The Impact of CT Perfusion Threshold on Predicted Viable and Nonviable Tissue Volumes in Acute Ischemic Stroke

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ABSTRACT

BACKGROUND AND PURPOSE: Perfusion imaging is used for patient selection in clinical practice and trials. Postprocessing and definitions of tissue viability are nevertheless not standardized. We compared the lesion volumes generated with two well-recognized perfusion tissue definitions in a single-center phase 2 thrombolysis study.

METHODS: We analyzed perfusion imaging data from the Alteplase-Tenecteplase Trial Evaluation for Stroke Thrombolysis (ATTEST) study using two popular tissue viability thresholds (ischemic core definition: (1) cerebral blood volume \( < 2.0 \text{ mL}/100 \text{ g}^{-1} \) or (2) relative cerebral blood flow \( < 40\% \) that of the contralesional hemisphere and relative delay time \( > 2 \) seconds; penumbra definitions: (1) mean transit time \( > 145\% \) of contralesional hemisphere or (2) relative delay time \( < 2 \) seconds). We compared volumes of core and penumbra, mismatch ratio, percentage, and volume of penumbra salvaged at 24 hours.

RESULTS: We included 73 (tenecteplase = 36, alteplase = 37) patients who had analyzable perfusion lesions at baseline. Significant differences were found in core volumes using the two thresholds (33 \( \pm 37 \text{ mL} \) vs. 26 \( \pm 32 \text{ mL} \), \( P < .001 \)), as was mismatch ratio (2.5 \( \pm .9 \) vs. 4.2 \( \pm 3.7 \), \( P < .001 \)). The volume of penumbra salvaged at 24 hours (30 \( \pm 19 \text{ mL} \) vs. 35 \( \pm 26 \text{ mL} \), \( P = .043 \)) differed significantly, although the percentages of penumbra salvaged did not (\( P = .2 \)). No difference was found between the two thrombolytic agents in the percentages of penumbra salvaged using either threshold.

CONCLUSION: Two commonly used tissue definitions generated significantly different lesion volumes and mismatch ratios. Threshold selection may have significant impact on patient selection for trials or reperfusion therapies.

Keywords: Perfusion imaging, patient selection, reperfusion, outcome.

Introduction

Computed tomography perfusion (CTP) imaging has been used widely in both clinical and research settings to select candidates for reperfusion therapy, or as a biomarker for efficacy and safety. There is no consensus regarding the most accurate thresholds that define ischemic core or penumbral tissue; however, literature-reported viability thresholds were derived using a variety of methods, some based on very small numbers of cases, and implementation on commercial software varies.

We aimed to compare the lesion volumes generated by two commonly used viability thresholds, and explored potential impact on patient selection.

Methods

We used the imaging data from the Alteplase-Tenecteplase Trial Evaluation for Stroke Thrombolysis (ATTEST) trial that compared the efficacy and safety of alteplase and tenecteplase as thrombolytic agents in acute ischemic stroke, in which imaging variables were the primary outcome but patients were not selected on the basis of imaging criteria. The study protocol of ATTEST has been detailed elsewhere. Briefly, eligible thrombolysis candidates within 4.5 hours of onset were randomized to receive alteplase (.9 mg/kg to a maximum 90 mg) or .25 mg/kg tenecteplase (to a maximum 25 mg). Baseline imaging comprised noncontrast CT (NCCT), CT perfusion (CTP), and CT angiography (CTA). CTP and CTA were undertaken either before or immediately following the thrombolysis bolus to avoid treatment delay. Follow-up imaging including NCCT and CTA was carried out between 24 and 48 hours postthrombolysis.

All scans were performed on a Philips Brilliance 64 multi-detector scanner. Whole brain NCCT was acquired first (5 mm slice thickness FOV 218 \( \times 218 \text{ mm} \), 120 kV, 171 mA or 0.9 mm slice thickness, FOV 250 \( \times 250 \text{ mm} \), 120 kV, 404 mA) followed by CTP with 40 mm slab coverage from the basal ganglia (8 \( \times 5 \) mm slices, FOV 25 cm, 80 kVp, 476 mA, 2 second cycle time, 30 cycles) using a 50 mL contrast bolus administered at 5 mL/second (Xenetix 350) via a large-gauge cannula. A CTA covering aortic arch to the top of the lateral ventricles (0-67 mm slice thickness, 120 kV, 475 mA) was acquired during the first arterial past of contrast (Xenetix 350, 60 mL, followed by 30 mL of saline bolus, both given at 5 mL/second). Follow-up CTA covered from base of skull to the top of lateral ventricles.

The detailed postprocessing and imaging analysis methods were described in the main study. In summary, CTP was processed offline with MIStar (Apollo Medical Imaging...
Technology, Melbourne, VIC, Australia), which uses a delay-corrected single-value decomposition (SVD) deconvolution algorithm.

We used the following definitions:

- Penumbra volume salvaged = penumbra volume on baseline CTP – penumbra volume that infarcted on 24 hours NCCT;
- Percentage of penumbra salvaged = (penumbra salvage/penumbra Volume) × 100.

We compared two tissue viability thresholds:

- Wintermark’s definition (MW):² Irreversible tissue – tissue with reduced cerebral blood volume (CBV) < 2.0 mL/100 g; viable tissue – tissue with relative mean transit time (MTT) > 145% of contralesional hemisphere and CBV > 2.0 mL/100 g.
- Bivard’s definition (AB):³ Irreversible tissue – tissue with reduced CBF (relative CBF < 40% that of the contralesional hemisphere) and prolonged delayed time (DT) (relative DT > 2 seconds); viable tissue – tissue with relative DT > 2 seconds and rCBF > 40%.

All imaging studies were analyzed by two research fellows (XH and BC) twice independently with an interval of 4 weeks between processing, and blind to CTA findings. Interrater agreements were evaluated. For baseline irreversible tissue volume, the intraclass correlation coefficient was .96 (95% limits of agreement −16–20 mL). For penumbra volumes, the correlation coefficient was .91 with 95% limits of agreement of −30–30 mL. The average of four readings was taken as the final reading for analysis.

Values were expressed as mean and standard deviation (SD) or median and interquartile range (IQR) depending on normal distribution or not. Paired T-tests and related-samples Wilcoxon signed-rank tests were used to compare the results produced by the two definitions. The differences in the percentage or volume of penumbra salvaged between the two treatment groups were compared with independent samples T tests. Statistical analyses were performed with IBM SPSS statistics (SPSS, Chicago, Illinois, USA v.19) and StatsDirect 2.8.

### Results

Among the 104 participants in the ATTEST study, 73 (mean age [SD] 73 [11] years; median baseline NIHSS [IQR] 13 [9–19]) had measureable perfusion lesions, of whom 36 received tenecteplase and 37 alteplase, at a mean (SD) 189 (46) minutes from symptoms onset. Sixty-nine out of 73 (93.5%) patients had occlusion on baseline CTA.

<table>
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<th>Table 1. Differences of Lesion Size and Penumbra Salvaged between the Measurements of the Two Tissue Viability Thresholds</th>
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AB = Bivard; MW = Wintermark; SD = standard deviation; IQR = interquartile range; CI = confidence interval; CTA = CT angiography; * P-value was calculated using paired T-tests for mean and related-samples Wilcoxon signed-rank tests for median. *Recanalization was defined as Thrombolysis in Myocardial Infarction (TIMI) 2–3.²²,²³

Fig 1. (A) Interobserver Bland-Altman 95% agreement plot for core volume between Bivard (AB) and Wintermark (MW) thresholds (mean [green] + 1.96SD [black]). Intraclass correlation coefficient = .89; 95% limits of agreement (−36.9 to 22.1). (B) Interobserver Bland-Altman 95% agreement plot for penumbra volume between AB and MW thresholds. Intraclass correlation coefficient = .78; 95% limits of agreement (−37 to 45).
Fig 2. We applied four commonly used imaging selection criteria to the 73 patients. This graph shows the percentage of patients that is excluded by imaging selection using different criteria. (selection criteria 1: CT perfusion [CTP] mismatch ratio; selection criteria 2: CTP mismatch ratio and large vessel occlusion [internal carotid artery, M1 (middle cerebral artery from the origin to bifurcation/trifurcation), M2 (from bifurcation to circular sulcus of insula)]; selection criteria 3: CTP mismatch ratio, large vessel occlusion, and core volume < 70 mL; selection criteria 4: CTP mismatch ratio, large vessel occlusion, core volume < 70 mL, and penumbra volume > 20 mL). AB (Bivard) threshold: irreversible tissue – tissue with reduced cerebral blood flow (CBF) (relative CBF < 40% that of the contralesional hemisphere) and prolonged delayed time (DT) (relative DT > 2 seconds); viable tissue – tissue with relative DT > 2 seconds and rCBF > 40%; MW (Wintermark) threshold: irreversible tissue – tissue with reduced cerebral blood volume (CBV) < 2.0 mL/100 g; viable tissue – tissue with relative mean transit time (MTT) > 145% of contralesional hemisphere and CBV > 2.0 mL/100 g.

Table 1 shows the differences between the lesion volumes measured with two thresholds, core/penumbra mismatch ratio, the volume, and percentage of penumbra salvaged at 24 hours. There was a systematic difference in core and penumbra volume estimates with the AB method estimating a smaller core and a larger penumbra compared to the MW thresholds (Fig 1). The mean differences of the volume and percentage of penumbra salvaged at 24 hours between the alteplase- and tenecteplase-treated groups using two thresholds were not different.

The numbers with different “mismatch” ratios did not differ significantly between the two thresholds. The effects of applying different patient selection criteria from recent clinical trials including core:penumbra ratio, vessel occlusion, and core volume are shown in Figure 2. Differences in eligibility between the two thresholds ranged from 0% to 43% depending upon criteria.

Discussion
We observed that different CTP tissue viability thresholds led to significantly different estimates of core volume and mismatch ratio. There was no difference in penumbra salvage at 24 hours using the two thresholds, however.

Despite increasing clinical use, perfusion imaging analysis is not standardized, with variability in postprocessing algorithms and various combinations of perfusion parameters and thresholds to define core and penumbral tissue. The principal purpose of defining tissue viability by perfusion imaging is to better estimate the risk:benefit balance for reperfusion treatments. Baseline ischemic core and penumbral volumes correlate with clinical outcome after intravenous thrombolysis, and the presence of a “large core” in particular signifies higher risk of both intracerebral hemorrhage and significant brain edema. Observational data suggest that intravenous thrombolysis < 4.5 hours after onset or late endovascular reperfusion are not beneficial in the absence of a “target mismatch” pattern, defined as the presence of a minimum penumbra volume and ratio of penumbral to core. Operational definitions of penumbral and core may thus be important for appropriate treatment decisions, but a single definition of what thresholds constitute the most reliable estimates of tissue viability may not be possible, as these may depend on the factors noted below.

Comparison of six commonly used postprocessing software and different tissue definitions concluded that Bivard’s threshold with delay-corrected SVD algorithm was the most accurate among several used in currently available postprocessing algorithms. Optimal thresholds may differ due to factors other than the postprocessing algorithm, however, and may depend on other factors that have not been investigated systematically including the time window for treatment, the specific treatment intervention, and the speed of reperfusion.

Several multicenter reperfusion studies used perfusion biomarkers to select patients. Variability in thresholds applied by both commercial software and in centers may lead to
variation in patient selection, even with clear imaging selection criteria. Such variation may have contributed to the lack of apparent treatment effect in the DIAS-2 trial of desmoteplase,\textsuperscript{18} and reclassification of patients is common when comparing clinician interpretation and automated “core lab” processing.\textsuperscript{11} Recent endovascular reperfusion trials that used CTP penumbral selection applied different criteria for “target mismatch” although the same postprocessing software was employed. The implications of variability in these criteria on patient selection are illustrated in Figure 2.

Additional acquisition and processing time for multimodal CT assessment may delay administration of thrombolytic treatment, with typical average times for acquisition of multimodal imaging\textsuperscript{21} of 15 minutes. Whether the potential reduction in benefit resulting from this delay is mitigated by improved patient selection and consequently better outcomes within the 4.5 hours time window are under investigation in the ongoing Penumbra and Recanalisation Acute Computed Tomography in Ischaemic Stroke Evaluation (PRACTISE) trial.\textsuperscript{22}

We evaluated only the effect of different perfusion thresholds since other aspects of postprocessing were identical. Multicenter experience using different equipment and software analysis methods will almost certainly be more variable. Several studies have suggested that thresholded CBV is more accurate in defining irreversible tissue.\textsuperscript{23–25} However, some commercial software still uses CBV to define infarct core. In addition to the modest sample size, our study has several limitations. The algorithm used in MIStar is a modified SVD with compensation for the effects of arterial delay and dispersion,\textsuperscript{26} whereas the MW thresholds were derived with software based on the central volume principle.\textsuperscript{2} It is possible that MIStar is not optimized to process perfusion imaging using the MW definition, as it is not configured to allow direct thresholding of core tissue based on CBV.\textsuperscript{13} Our analysis was carried out prior to a recent report that tissue with tDT > 3 seconds more closely corresponds to penumbra than rDT > 2 seconds,\textsuperscript{11} which may affect our results. Longer acquisition times for CTP than were employed in our study may more fully characterize the time:attenuation curve, reducing the risk of truncation of the contrast bolus that may occur with low cardiac output states, and improving reliability of CBV and CBF estimation. Other technical limitations include using CT to measure final infarct volume, as 24 hours postthrombolysis, the infarcted tissue is still poorly defined, and the limited \textit{z}-axis coverage of CTP of 4 cm.

Conclusion

Different viability thresholds alone can generate significantly different core volume estimates leading to variable mismatch ratio. Clinicians need to consider standardized definitions and processing in multicenter studies.

References


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