The goal of acute stroke therapy is to restore perfusion to the ischemic penumbra. Without timely reperfusion, the penumbra undergoes irreversible injury. The rate at which this occurs is variable. In some patients, the neuronal loss occurs rapidly, whereas in others the penumbra survives for hours. Because of this variability, symptom duration does not closely correlate with the presence of penumbral tissue. An assessment of penumbral presence could be used to identify patients who are outside the established time window for acute stroke treatment but may still benefit from reperfusion therapy.

Various imaging methods exist to assess the presence of penumbral tissue. The magnetic resonance imaging (MRI) perfusion–diffusion (perfusion-weighted imaging–diffusion-weighted imaging, PWI–DWI) mismatch is one such method. It is promising for patient selection based on the results of cohort studies, which showed an association between reperfusion and good outcome in patients with a substantial PWI–DWI mismatch, but not in patients without a PWI–DWI mismatch. However, no data are available from randomized trials to demonstrate that patients with a PWI-DWI mismatch have a greater benefit than non-mismatch patients to any specific stroke therapy. The magnetic resonance angiography (MRA)–DWI mismatch and the clinical–DWI mismatch are 2 alternative selection strategies. The MRA–DWI mismatch model uses the presence of a vessel occlusion as a surrogate for the volume of the perfusion lesion. The clinical–DWI mismatch model uses the severity of a patient’s stroke symptoms as a surrogate for the volume of the perfusion lesion. The MRA–DWI mismatch model uses the presence of a vessel occlusion as a surrogate for the volume of the perfusion lesion.

Contemporary clinical trials such as Solitaire FR as Primary Treatment for Acute Ischemic Stroke (SWIFT-PRIME) often...
use combinations of clinical, angiographic, perfusion, and diffusion criteria for patient selection.15

The aim of this post hoc analysis of the Diffusion and Perfusion Imaging Evaluation for Understanding Stroke Evolution 2 (DEFUSE 2) study was to determine the optimal strategy to select patients for acute stroke trials. We compared the PWI–DWI mismatch model to a variety of alternative mismatch models and assessed which mismatch model most effectively differentiates patients who have a favorable clinical response with reperfusion from patients who do not have a favorable clinical response with reperfusion.

Methods

Patients

The eligibility criteria for the DEFUSE 2 study were intention to start endovascular stroke therapy <12 hours of symptom onset, age ≥18 years, baseline National Institutes of Health Stroke Scale (NIHSS) ≥5, nonpregnant state, modified Rankin Scale ≤2, and no contraindication for MRI.10 All patients underwent serial MRI before and after the endovascular procedure.10 The baseline MRI (gradient echo, MRA, DWI, and PWI sequences) was obtained <90 minutes before the start of the endovascular procedure, the early follow-up scan (gradient echo, MRA, DWI, and PWI) <12 hours of the endovascular procedure, and the late follow-up MRI (gradient echo, DWI, and FLAIR) on day 5 or at discharge from the hospital, whichever occurred first.10 Patients enrolled in the DEFUSE 2 study were eligible for this substudy if alternative mismatch status (MRA–DWI mismatch) was primarily defined according to previously published criteria.10

Definitions

PWI–DWI Mismatch Criteria

In the DEFUSE 2 study, RAPID software was used to postprocess the perfusion and diffusion data.10 Segmentation of the DWI lesion was based on an apparent diffusion coefficient threshold <600 s/mm², and the PWI lesion was segmented based on a Tmax threshold >6 seconds.10,13–15 The PWI–DWI mismatch was defined as a PWI–DWI ratio ≥1.8, an absolute difference between the PWI and DWI lesions of ≥15 mL, a DWI volume <70 mL, and ≤100 mL of tissue with a severe bolus delay (Tmax >10 seconds). This combination of criteria was termed the Target Mismatch Profile.10

Alternative Mismatch Criteria

MRA–DWI mismatch was primarily defined according to previously reported criteria: an occlusion of the internal carotid artery or the first segment of the middle cerebral artery (M1 segment) and a DWI lesion volume <25 mL; an M2 occlusion with a DWI lesion volume <15 mL; or a nonocclusive narrowing of any intracranial vessel with a DWI lesion volume <15 mL.14 We also examined alternative definitions of the MRA–DWI mismatch.14 The clinical–DWI mismatch was defined according to previously proposed criteria: NIHSS ≥28 and DWI lesion volume <25 mL.15

Reperfusion and Clinical Outcome

Definitions for reperfusion and favorable clinical response were adopted from the parent study.10 Reperfusion was defined as a >50% reduction in the volume of PWI (Tmax >6 seconds) lesion between the baseline and the early follow-up MRI. If the follow-up PWI was not obtained or if it was of insufficient quality, reperfusion was assessed based on dual-plane digital subtraction angiography and defined as restoration of blood flow at the completion of the angiographic procedure in >50% of the territory (ie, thrombolysis in cerebral infarction 2B) that showed impaired perfusion on the first angiographic run.10 The primary outcome measure was favorable clinical response defined as an improvement on the NIHSS of ≥8 points between day 0 and day 30, or an NIHSS score of ≤1 at day 30.

Statistical Analyses

The association between reperfusion and favorable clinical response was compared between patients with and without mismatch. Adjusted odds ratios for favorable clinical response with reperfusion were calculated using multivariate logistic regression models. Variables that were associated with favorable clinical response at an α of 0.1 in univariable analyses were included in the multivariable model. Variables that were significant at an α of 0.1 in the multivariable analysis were retained in the model. We evaluated the difference in the response to reperfusion between patients with and without mismatch using regression models that included the significant covariates and the interaction between reperfusion and mismatch status as independent variables:

\[
\text{Logit (outcome)} = C + R + M + R \times M + \sum_{i=1}^{n} \text{covariate}(i),
\]

where C is a constant, R is the presence of reperfusion, and M is the presence of mismatch. All analyses were conducted with SAS 9.3 and Stats Direct.

Results

MRA–DWI Mismatch Criteria

Data on PWI–DWI mismatch status were available for 99 patients from the DEFUSE 2 cohort. Five of these patients did not have an MRA, or their MRA was of insufficient quality to assess vessel status. Table 1 shows the baseline characteristics of the 94 patients who had sufficient quality MRAs to assess MRA–DWI mismatch status. Fifty-eight (61.7%) of the 94 patients met MRA–DWI mismatch criteria compared with 76 (80.9%) who met PWI–DWI criteria. Agreement between MRA–DWI and PWI–DWI mismatch models was fair (κ=0.35; 95% confidence interval [CI], 0.17–0.54). Twenty-two out of 76 patients with a PWI–DWI mismatch did not meet MRA–DWI mismatch criteria. The reperfused (N=14) and nonreperfused (n=8) patients in this subgroup had similar baseline characteristics. The odds ratio for favorable clinical response with reperfusion in this subgroup was 6.8 (95% CI, 0.7–70.1). There was no differential response to reperfusion in patients categorized according to the primary MRA–DWI mismatch model (P=0.5; Table 2). Among the alternative MRA–DWI mismatch models tested (Table 2), only the version 3 model with MRA–DWI mismatch defined as an internal carotid artery (ICA) or middle cerebral artery (MCA)–M1 occlusion and DWI volume <50 mL had a differential response to reperfusion (P=0.01; see Figure). For this model, the agreement with the PWI–DWI mismatch model was good (κ=0.68; 95% CI, 0.50–0.86).

Clinical–DWI Mismatch Criteria

The correlation between PWI lesion volumes (Tmax >6 seconds) and the NIHSS scores was fair (r²=0.18; 95% CI, 0.06–0.32; P=0.0001). Data on clinical–DWI mismatch status were available for all 99 patients from the DEFUSE 2 cohort. Table 1 lists the baseline characteristics for patients with and without the clinical–DWI mismatch. Sixty (61%) of the 99 patients met clinical–DWI mismatch criteria compared with 81 (82%) who met PWI–DWI criteria. Agreement between clinical–DWI and PWI–DWI mismatch models was fair (κ=0.23; 95% CI, 0.05–0.41). Twenty-seven out of the 81 patients with PWI–DWI mismatch did not meet the clinical–DWI mismatch criteria; 20 patients did not have a DWI volume <25 mL, 4 did
Table 1. Baseline Characteristics and 30-Day Outcome According to Mismatch Status

<table>
<thead>
<tr>
<th>Baseline characteristics</th>
<th>MRA–DWI Mismatch (n=58)</th>
<th>No MRA–DWI Mismatch (n=36)</th>
<th>Clinical–DWI Mismatch (n=60)</th>
<th>No Clinical–DWI Mismatch (n=39)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reperfusion</td>
<td>No Reperfusion</td>
<td>Reperfusion</td>
<td>No Reperfusion</td>
</tr>
<tr>
<td>N</td>
<td>35</td>
<td>23</td>
<td>14</td>
<td>34</td>
</tr>
<tr>
<td>Age, y, mean (SD)</td>
<td>66.1 (16.3)</td>
<td>66.1 (18.5)</td>
<td>62.7 (14.1)</td>
<td>62.6 (13.0)</td>
</tr>
<tr>
<td>Male sex, no. (%)</td>
<td>14 (40%)</td>
<td>13 (56.5%)</td>
<td>13 (59.1%)</td>
<td>8 (57.1%)</td>
</tr>
<tr>
<td>White race, no. (%)</td>
<td>34 (97.1%)</td>
<td>22 (95.7%)</td>
<td>20 (90.9%)</td>
<td>12 (85.7%)</td>
</tr>
<tr>
<td>NIHSS, median (IQR)</td>
<td>13 (9–17)</td>
<td>15 (11–18)</td>
<td>19 (14–21)</td>
<td>18 (14–20)</td>
</tr>
<tr>
<td>mRS, median (IQR)</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
</tr>
<tr>
<td>SBP, mm Hg, mean (SD)</td>
<td>143.4 (24.7)</td>
<td>149.5 (26.5)</td>
<td>147.1 (24.4)</td>
<td>147.8 (11.5)</td>
</tr>
<tr>
<td>DBP, mm Hg, mean (SD)</td>
<td>79.7 (16.8)</td>
<td>75.3 (23.6)</td>
<td>83.4 (21.1)</td>
<td>82.7 (10.9)</td>
</tr>
<tr>
<td>WBC, ×1000/μL, mean (SD)</td>
<td>9.2 (2.9)</td>
<td>9.0 (2.6)</td>
<td>8.1 (3.1)</td>
<td>9.7 (4.6)</td>
</tr>
<tr>
<td>Platelets, ×1000/μL, mean (SD)</td>
<td>229.7 (58.7)</td>
<td>214.7 (74.0)</td>
<td>234.5 (82)</td>
<td>211.1 (54)</td>
</tr>
<tr>
<td>Glucose, mg/100 mL, mean (SD)</td>
<td>119.2 (25.8)*</td>
<td>148.3 (69.3)*</td>
<td>146.2 (58)</td>
<td>128.5 (37.6)</td>
</tr>
<tr>
<td>Myocardial infarction, no. (%)</td>
<td>4 (11.4%)</td>
<td>2 (8.7%)</td>
<td>1 (4.5%)</td>
<td>1 (7.7%)</td>
</tr>
<tr>
<td>Heart failure, no. (%)</td>
<td>3 (8.6%)</td>
<td>1 (4.3%)</td>
<td>3 (13.6%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Atrial fibrillation, no. (%)</td>
<td>11 (31.4%)</td>
<td>7 (30.4%)</td>
<td>10 (45.5%)</td>
<td>4 (30.8%)</td>
</tr>
<tr>
<td>Previous CABG, no. (%)</td>
<td>2 (5.7%)</td>
<td>0 (0%)</td>
<td>2 (9.1%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Hypercholesterolemia, no. (%)</td>
<td>18 (51.4%)</td>
<td>14 (60.9%)</td>
<td>6 (27.3%)†</td>
<td>8 (61.5%)†</td>
</tr>
<tr>
<td>Diabetes mellitus, no. (%)</td>
<td>4 (11.4%)</td>
<td>5 (21.7%)</td>
<td>6 (27.3%)</td>
<td>2 (15.4%)</td>
</tr>
<tr>
<td>Hypertension, no. (%)</td>
<td>22 (62.9%)</td>
<td>18 (78.3%)</td>
<td>13 (59.1%)</td>
<td>9 (69.2%)</td>
</tr>
<tr>
<td>Smoker, no. (%)</td>
<td>14/34 (41.2%)</td>
<td>10/21 (47.6%)</td>
<td>11 (50%)</td>
<td>10 (71.4%)</td>
</tr>
<tr>
<td>Previous stroke, no. (%)</td>
<td>3 (8.6%)</td>
<td>6 (26.1%)</td>
<td>4 (18.2%)</td>
<td>1 (8.6%)</td>
</tr>
<tr>
<td>Previous TIA, no. (%)</td>
<td>3 (8.6%)</td>
<td>3 (13.0%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>30-day outcome</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mRS, median (IQR)</td>
<td>2 (1–4)</td>
<td>4 (2–6)</td>
<td>3 (3–5)</td>
<td>4 (3–5)</td>
</tr>
<tr>
<td>NIHSS, median (IQR)</td>
<td>2 (1–10)</td>
<td>13 (2–42)</td>
<td>7.5 (4–21)</td>
<td>8.5 (6–19)</td>
</tr>
</tbody>
</table>

Absolute numbers are followed by percentage in parentheses, mean values are followed by SDs, and median values by interquartile ranges (IQRs). CABG indicates coronary artery bypass grafting; DBP, diastolic blood pressure; mRS, modified Rankin Scale score; NIHSS, National Institutes of Health Stroke Scale; SBP, systolic blood pressure; TIA, transient ischemic attack; and WBC, white blood cells.

†Patients without MRA–DWI mismatch who did not reperfuse more often had a history of hypercholesterolemia (P=0.03).

not have an NIHSS ≥8, and 3 had neither. For patients who met PWI–DWI mismatch criteria but did not meet clinical–DWI mismatch criteria, the odds ratio for favorable clinical response with reperfusion was 9.6 (95% CI, 1.2–77.6). There was no differential response to reperfusion in patients categorized according to the clinical–DWI mismatch model (P for the Reperfusion×Mismatch interaction term, 0.9; Table 2).

Discussion

This study suggests that the MRA–DWI mismatch, defined as the presence of an ICA or MCA–M1 occlusion and a DWI lesion volume <50 mL at baseline, differentiates patients according to their response to reperfusion. Differentiating patients based on these MRA–DWI mismatch criteria seems to be comparable to differentiating patients based on PWI–DWI mismatch criteria.10,20 Other MRA–DWI mismatch criteria and clinical–DWI mismatch criteria did not differentiate patients according to their response to reperfusion.

The failure of clinical–DWI mismatch model to differentiate patients according to their response to reperfusion is explained by the limited agreement in patient selection between this model and the PWI–DWI mismatch criteria from the DEFUSE 2 study. One third of the patients who met these PWI–DWI mismatch criteria did not meet the clinical–DWI mismatch criteria; these patients had an increased likelihood of favorable clinical response with reperfusion (OR, 9.6) thus obscuring a differential response to reperfusion between patients with and without clinical–DWI mismatch. For similar reasons, the primary MRA–DWI mismatch criteria did not differentiate patients according to their response to reperfusion.

We explored alternatives to the primary MRA–DWI mismatch criteria. The selection based on stricter angiographic
criteria that limit inclusion to patients with ICA or M1 occlusions (Table 2) improves the specificity for identifying patients in whom reperfusion is associated with a favorable clinical response. For example, patients who meet strict MRA–DWI mismatch criteria (ie, ICA or M1 occlusions and a DWI volume <25 mL) show a very strong association between reperfusion and favorable clinical outcome (OR, 12.9). Randomized controlled trials that use such strict MRA–DWI criteria to select patients are thus most likely to demonstrate benefit of acute stroke treatments aimed at restoring perfusion. However, this comes at a cost of reducing the proportion of patients with mismatch from ≈80% with the PWI–DWI criteria from the DEFUSE 2 study to 50% with strict MRA–DWI criteria. This leads to the exclusion of some patients who may benefit from

Table 2. Association Between Reperfusion and Favorable Clinical Response According to Mismatch Status

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Penumbral Criteria</th>
<th>Core Criteria</th>
<th>Mismatch Present</th>
<th>Mismatch Absent</th>
<th>( P ) Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEFUSE 2 PWI–DWI mismatch criteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWI–DWI</td>
<td>PWI/DWI ≥1.8 and PWI-DWI ≥15 mL</td>
<td>DWI &lt;70 mL</td>
<td>7.1</td>
<td>2.0–25.0</td>
<td>76</td>
</tr>
<tr>
<td>MRA–DWI mismatch criteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MRA–DWI v1</td>
<td>ICA or M1 occlusion</td>
<td>DWI &lt;25 mL</td>
<td>7.6</td>
<td>1.4–39.7</td>
<td>58</td>
</tr>
<tr>
<td>MRA–DWI v2</td>
<td>ICA or M1 occlusion</td>
<td>DWI &lt;15 mL</td>
<td>12.9</td>
<td>1.9–88.8</td>
<td>50</td>
</tr>
<tr>
<td>Clinical–DWI mismatch criteria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clinical–DWI NIHSS ≥ 8</td>
<td>DWI &lt;25 mL</td>
<td>4.3</td>
<td>1.1–17.3</td>
<td>60</td>
<td>3</td>
</tr>
</tbody>
</table>

ACA indicates anterior cerebral artery; CI, confidence interval; DEFUSE, Diffusion and Perfusion Imaging Evaluation for Understanding Stroke Evolution; DWI, diffusion-weighted imaging; ICA, internal carotid artery; MRA, magnetic resonance angiography; OR, odds ratio; PCA, posterior cerebral artery; and PWI, perfusion-weighted imaging.

*\( P \) value for the interaction term Reperfusion×Mismatch. ORs are adjusted for age, natural log of DWI, and previous stroke.

Figure. Distribution of 30-day modified Rankin Scale (mRS) scores among patients with and without magnetic resonance angiography–diffusion-weighted imaging (MRA–DWI) mismatch defined as internal carotid artery or M1 occlusion and DWI volume <25 mL (v3). The numbers in the box indicate the percentage of patients belonging to each mRS category.
reperfusion such as patients with DWI lesion volumes in the 25 to 50 mL range.

Less strict MRA–DWI mismatch selection criteria, defined as the presence of an ICA or MCA–M1 branch occlusion and a DWI lesion volume <50 mL, select ≥75% of the population, agree more closely with selection based on the PWI–DWI mismatch criteria from the DEFUSE 2 study, and were associated with a differential response to reperfusion. Given the good agreement between this MRA–DWI mismatch model and the PWI–DWI mismatch criteria from DEFUSE 2, and given the previously reported DEFUSE 2 results showing a differential response to reperfusion according to PWI–DWI mismatch criteria, it is not surprising that these MRA–DWI mismatch criteria are also associated with a differential response to reperfusion. These MRA–DWI mismatch criteria, therefore, present a suitable alternative to the PWI–DWI mismatch.

The post hoc nature of the analyses is a limitation of this study. The results, therefore, require validation in independent cohorts. Another limitation is that, despite the positive association between reperfusion and favorable outcome in patients with mismatch shown in this study and in previous cohort studies,10,21 patient selection based on perfusion imaging is not supported by results from randomized controlled trials. Desmoteplase in Acute Ischemic Stroke Trial (DIAS) II, a randomized controlled trial of intravenous desmoteplase, selected patients based on a visual, qualitative assessment of mismatch on CTP or PWI–DWI maps and failed to show a benefit from treatment in this population. Recently, the Mechanical Recanalization and Recanalization of Stroke Clots Using Embolectomy (MR RESCUE) trial failed to show a benefit from endovascular therapy in patients with a penumbra profile based on MR or CT perfusion imaging.11 Several factors may have contributed to the negative results of these studies. This includes the introduction of heterogeneity in the patient population because both CT perfusion and MRI-based criteria were used, limited effectiveness of the intervention, and inclusion of patients who may not benefit from reperfusion. Patients who do not benefit from reperfusion may include those with mild deficits due to distal MCA branch occlusions,22 patients with large stroke cores who have a poor prognosis regardless of treatment,23 and patients who have no or little penumbral tissue because the volume of critically hypoperfused tissue is overestimated.24 Ultimate proof of the utility of image-based patient selection, therefore, will need to come from randomized controlled trials that demonstrate a benefit of treatment in patients with mismatch and no benefit in patients without mismatch.

In conclusion, the response to reperfusion varies markedly among patients. The PWI–DWI mismatch criteria of the DEFUSE 2 study and MRA–DWI mismatch criteria that require an ICA or MCA–M1 occlusion and a DWI lesion volume <50 mL show good agreement in terms of patient selection and perform optimally in terms of differentiating patients according to their response to reperfusion. Randomized controlled trials that use these criteria to select patients are, therefore, warranted.

Acknowledgments

N.K. Mishra contributed to study design, analyses, and drafting of the article. G.W. Albers contributed to study design, supervision, data acquisition, editing, and funding. S. Christensen contributed to data analysis, image analyses, supervision, and editing. M. Marks contributed to data acquisition. S. Hamilton contributed to data acquisition and analysis. M. Straka contributed to data acquisition and image analysis. J.T.P. Liggins contributed to writing. S. Kemp contributed to data acquisition and supervision. M.G. Lansbergen contributed to study design, drafted article, supervision, and funding.

Sources of Funding

The work was supported by the National Institute for Neurological Disorders and Stroke (R01 NS03932505 and R01 NS075209).

Disclosures

Dr Albers: equity interest in IschemaView; advisory board: CoviDien, Codman, and Lundbeck. Dr Christensen: consultant to IschemaView Inc and Toshiba. Dr Straka: consultant for IschemaView Inc. Dr Bammer: owner/stockholder of IschemaView Inc. The other authors have no conflicts to report.

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Comparison of Magnetic Resonance Imaging Mismatch Criteria to Select Patients for Endovascular Stroke Therapy

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Stroke. published online April 3, 2014;
Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0039-2499. Online ISSN: 1524-4628

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