematic, nor did varying the previous distribution of \( \lambda \) (within reasonable choices)
seriously affect the results. Correlation coefficients presented are Spearman rank rho (ρ) with P values for the 2-tailed test. Comparison of groups was conducted using the Mann–Whitney U test. The Friedman test was applied as a measure of decrement of AI over time when AI was measured repeatedly.

### Outcome

Clinical assessment on admission, at 4 to 7 days, 8 to 15 days, and 3 months included functional rating on Barthel and Rankin scales and neurological rating on the National Institute of Health Stroke Scale (NIHSS). These scales have been validated in large-scale trials.

Fifteen patients were entered into the study. Administered activity for each study ranged from 7.5 to 18.5 MBq with a calculated radiation burden range of 3.4 to 8.3 mSv ED. All patients were imaged with CT within 24 hours of symptom onset, except patient 10 who was imaged with magnetic resonance imaging and died after the first 111In SPECT study. Mean time from clinical onset (and ranges) to respective SPECT scanning sessions were 38.7 hours (23 to 49), 5.9 days (4 to 7), and 12.1 days (10 to 14), and corresponding intervals for CT were 10.9 hours (2 to 24), 4.9 days (3 to 7), and 11 days (8 to 12). Primary cerebral hemorrhage was excluded in all subjects. Quality of images varied according to movement and the clinical state of the patient.

Neutrophils were separated, labeled with 111In, and injected into all patients initially. Cell recovery, labeling efficiency data, and AIs derived from a total of 40 studies are given in Table 2. Assuming a blood volume of 5 L was assumed for all patients to allow for recovery calculation.

### Results

**Imaging**

Fifteen patients were entered into the study. Administered activity for each study ranged from 7.5 to 18.5 MBq with a calculated radiation burden range of 3.4 to 8.3 mSv ED. All patients were imaged with CT within 24 hours of symptom onset, except patient 10 who was imaged with magnetic resonance imaging and died after the first 111In SPECT study. Mean time from clinical onset (and ranges) to respective SPECT scanning sessions were 38.7 hours (23 to 49), 5.9 days (4 to 7), and 12.1 days (10 to 14), and corresponding intervals for CT were 10.9 hours (2 to 24), 4.9 days (3 to 7), and 11 days (8 to 12). Primary cerebral hemorrhage was excluded in all subjects. Quality of images varied according to movement and the clinical state of the patient.

Neutrophils were separated, labeled with 111In, and injected into all patients initially. Cell recovery, labeling efficiency data, and AIs derived from a total of 40 studies are given in Table 2. Assuming a blood volume of 5 L, our figures are comparable to those in established literature. AIs showed a trend toward decrement over the time period (Figure 1); the Friedman test for the 12 patients with repeated measures gave $P=0.038$, with the mean rank monotonically decreasing with time point. Significant AIs were seen in 9 patients (range: 0.07 to 0.72) (Figures 2 and 3 and Table 2). Volume-metric CT data did not correlate with AI across all time points (rho=0.11, $P=0.53$, n=35).

### Histology

Consent for histopathological study was obtained for patients 10 and 7 who died at 3 and 11 days after ictus from brain stem herniation and cardiac failure, respectively.

### Table 2. Asymmetry Indices, Cell Recovery, and Labeling Efficiency for Each Patient

<table>
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<tbody>
<tr>
<td></td>
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<td>%</td>
<td>%</td>
<td>$A_2$</td>
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<td>85</td>
<td>0.03</td>
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<td>88</td>
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</tbody>
</table>

*Significant AIs, $P<0.05$.

Patients 5, 7, and 10 died before follow-up imaging studies. A blood volume of 5 L was assumed for all patients to allow for recovery calculation. N/A indicates not available.
For patient 10 (Figure 4A through 4C), a macroscopic examination of a coronal slice revealed left hemisphere infarction throughout the entire territory of the MCA cerebral artery with involvement of subcortical structures. Microscopically, a brisk inflammatory infiltrate was noted in both meninges and superficial cortex in peri-infarct zones with evidence of perivascular neutrophil aggregation in underlying white matter. Macrophages were also present in this cellular reaction.

For patient 7 (Figure 4D through 4F), macroscopic examination of coronal sections revealed infarction of the right MCA cortex with involvement of subcortical structures. Microscopic examination revealed cellular infiltrate, consisting of neutrophils and macrophages in the cerebral cortex extending into the Virchow–Robin spaces.

Clinical Progression and Outcome

AI did not correlate with any outcome measure at any time point. Although high AIs were associated with worse neurological scores, these were not predictive. No significant differences in NIHSS were detected between groups 1 and 2 (P=0.5) or in AI between groups A and B or X and Y, (P=0.5 and 0.4, respectively). The ΔCT,coronal peri-infarct hematoxylin and eosin sections. A, ×10, dense meningeal inflammatory infiltrate adjacent to blood vessel. B, ×40, infiltrate in Virchow–Robin spaces. C, ×40, intraparenchymal inflammatory infiltrate. D to F, Patient 7, who died on day 11. AI=0.26; transaxial peri-infarct hematoxylin and eosin sections. D, ×40, intramural infiltrate in blood vessel in peri-infarct zone showing intravascular red cells. E, Dilated vessel with intraluminal accumulation of leukocytes. F, ×40, marginating granulocytes within blood vessel adjacent to infarct.

Discussion

Using robust, quality-controlled methods, we have demonstrated that within the first 24 hours of IS, autologous neutrophils may be separated, labeled with 111In troponolate, and used for quantitative and sequential studies of ipsilateral cerebral hemispheric recruitment. This is the first study to our knowledge to use histological confirmation in this context. The labeling process does not activate neutrophils and hence provides a measure of in vivo recruitment, presumably triggered by ischemia. Neutrophils appear early in regions of ischemic cerebral hemisphere defined structurally by coregistration of SPECT images and CT, and may be present from as early as 19 hours. Consistent with previous studies, recruitment shows a trend toward ipsilateral attenuation over time. Late or persisting neutrophil recruitment could not be...
attributed to hemorrhagic transformation. AI$_1$ values appear to be associated with the rate at which stroke volume expands as defined by CT. However, the extent of eventual (presumably penumbral) brain recruitment into the stroke was unrelated to AI in our study. Further AI values did not discriminate between patients with different clinical progression patterns or outcome.

**Methodological Issues**

Although previous studies have addressed leukocyte recruitment after stroke, these results are confounded by the use of mixed cells or $^{99m}$Tc-based techniques, because label elution is a significant problem. In contrast to earlier studies, we can be confident that ipsilateral cerebral signal relates not to eluted complexes, but specifically to the neutrophil component of the inflammatory response. $^{99m}$Tc-HMPAO decomposition products are hydrophilic and are unable to cross an intact BBB. Where BBB is disrupted, as is likely in IS patients, $^{99m}$Tc-HMPAO–labeled leukocyte studies remain uninterpretable. The imaging data do not discriminate between intravascular and intraparenchymal neutrophils when histology remains key. Cell recovery and labeling efficiency were comparable to optimal figures in the literature, suggesting that variations in AI were unlikely to be caused by deficiencies in labeling methodology.

This study used validated, neurological, and functional stroke scales, shown to be reproducible in larger trials; this contrasts with the Mathew scale used in one study. The Mathew scale is dominated by consciousness, combines impairments and disabilities, and its validity and reliability have not been proven.

**Pathophysiological Implications**

In our small sample of patients, a statistically significant relationship between AI and outcome could not be established. In a larger sample, AI may predict outcome but this remains speculative. Given the available data, the contribution of neutrophils to pathophysiology also remains speculative. Instead, neutrophils may act as biological markers of disease. A pathophysiological role of neutrophils in clinical stroke may only be put beyond doubt within the context of clinical interventional studies or by satisfying more stringent etiological criteria. Such criteria, as set out in this article, are not met in our study, and the results of such interventions have, to date, been disappointing. Significant AI values were observed at later time points, but only in those patients with higher values of AI initially. Our data are consistent with animal models in which polymorphonuclear leukocytes (PMNL) were observed histologically 24 hours after MCA occlusion in rats. The data presented further serve to illustrate the heterogeneity of cellular inflammatory pathophysiological responses to IS.

Insignificant AI values could not be attributed to variations in cell recovery and labeling efficiency. However, a number of possibilities could account for these negative results. First, we did not know if patients spontaneously recanalized. Complete and persistent MCA occlusion, accompanied by a concurrent lack of collateral circulation, may have prohibited neutrophil recruitment to densely ischemic areas. Hence, it is possible that significant neutrophil recruitment may be not only dependent on the ischemic process per se but also a marker of reperfusion injury. This is consistent with experimental models in which temporary MCA occlusion results in more a rapid and dense pattern of cerebral leukocyte recruitment. Opportunities for assessment of recanalization are provided by modern magnetic resonance angiography techniques or transcranial Doppler. This type of data was not available in this study. Second, an early time window of neutrophil recruitment to ischemic brain may be being missed. Granulocytes have been documented as early as 6 hours after experimental ischemia, whereas clinical studies suggest 15 hours as the earliest time point at which cerebral neutrophils appear. Signal derived from contralateral hemisphere may itself represent pathological invasion and hence may not provide an adequate control ROI for comparison. In contrast to other studies, in which many ROIs from ipsilateral hemisphere were selected (and in which the corresponding control ROIs are not explicitly defined), we have tested activity on a hemispheric basis as defined on planar images, with individual AI values tested statistically for significance. Given the spatial resolution of SPECT, it is currently not possible to precisely coregister areas of maximal neutrophil density with areas of infarction as defined by CT. The use of appropriate fiducial markers would improve anatomical localization within this context. Furthermore, we can only speculate as to whether such signal relates to ischemic penumbral areas, ie, areas that may represent a neuroprotective target or to core infarction. The limited histological evidence that we have would suggest that the former was indeed the case.

The $^{111}$In neutrophil SPECT provides evidence of acute neutrophil localization to infarcted hemispheres after IS. Extent of hemispheric neutrophil recruitment appeared unrelated to stroke severity at onset, clinical progression, or outcome, but may be related to early infarct expansion. Whether such findings represent a causal relationship remains to be established. The $^{111}$In neutrophil SPECT may be a useful tool for the initial assessment of the efficacy of antiinflammatory interventions aimed at reducing neutrophil-mediated injury in stroke. Failure to improve clinical outcomes with such interventions may be because of the fact that the agent is not effective in preventing neutrophil recruitment at the time points or dosages used. However, the agent may be efficacious in reducing neutrophil recruitment but fail to improve outcome because these cells may not cause pathology in IS. Labeled leukocyte studies may be useful in making the important distinction between these two scenarios.

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