Imaging of the brain in acute ischaemic stroke: comparison of computed tomography and magnetic resonance diffusion-weighted imaging

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Background and objectives: Controversy exists about the optimal imaging technique in acute stroke. It was hypothesised that CT is comparable with DWI, when both are read systematically using quantitative scoring.

Methods: Ischaemic stroke patients who had CT within six hours and DWI within seven hours of onset were included. Five readers used a quantitative scoring system (ASPECTS) to read the baseline (b) and follow up CT and DWI. Use of MRI in acute stroke was also assessed in patients treated with tissue plasminogen activator (t-PA) by prospectively recording reasons for exclusion. Patients were followed clinically at three months.

Results: bDWI and bCT were available for 100 consecutive patients (admission median NIHSS = 9). The mean bDWI and bCT ASPECTS were positively related (p<0.001). The level of interrater agreement ranged from good to excellent across all modalities and time periods. Bland–Altman plots showed more variability between bCT and bDWI than at 24 hours. The difference between bCT and bDWI was ≤ 2 ASPECTS points. Of bCT scans with ASPECTS 8–10, 81% had DWI ASPECTS 8–10. Patients with bCT ASPECTS of 8–10 were 1.9 times more likely to have a favourable outcome at 90 days than those with a score of 0–7 (95% CI 1.1 to 3.1, p = 0.002). The relative likelihood of favourable outcome with a bDWI ASPECTS of 8–10 was 1.4 (95% CI 1.0 to 1.9, p = 0.10). Of patients receiving t-PA 45% had contraindications to urgent MRI.

Conclusion: The differences between CT and DWI in visualising early infarction are small when using ASPECTS. CT is faster and more accessible than MRI, and therefore is the better neuroimaging modality for the treatment of acute stroke.

Tissue plasminogen activator (t-PA) when administered for acute ischaemic stroke produces improved outcome, and benefit may exist within a treatment window as long as six hours. However, a small proportion of patients are harmed by symptomatic intracerebral haemorrhage, and more importantly, a large number of patients still have a functionally dependent outcome despite treatment. The importance of early ischaemic changes (EIC) on computed tomography (CT) have been underappreciated until recently, but there is accumulating evidence that EIC on CT prior to the administration of acute stroke therapies can predict both functional outcome and the risk of intracerebral haemorrhage. Recent advances in neuroimaging, particularly diffusion-weighted imaging (DWI) and perfusion magnetic resonance imaging (MRI), have raised hopes about accurate identification of ischaemic tissue and the ability to discriminate between dead and salvageable ischaemic brain. It is considered that acute ischaemic lesions in DWI can be identified with greater sensitivity than in either conventional MRI or CT. The technical superiori...
PATIENTS AND METHODS

Patients
We recruited patients for this study between October 1999 and July 2001. The principal inclusion criterion for the study was acute disabling ischaemic stroke (National Institutes of Health Stroke Scale (NIHSS) score equal or greater than 1), measured by the NIHSS score within six hours of onset of stroke. We documented the admission NIHSS and enrolled patients if they deteriorated neurologically and fulfilled the inclusion criteria. We included all stroke subtypes (that is, large artery cortical strokes as well as posterior circulation and lacunar strokes). Patients were not excluded on the basis of age alone. All patients sequentially had a CT brain scan within six hours of the onset of stroke followed by an MRI within 7 hours of onset. The rationale for this inclusion criterion was that there is convincing evidence from meta-analyses including tPA trial data that the therapy is beneficial for acute ischaemic stroke as long as six hours from the onset of symptoms when the CT scan excludes haemorrhage. An additional hour was allowed in such patients to organise the MRI. Some patients who met accepted criteria were treated with intravenous thrombolysis and the ensuing MRI was performed while the tPA infusion was running. No attempt was made to randomise patients to CT or MRI as the initial imaging technique because CT is considered to be the standard imaging modality among patients being considered for tPA, and to avoid unnecessary treatment delays we collected all information prospectively, including the demographic characteristics, NIHSS score on initial presentation, time of symptom onset and time at each imaging procedure, and functional outcome at three months assessed by the modified Rankin scale (mRS). An experienced stroke neurologist assessed the patients at presentation. A nurse practitioner blinded to admission and imaging details administered the mRS. We defined favourable outcome as independence (mRS 0–2). The data include all patients in a practitioner blinded to admission and imaging details who were treated with thrombolysis and the ensuing MRI was performed at 24 hours.

Image reading protocol
Each of five readers blinded to all clinical and patient information apart from side of stroke symptoms independently read each patient’s set of images. The rationale for this was to make the imaging interpretation more clinically relevant. The readers were two “expert” neuroradiology raters and three stroke neurologists. Each set of images was read in isolation and independent of another sequence and technique. The sequence of reading had a specific order: baseline CT, FLAIR, and DWI folllowed by the follow-up CT scan, FLAIR, and DWI. There was a minimum period of one week between readings of images from the same patient. Each baseline and follow up axial CT or MRI was assessed for ischaemic change and quantified using ASPECTS. The ASPECTS regions were idealised from two standardised axial cuts, but in practice each reader reviewed the entire sequence of slices to determine the score. The middle cerebral artery territory was allotted 10 points. A single point was subtracted for an area of EIC on CT, which included any or all of parenchymal hypodensitisation, loss of grey–white differentiation, and focal brain swelling. Parenchymal hypodensitisation was defined as a region of abnormally decreased attenuation of brain structures relative to attenuation of other parts of the same structures or of the contralateral hemisphere. We defined focal brain swelling as any focal narrowing of the cerebrospinal fluid space due to compression by adjacent brain structures producing effacement of the cortical sulci or ventricular compression. For FLAIR and DWI sequences, focal ischaemia was defined by hyperintense signal. ASPECTS methodology was applied to the MRI sequences in an analogous topographical technique as used for CT. A CT or MRI scan without involvement of these areas received an ASPECTS score of 10 points. A score of 0 indicated complete ischaemic involvement throughout the middle cerebral artery territory. All CT and MRI scans were included in the analysis irrespective of stroke vascular stroke territory involved. For instance, a stroke isolated to the brainstem or cerebellum would be given an ASPECTS of 10.

Statistical analysis
The unit of analysis for comparing CT with DWI was the median of the five readers’ assessment of a patient’s image. The median was chosen to represent a consensus measure of a patient’s ASPECTS for a particular modality. Intermodality agreement (among CT, DWI, and FLAIR) was estimated using an intraclass correlation coefficient from a random effects analysis of variance model. Estimates of interrater agreement, using the single reading as the unit of analysis, were calculated from a two-way mixed effects analysis of variance (modality was the fixed effect and rater was the random effect). Levels of clinical significance for agreement were defined according to the criteria: >0.75 as excellent, 0.40–0.75 as fair to good, and <0.40 as poor. A Bland–Altman plot was used to illustrate the magnitude of differences between baseline CT and DWI ASPECTS, and between 24 h CT and DWI ASPECTS. Using median scores for each patient and assuming DWI as the reference test the sensitivity and specificity of the baseline CT ASPECTS is presented using a cut-off value of ASPECTS >7 versus ASPECTS ≤7 as has been described previously. In addition, the sensitivity and specificity of each individual baseline CT ASPECTS point is presented by considering the baseline DWI ASPECTS as the gold standard using the median score of the five readers at each ASPECTS point (which yields at
minimum a 3 of 5 consensus at each point). Rate ratios (RR) were used to quantify the relation between the dichotomised baseline ASPECTS (categorised as 0–7 vs 8–10) and favourable patient outcome at 90 days. The chosen ASPECTS cut-points have been previously used for acute ischaemic stroke patients. Exact methods were used where appropriate at conventional levels of statistical significance (\(z = 0.05\)).

**RESULTS**

We enrolled 100 consecutive patients into the study (69% men, mean (SD) age 68 (13.9) years). The admission median NIHSS was 9 (interquartile range 3–16, range 0–32). Two patients were neurologically normal on admission (NIHSS = 0), but both deteriorated neurologically prior to imaging (NIHSS 7 and 19). The mean time from symptom onset to CT was 117 (70) minutes compared with 219 (80) minutes to initiating MRI (mean difference of 102 (51) minutes, p<0.001). A total of 82 patients had CT scans within three hours of the onset of symptoms, of which 42 also had an MRI within the same period. All patients had follow up imaging at 24 hours (80 patients had MRT, 71 patients had CT, and 56 had both). Thirty nine patients received tPA: 33 patients received intravenous tPA alone, and six received a combined approach of intravenous tPA followed by intra-arterial thrombolysis into the angiographically defined thrombus. There were nine deaths, of which two were due to tPA related fatal intracerebral haemorrhage. At three months 61% of the patients were independent (mRS 0–2) (two patients were lost to follow-up at three months).

The median baseline CT ASPECTS was 9, and the median baseline DWI ASPECTS was 8. Early CT ischaemic change was found in 66% of the patients (95% confidence interval (CI) 56 to 75), and areas of hyperintense signal were identified in 81% of the DWI scans (95% CI 72 to 88). Six patients (6%) had evidence of posterior circulation ischaemia on baseline DWI with or without coincident anterior circulation stroke.

The level of interrater agreement ranged from good to excellent across all modalities and time periods (table 1). The level of agreement between FLAIR and both CT and DWI was poor at baseline, but reached excellent at 24 hours. Only the level of agreement between CT and DWI was consistently excellent at baseline and at 24 hours. The time interval between baseline CT and DWI scans did not affect the level of agreement: \(r = 0.80, n = 71, 95\% \text{ CI } 0.71 \text{ to } 1 \) when the time interval was \(<120 \text{ minutes}; \) and \(r = 0.81, n = 29, 95\% \text{ CI } 0.67 \text{ to } 1 \) when the time interval was \(>120 \text{ minutes.} \) The mean baseline DWI ASPECTS was positively related to the baseline CT ASPECTS (\(p<0.001, \text{fig 1}\)). The linear relationship between the baseline CT ASPECTS and DWI ASPECTS (\(\beta = 0.82\) (95% CI 0.73–0.92)) also applied to: follow up CT predicts follow up DWI (\(\beta = 0.85\) (95% CI 0.83–1.04)); follow up FLAIR versus follow up DWI (\(\beta = 0.99\) (95% CI 0.92–1.07)); follow up CT predicts follow up FLAIR (\(\beta = 0.90\) (95% CI 0.80–1.0)).

The Bland–Altman plots showed more variability between CT and DWI at baseline (fig 2A) than at 24 hours (fig 2B). The difference between CT and DWI at baseline was no greater than 2 ASPECTS points. The sensitivity and specificity of the baseline CT ASPECTS using baseline DWI ASPECTS as the reference test is presented in table 2, and for each individual ASPECTS point in table 3. These figures can be compared with baseline CT ASPECTS and follow up CT ASPECTS (\(n = 71\)) as a reference for irreversible tissue injury (sensitivity 91%; specificity 71%). We would recommend caution in the interpretation of the latter as EIIC consisting solely of swelling without either loss of grey–white differentiation or parenchymal hypointenaltuion may not represent irreversible tissue injury. There were 34 patients with baseline CT ASPECTS score of 10. Of these, 18 had baseline DWI ASPECTS score of 10. The baseline DWI was less than 10 in 16: ASPECTS 9 (\(n = 8\)); ASPECTS 8 (\(n = 6\)); ASPECTS 7 (\(n = 2\)). Baseline DWI was therefore abnormal in 47% (95% CI 30 to 65) of this select group.

Patients with a baseline CT ASPECTS of 8–10 were 1.9 times more likely to have a favourable outcome at 90 days than those with a score of 0–7 (95% CI 1.1 to 3.1, \(p = 0.002\)). The relative likelihood of favourable outcome was less with a baseline DWI ASPECTS of 8–10 (RR 1.4, 95% CI 1.0 to 1.9, \(p = 0.10\)).

Of 112 patients who were treated with tPA during the study period, 39 patients (34.8%) were enrolled into the present study. Fifty patients (45% of the 112) had contraindications to urgent MRI, a very similar figure to a recent report: 26 (23.2%) were medically unstable and unsafe for MRI (reduced level of consciousness, vomiting, cardiac arrhythmia, aspiration) despite our ability to monitor blood

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**Table 1**

<table>
<thead>
<tr>
<th>Modality</th>
<th>Intermodality agreement (95% CI)</th>
<th>Intermodality clinical significance</th>
<th>Interrater agreement (95% CI)</th>
<th>Interrater clinical significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline CT vs baseline DWI</td>
<td>0.80 (0.73 to 1)</td>
<td>Excellent</td>
<td>0.80 (0.74 to 1)</td>
<td>Excellent</td>
</tr>
<tr>
<td>Baseline CT vs baseline FLAIR</td>
<td>0.06 (0.00 to 1)</td>
<td>Poor</td>
<td>0.66 (0.48 to 1)</td>
<td>Good</td>
</tr>
<tr>
<td>Baseline DWI vs baseline FLAIR</td>
<td>0.00 (0.00 to 1)</td>
<td>Poor</td>
<td>0.68 (0.51 to 1)</td>
<td>Good</td>
</tr>
<tr>
<td>24 h CT vs 24 h DWI</td>
<td>0.88 (0.83 to 1)</td>
<td>Excellent</td>
<td>0.88 (0.85 to 1)</td>
<td>Excellent</td>
</tr>
<tr>
<td>24 h CT vs 24 h FLAIR</td>
<td>0.88 (0.83 to 1)</td>
<td>Excellent</td>
<td>0.88 (0.84 to 1)</td>
<td>Excellent</td>
</tr>
<tr>
<td>24 h DWI vs 24 h FLAIR</td>
<td>0.91 (0.88 to 1)</td>
<td>Excellent</td>
<td>0.91 (0.89 to 1)</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

95% confidence intervals (CI) are one-sided.

CT, computed tomography; DWI, diffusion-weighted imaging; FLAIR, fluid attenuated inversion recovery.
pressure, pulse oximetry; 14 (12.5%) patients were too restless to cooperate with imaging; 10 (8.9%) had MRI exclusions (pacemakers, cardiac prostheses). The remaining 23 (20.5%) either did not meet the time restrictions of the study or were not imaged because of unavailability or servicing of the MR scanner.

**DISCUSSION**

Our study shows that CT and DWI are comparable for detecting and quantifying signs of cerebral ischaemia in acute disabling stroke when they are of good quality and are assessed systemically using ASPECTS. However, this does not imply the two modalities are equivalent. ASPECTS values were lower for diffusion MR images implying that DWI is more sensitive than CT at detecting ischaemic tissue changes. Analogous to CT stroke lesion quantification, ASPECTS provides a reliable and novel method of assessing the DWI stroke lesion, despite differences in the image contrast mechanisms. There is a positive relation between the CT ASPECTS and the DWI ASPECTS—that is, CT predicts the DWI lesion performed at a later time point (fig 1). DWI was performed on average 102 minutes after CT and may have accounted for some of the differences in ASPECTS values, although statistically we were not able to demonstrate that time was a confounder.

The interobserver reliability was very good between the neuroradiologists and stroke neurologists and suggests that the application of ASPECTS in acute stroke can be generalised. It has been previously shown that radiology trainees and prospective non-expert assessment of the CT at the bedside can obtain very good interobserver reliability using ASPECTS.\(^6\)\(^2\) \(^5\) However, despite excellent intermodality

### Table 2

<table>
<thead>
<tr>
<th>Test</th>
<th>DWI ASPECTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;7</td>
</tr>
<tr>
<td>CT ASPECTS &gt;7</td>
<td>54</td>
</tr>
<tr>
<td>CT ASPECTS &lt;7</td>
<td>4</td>
</tr>
</tbody>
</table>

|     |     |     |      |
|     | 58 | 42 | 100  |

Sensitivity = 54/67 = 0.81.
Specificity = 29/33 = 0.88.
Positive predictive value = 54/58 = 0.93.
Negative predictive value = 29/42 = 0.69.

See table 1 for abbreviations.

### Table 3

<table>
<thead>
<tr>
<th>Individual ASPECTS point</th>
<th>Sensitivity</th>
<th>95% CI</th>
<th>Specificity</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal capsule</td>
<td>1.00</td>
<td>0.96 to 1.00</td>
<td>0.00</td>
<td>0.00 to 0.37</td>
</tr>
<tr>
<td>Caudate nucleus</td>
<td>0.98</td>
<td>0.93 to 0.99</td>
<td>1.00</td>
<td>0.48 to 1.00</td>
</tr>
<tr>
<td>Lenticular nucleus</td>
<td>0.92</td>
<td>0.84 to 0.97</td>
<td>0.81</td>
<td>0.54 to 0.96</td>
</tr>
<tr>
<td>Insula</td>
<td>0.90</td>
<td>0.79 to 0.97</td>
<td>0.67</td>
<td>0.52 to 0.80</td>
</tr>
<tr>
<td>Cortical regions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>0.88</td>
<td>0.91 to 0.99</td>
<td>0.97</td>
<td>0.47 to 0.99</td>
</tr>
<tr>
<td>M2</td>
<td>0.89</td>
<td>0.79 to 0.96</td>
<td>0.59</td>
<td>0.41 to 0.75</td>
</tr>
<tr>
<td>M3</td>
<td>0.94</td>
<td>0.86 to 0.98</td>
<td>0.56</td>
<td>0.31 to 0.78</td>
</tr>
<tr>
<td>M4</td>
<td>0.93</td>
<td>0.86 to 0.98</td>
<td>0.44</td>
<td>0.18 to 0.79</td>
</tr>
<tr>
<td>M5</td>
<td>0.87</td>
<td>0.73 to 0.95</td>
<td>0.53</td>
<td>0.39 to 0.66</td>
</tr>
<tr>
<td>M6</td>
<td>0.97</td>
<td>0.91 to 0.99</td>
<td>0.31</td>
<td>0.14 to 0.52</td>
</tr>
</tbody>
</table>

Figure 2 (A) Bland–Altman plot of baseline DWI (bDWI) and CT (bCT) ASPECTS. The mean ASPECTS difference between the two modalities was +0.43 indicating that slightly more ischaemic change is observed on average in DWI scans. Random jitter has been added to illustrate the number of measurements at each ASPECTS point. The horizontal lines represent the mean difference in scores and the mean (SD). (B) Bland–Altman plot of 24 hour follow up DWI (fuDWI) and CT (fuCT) ASPECTS. The mean ASPECTS difference between the two modalities was +0.64 indicating that more ischaemic change is observed on average in DWI scans. Random jitter has been added to illustrate the number of measurements at each ASPECTS point. The horizontal lines represent the mean difference in scores and the mean (SD).
The strong evidence of benefit from intravenous thrombolysis based upon a systematic review (Cochrane) of six randomised clinical trials is heavily time dependent. While CT and MRI provide complementary information in some respects, time dictates choosing one imaging procedure over the other. In acute stroke patients, MRI appears to be the imaging technique of choice, as it is sensitive to areas of ischaemic brain with restricted diffusibility of water and can detect very small areas of ischaemic cerebrum. However, controversy still remains as to whether the DWI lesion represents irreversibly damaged tissue (that is, the “core”). Recent published work suggests that the DWI lesion includes both core and penumbra, and that an apparent diffusion threshold (ADC) cannot be determined within the first few hours of stroke.

Studies comparing CT and DWI, including those reported recently, used the 1/3 middle cerebral artery (MCA) rule which broadly categorises stroke size into “large” or “small”, whereas ASPECTS allows the opportunity to quantify topographical differences between CT and DWI. The improved reliability of ASPECTS over the 1/3 MCA rule in the detection of EIC has been recently contradicted. One study randomised the order in which CT and MRI were performed. In this study, the main outcome was the presence or absence of stroke signs on the neuroimaging procedure. The study did not assess the feasibility of performing urgent MRI in acutely ill stroke patients or address the clinical impact of DWI.

The two modalities provide complementary information in terms of the extent of the stroke lesion but there are also significant differences. DWI is sensitive to areas of ischaemic brain with restricted diffusibility of water and can detect very small areas of ischaemic cerebrum. However, controversy still remains as to whether the DWI lesion represents irreversibly damaged tissue (that is, the “core”). Recent published work suggests that the DWI lesion includes both core and penumbra, and that an apparent diffusion threshold (ADC) cannot be determined within the first few hours of stroke. This issue is critical if DWI is to be used in patient selection for thrombolysis. The value of CT in detecting ischaemic brain injury is supported by this study. Early parenchymal hypoattenuation seen in CT soon after stroke has been previously correlated with early cytotoxic oedema, but our study would also support the hypothesis that hypoattenuation, particularly observed in the cortical areas may represent changes in blood flow.

Reliance on MRI as the preferred imaging modality for the urgent assessment of stroke patients may restrict the use of the therapy in eligible patients; acutely ill stroke patients make very poor MRI subjects. This is of even greater importance in the light that a superior clinical benefit of DWI over CT in terms of determining prognosis could not be defined in this study when employing ASPECTS. Approximately half of patients treated with intravenous tPA and considered eligible for this study were discovered to have had an exclusion to MRI during the screening process, or were intolerant of the procedure or were considered to be medically unstable. This observation is consistent with a smaller study in the literature. Overreliance on DWI MRI may restrict the availability and accessibility of thrombolysis for acute stroke patients.

The strong evidence of benefit from intravenous thrombolysis based upon a systematic review (Cochrane) of six randomised clinical trials is heavily time dependent. While CT and MRI provide complementary information in some respects, time dictates choosing one imaging procedure before making a therapeutic decision. Both MR and CT are evolving ultrafast imaging protocols that can provide supplementary non-invasive angiographic and tissue perfusion data. Also of importance, gradient echo sequences are
available for the detection of haemorrhagic transformation and “microbleeds” with greater sensitivity than CT. However, within current stroke guidelines for thrombolysis administration, and outside of the current three hour paradigm both multimodal MR or CT imaging (CT angiography and CT perfusion) may show great promise in refining patient selection but neither technique has yet been shown to be more efficacious than non-contrast CT.

SUMMARY

Among patients with moderate to severe acute ischemic stroke, the ability of CT to detect signs of early cerebral infarction is comparable with DWI. The decision about which imaging technology to use in acute stroke will depend on the feasibility and availability of that modality. Non-contrast CT is accessible, versatile, and fast, and therefore is a better choice in the imaging of acute stroke than MRI when considering thrombolytic therapy. Its use extends beyond that of identifying intracranial haemorrhage. We emphasise the importance of clinical assessment of the patient, supported by a systematic approach (ASPECTS) to assessing the CT for defining the extent of ischaemic brain injury.

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