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Automated CT angiography collateral scoring in anterior large vessel occlusion stroke: A multireader study

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Abstract

Background

Computed tomography (CT) angiography collateral score (CTA-CS) is an important clinical outcome predictor following mechanical thrombectomy for ischemic stroke with large vessel occlusion (LVO). The present multireader study aimed to evaluate the performance of e-CTA software for automated assistance in CTA-CS scoring.

Materials and Methods

Brain CTA images of 56 patients with anterior LVO were retrospectively processed. Twelve readers of various clinical training, including junior neuroradiologists, senior neuroradiologists, and neurologists graded collateral flow using visual CTA-CS scale in two sessions separated by a washout period. Reference standard was the consensus of three expert readers. Duration of reading time, inter-rater reliability, and statistical comparison of readers' performance metrics were analyzed between the e-CTA assisted and unassisted sessions.

Results

e-CTA assistance resulted in significant increase in mean accuracy (58.6% to 67.5%, p = 0.003), mean F1 score (0.574 to 0.676, p = 0.002), mean precision (58.8% to 68%, p = 0.007), and mean recall (58.7% to 69.9%, p = 0.002), especially with slight filling deficit (CTA-CS 2 and 3). Mean reading time was reduced across all readers (103.4 to 59.7 s, p = 0.001), and inter-rater agreement in CTA-CS assessment was increased (Krippendorff's alpha 0.366 to 0.676). Optimized occlusion laterality detection was also noted with mean accuracy (92.9% to 96.8%, p = 0.009).

Conclusion

Automated assistance for CTA-CS using e-CTA software provided helpful decision support for readers in terms of improving scoring accuracy and reading efficiency for physicians with a range of experience and training backgrounds and leading to significant improvements in inter-rater agreement.

Keywords: Decision support system, artificial intelligence, computed tomography angiography, ischemic stroke, machine learning

Introduction

Collateral cerebral blood flow can be quantified through different imaging modalities, including computed tomography angiography (CTA), CT perfusion, and magnetic resonance imaging. Assessment of collaterals using CTA is universally and routinely used to establish eligibility for mechanical thrombectomy in treating large vessel occlusions of the anterior circulation.[1–3] Patients with robust collateralization tend to benefit from a longer therapeutic window, with the collateral blood supply volume being an important predictor of clinical outcome following endovascular procedures[3–5] and is commonly quantified using the CTA collateral score (CTA-CS).[6–9] Despite multiple scoring systems being suggested for estimating brain CTA collateral blood flow,[7–9] CTA-CS, also known as Tan score, remains the most popular system utilized.[6, 7]

Given the growing relevance of collateral vasculature assessment in patient selection for thrombectomy, finding ways to improve accuracy and decrease image interpretation time for collateral assessment is becoming increasingly important.[8–11] Automated applications offer the potential to improve both of these variables.[12–16] This is especially important as many stroke studies are being interpreted by less experienced radiologists or nonradiology specialists and such readers may be able to benefit from the assistance of an accurate automated algorithm.[17–22]

Applications of artificial intelligence (AI) modeling have the potential to accelerate ischemic stroke triaging and provide a consistent and quantitative measurement of collateral filling. Evaluating real-world implementation of these advanced tools is imperative to ensure their safety and effectiveness, which represents the basis of our study hypothesis relating to automated CS using e-CTA. The primary goal of the present multireader study was to validate the e-CTA (e-Stroke Suite, Brainomix Ltd, Oxford, UK), and examine the value of automated assistance in improving CTA-CS assessment for physicians of varied backgrounds and experience. Secondary objectives included analyzing the time taken to score and occlusion laterality detection in patients with acute ischemic stroke (AIS) from large vessel occlusion in the anterior circulation.

Materials and methods

Patient selection

Institutional board review approval was granted, and consent was waived for the study given the retrospective and anonymized nature of the data. Inclusion eligibility criteria comprised of adult patients admitted between 2015 and 2020 with large vessel occlusion. The total number of selected cases was limited to one-fifth of the eligible patients for feasibility purposes considering the readers' possible time allocation, while ensuring statistically relevant sample size. Random case selection was performed maintaining CTA-CS distribution. Brain scans of the included patients were retrospectively retrieved and uploaded. Acquired images came from CT scanners and protocols used in routine clinical practice. Processed CTA images had a maximum slice thickness of 1 mm.

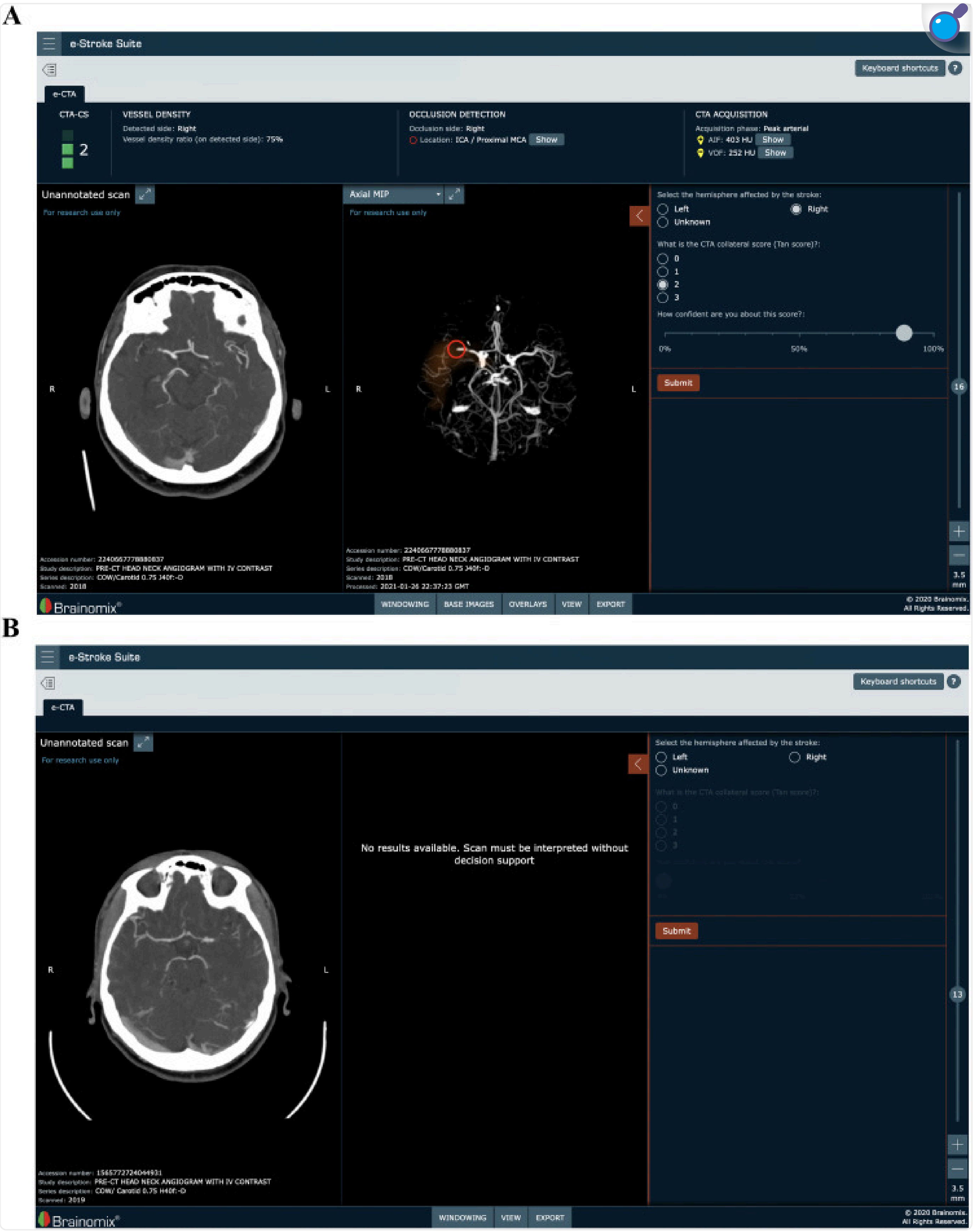
e-CTA

e-CTA (version 10, e-Stroke, Brainomix Ltd, Oxford, UK) is a decision support software that uses machine learning and image processing for automatic localization of large vessel occlusion, arteriovenous phases, and computation of CTA-CS (automated Tan score).[23] It aims to provide decision support in identifying patients who are eligible for and would most likely benefit from mechanical thrombectomy upon admission.

Reader study

Instructions were provided to the readers on how to use the e-CTA platform prior to the experiment. All readers were familiar with Tan score and given their practice and expertise. CTA images of the included patients were consecutively displayed to each of the 12 readers to determine the CTA-CS (Tan score). Each scan was randomly allocated to one of the two reading sessions: with or without the assistance of the e-CTA software. After a washout period of at least 4 weeks, each reader then reviewed the same scans but with the inverse allocation of decision support. Four junior neuroradiologists with up to 5 years of experience, four senior neuroradiologists with at least 10 years of experience, and four neurologists were blinded to any other clinical data and were not subjected to any time restrictions. Data captured included laterality of collateral deficit, extent of collateral vessel density (CS), scoring confidence (subjective experienced confidence from 0% to 100%), and time taken to score each scan. Demonstration of an example case is shown in Figure 1. The reference standard was the consensus read of three expert reviewers who scored CTAs without e-CTA assistance according to the Tan scoring system. The CTA-CS system ranges in four categories from 0 to 3, with 0 corresponding to complete absence of collateral filling, 1 for diminished collateral filling >0% and < 50%, 2 for reduced collateral filling >50% but <100%, and 3 where collaterals are 100% filled and equal to contralateral side.

Figure 1.



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e-CTA collateral scoring assessment with (A) and without (B) automated assistance. CTA: computed tomography angiography.

Statistical analysis

Statistical analysis comparing the e-CTA assisted and unassisted readings was conducted using Python programming language and scientific computing library SciPy (version 1.6.2). To quantify the impact of e-CTA, evaluation metrics of the readers of different expertise and backgrounds performance regarding both CTA-CS, and laterality detection. These metrics were accuracy, F1 score, precision (1-specificity), and recall (sensitivity). Sub-analysis of the different readers according to their level of expertise and background was also performed with and without automated e-CTA assistance.

Considering the quantitative nature of the variables, the normality of their distribution was tested using Shapiro–Wilk test and Q-Q plot. A nonsignificant result on the normality test indicated the normally distributed data, and as a consequence, the findings were reported using mean and standard deviation. To examine differences between the e-CTA assisted and unassisted readings, parametric paired t-test was utilized. All tests with a p value of less than 0.05 were considered significant. In view of the multireader comparison and the ordinal nature of the multiclass score, inter-rater reliability of CTA-CS was examined by computing Krippendorff's alpha, which is based on the observed disagreement corrected for disagreement expected by chance, and where 0 represents perfect disagreement and 1 is perfect agreement.

Results

Patient population

Out of 281 patients with ischemic stroke from large vessel occlusion, a total of 56 patients were randomly selected with CTA-CS distribution being represented. The mean patient age was 66 (±16) years with females representing 53% of the cohort. As many as 52% of the patients had M1 occlusion, 30% had internal carotid artery terminus occlusion, 16% had M2 occlusion, and 2% had M3 occlusion. Occlusions leading to filling defect were left sided in 26 patients and right sided in 30 patients. Reference standard CTA-CS of the 56 patients were as follows: 7 (12.5%) had a score of 0, 22 (39.2%) of 1, 16 (28.5%) of 2, and 11 (19.64%) of 3. The CTA images were distributed across the different phases with 14 in early arterial, 18 in equilibrium, and 24 in peak arterial phases.

CTA-CS results

With regard to CTA-CS, statistically significant increase was noted in the e-CTA-assisted session in terms of mean accuracy (58.6% to 67.5%, p = 0.003), mean F1 score (0.574 to 0.676, p = 0.002), mean precision (58.8% to 68%, p = 0.007), and mean recall (58.7% to 69.9%, p = 0.002), particularly in CTA-CS 2 and 3, as shown in Table 1. Time taken to score was significantly reduced with e-CTA assistance overall across all readers (103.4 to 59.7 s, p = 0.001), and especially among the neurology readers group (92.5 to 47.2 s, p = 0.04), as summarized in Table 2. The mean reader confidence in CTA-CS was (62.8%, 74.3%, p = 0.001), respectively, without and with software assistance, as described in Supplementary Table 8 and Supplementary Figure 1 .

Table 1.

Statistical analysis comparing CTA-CS assessment with and without e-CTA assistance.

Metrics (mean)	Without e-CTA	With e-CTA	p value
Mean accuracy	0.586 (±0.081)	0.675 (±0.056)	0.003*
Mean F1	0.574 (±0.083)	0.676 (±0.062)	0.002*
Mean precision	0.588 (±0.085)	0.68 (±0.055)	0.007*
Mean recall	0.587 (±0.089)	0.699 (±0.076)	0.002*
Mean F1 (CS: 0)	0.619 (±0.152)	0.625 (±0.11)	0.896
Mean F1 (CS: 1)	0.68 (±0.09)	0.676 (±0.061)	0.894
Mean F1 (CS: 2)	0.453 (±0.169)	0.62 (±0.067)	0.004*
Mean F1 (CS: 3)	0.546 (±0.099)	0.784 (±0.109)	<0.001*
Mean precision (CS: 0)	0.612 (±0.095)	0.599 (±0.103)	0.764
Mean precision (CS: 1)	0.734 (±0.127)	0.758 (±0.119)	0.724
Mean precision (CS: 2)	0.432 (±0.148)	0.616 (±0.092)	0.003*
Mean precision (CS: 3)	0.573 (±0.182)	0.745 (±0.136)	0.030*
Mean recall (CS: 0)	0.667 (±0.22)	0.693 (±0.192)	0.726
Mean recall (CS: 1)	0.644 (±0.091)	0.626 (±0.096)	0.605
Mean recall (CS: 2)	0.481 (±0.201)	0.636 (±0.088)	0.013*
Mean recall (CS: 3)	0.556 (±0.135)	0.842 (±0.135)	<0.001*

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* Statistically significant p value at the 0.05 level. CS: collateral score; CTA: computed tomography angiography.

Table 2.

Analysis of time taken to score CTA-CS with and without e-CTA assistance.

	Without e-CTA	**With e-CTA**	**p value**
Scoring time (all) (seconds)	103.432 (±63.582)	59.701 (±40.796)	0.001*
Scoring time (JNR) (seconds)	125.554 (±87.121)	90.929 (±58.582)	0.129
Scoring time (neurology) (seconds)	92.585 (±31.968)	47.251 (±27.36)	0.040*
Scoring time (SNR) (seconds)	89.826 (±74.536)	44.808 (±27.787)	0.163

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* Statistically significant p value at the 0.05 level. CS: collateral score; CTA: computed tomography angiography; JNR: junior neuroradiologist; SNR: senior neuroradiologist

Laterality results

Similarly, regarding occlusion laterality detection, there was significant improvement for the whole readers group as described in Table 3, with mean accuracy (92.9% to 96.8%, p = 0.009), mean F1 score (92.9% to 96.8%, p = 0.009), mean precision (93% to 96.8%, p = 0.008), and mean recall (0.93.1% to 96.8%, p = 0.018).

Table 3.

Statistical analysis of occlusion laterality detection with and without e-CTA assistance.

Metrics (mean)	Without e-CTA	With e-CTA	p value
Mean accuracy	0.929 (±0.027)	0.968 (±0.034)	0.009*
Mean F1	0.929 (±0.027)	0.968 (±0.034)	0.009*
Mean precision	0.93 (±0.028)	0.968 (±0.034)	0.008*
Mean recall	0.931 (±0.027)	0.968 (±0.034)	0.018*
Mean F1—left	0.923 (±0.03)	0.967 (±0.034)	0.005*
Mean F1—right	0.935 (±0.025)	0.969 (±0.034)	0.016*
Precision—left	0.911 (±0.05)	0.963 (±0.042)	0.007*
Precision—right	0.949 (±0.046)	0.974 (±0.036)	0.255
Recall—left	0.939 (±0.056)	0.972 (±0.036)	0.201
Recall—right	0.923 (±0.041)	0.965 (±0.041)	0.013*

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* Statistically significant p value at the 0.05 level. CTA: computed tomography angiography.

Inter-rater agreement

Inter-rater agreement showed overall elevation among the readers following e-CTA assistance in CTA-CS prediction, with a Krippendorff's alpha value increase from 0.366 to 0.676. Comparison between the e-CTA assisted and unassisted readings relating to inter-rater reliability and the different score classes are detailed in Table 4. Subgroup analysis of inter-rater agreement inside the various reader groups and classes is listed in Supplementary Table 1 .

Table 4.

Inter-rater agreement analysis comparing CTA-CS in relation to e-CTA assistance.

CTA-CS	Without e-CTA	With e-CTA
CTA-CS (all)	0.366	0.676
CTA-CS (0)	0.175	0.537
CTA-CS (1)	0.213	0.542
CTA-CS (2)	0.136	0.504
CTA-CS (3)	0.064	0.416

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CS: collateral score; CTA: computed tomography angiography.

Individual reader performance with and without e-CTA assistance are provided in Supplementary Table 2 for the junior group, Supplementary Table 3 for the neurology group, and Supplementary Table 4 for the senior group. Likewise, individual reader performance comparing laterality detection with and without e-CTA assistance are detailed in Supplementary Tables 5–7, for the junior, neurology, and senior groups, respectively.

Discussion

The major finding of this study was that all performance evaluation metrics of CTA-CS improved significantly across the different readers with automated e-CTA assistance. Significant time reduction as well as increased inter-rater agreement on CTA-CS assessment were noted. The software also helped optimize the readers' clot laterality detection. It was also noted the value of the AI decision support is greatest for ordinary performing readers overall and can exceptionally be limited at times with outstandingly well preforming ones.

While multiple published studies examined CTA clot detection and localization using deep learning and various algorithmic methods,[24–28] a few looked into automating CTA-CS. These studies, however, focused on comparing the performance of automated scoring with visual scoring and not the impact such tools have on the reader's performance.[24, 25]

Grunwald et al. validated the performance of the same e-CTA software for CTA-CS assessment in agreement with visual CS. They reported, in line with our findings, that e-CTA assistance reduced inter-rater variability and improved intraclass correlation coefficient across 3 reference neuroradiologist raters. However, these readers were themselves the ground truth reference standard, and their findings were reported as a validation study rather than a reader-study for decision support system evaluation.[23]

In a recent study, Wolff et al. found an interobserver agreement of 65% between two expert radiologists assessing CTA-CS in a sample of 200 exams. The reported limitations included a mean image processing time to produce the automatic CS being 5 min, and the ground truth visual CS being scored by one observer per scan. The main focus of their study was to evaluate the performance automatic prediction of dichotomized and categorized CTA-CS rather than comparing readers experience related to AI software support,[29] which none of the previous studies examined.

AI-enabled CTA-CS assistance against a reference standard, highlights the substantial role machine learning can play in real-time decision support systems applied to CS to produce reliable and consistent CTA-CS assessment, as well as the value of these systems in stroke care in general. Automating a recognized treatment effect modifier and a predictor of patient outcome such as CTA-CS,[26–28] could have positive impact in enhancing the precision and streamlining a time sensitive step in ischemic stroke care. Determining patients who are the best eligible candidates for mechanical thrombectomy procedures could significantly benefit from automated CTA-CS. Applying such tools could serve as a solution to inter-rater variability so improving consistency of scoring, as well as lead to faster assessments in ischemic stroke triaging.

This experiment comes following previous studies validating e-ASPECTS for automatic ASPECTS assessment and e-CTA for the occlusion detection,[13, 14, 16] and showcases the opportunity to improve decision making using AI in stroke imaging interpretation using different complementary modalities and put at the disposal of physicians a new arsenal of diagnostic and prognostic tools to enhance stroke care.

Limitations

Concerning the included population, our study is to be interpreted within the scope of its sample size and could serve as a basis for future multicenter automated software investigations in stroke imaging. Another limitation is the fact that CT scanners and CTA protocols parameters were not taken into consideration, this, however, was with the intention of having results that are representative of real-world practice and outcomes.

Conclusion

Our study results indicate that automated Brainomix e-CTA software provided helpful assistance for collateral filling evaluation and led to significant improvements in inter-rater agreement, accuracy, F1 score, precision, and recall in assessment CTA-CS as well as shortened scoring time among stroke physicians of various expertise and academic backgrounds. These findings are in favor of further investigation to validate the use of this tool in clinical care of acute ischemic stroke patients.

Supplemental Material

sj-docx-1-ine-10.1177_15910199221150470 - Supplemental material for Automated CT angiography collateral scoring in anterior large vessel occlusion stroke: A multireader study

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Footnotes

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Associated Data

This section collects any data citations, data availability statements, or supplementary materials included in this article.

Supplementary Materials

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