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Original Article

Brain CT perfusion improves intracranial vessel occlusion detection on CT angiography☆

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ABSTRACT

Background and purpose. – To evaluate whether brain CT perfusion (CTP) aids in the detection of intracranial vessel occlusion on CT angiography (CTA) in acute ischemic stroke.
Materials and methods. – Medical-ethical committee approval of our hospital was obtained and informed consent was waived. Patients suspected of acute ischemic stroke who underwent non-contrast CT(NCCT), CTA and whole-brain CTP in our center in the year 2015 were included. Three observers with different levels of experience evaluated the imaging data of 110 patients for the presence or absence of intracranial arterial vessel occlusion with two strategies. In the first strategy, only NCCT and CTA were available. In the second strategy, CTP maps were provided in addition to NCCT and CTA. Receiver-operating-characteristic (ROC) analysis was used for the evaluation of diagnostic accuracy.
Results. – Overall, a brain perfusion deficit was scored present in 87–89% of the patients with an intracranial vessel occlusion, more frequently observed in the anterior than in the posterior circulation. Performance of intracranial vessel occlusion detection on CTA was significantly improved with the availability of CTP maps as compared to the first strategy ($P = 0.023$), due to improved detection of distal and posterior circulation vessel occlusions (P-values of 0.032 and 0.003 respectively). No added value of CTP was found for intracranial proximal vessel occlusion detection, with already high accuracy based on NCCT and CTA alone.
Conclusion. – The performance of intracranial vessel occlusion detection on CTA was improved with the availability of brain CT perfusion maps due to the improved detection of distal and posterior circulation vessel occlusions.

Introduction

The diagnostic workup and treatment of cerebral ischemic stroke have changed significantly in the last decade. Computed Tomography (CT) is the primary imaging technique in the diagnostic work-up of acute cerebral stroke in most institutes, usually with a CT-scanner available at or in the vicinity of the emergency room. CT is a fast imaging technique with high accuracy for the detection of intracranial hemorrhage on non-contrast CT (NCCT), and intracranial vessel occlusion on CT angiography (CTA) [1,2]. Until recently, systemic intravenous thrombolytic therapy with tissue-type plasminogen activator was the only reperfusion therapy available with evidence of improved clinical outcome when administered within 4.5 h after onset of symptoms [2,3]. Recent randomized controlled trials show that in case of a proximal intracranial vessel occlusion, clinical outcome is significantly improved when intra-arterial thrombectomy (IAT) is initiated within 6, and possibly even up to 12 h, after onset of stroke [4–9]. As a consequence, this puts a greater demand on adequate and fast diagnostic evaluation in the acute stage. For patient selection for IAT, a subsequent CTA is essential to evaluate the presence of an intracranial proximal vessel occlusion [10].

As early signs of ischemic stroke can be missed on NCCT, CT perfusion (CTP) can be added to the scanning protocol for the evaluation of a brain perfusion deficit both for the purpose of increasing

Abbreviations: IAT, intra-arterial thrombectomy; NCCT, non-contrast CT; CTA, CT angiography; CTP, CT perfusion; ROC, receiver operating characteristic; AUC, area under the curve.

☆ Results of the study have been presented in an oral presentation during the RSNA annual meeting in December 2016 and the annual meeting of the Dutch Radiology Society in May 2017.

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confidence about the diagnosis of ischemic stroke, and to estimate tissue viability of the affected parenchyma [11,12]. Small cerebral infarcts can, however, still be missed on CTP [13]. Both CTA and CTP have additional value for predicting infarct presence and infarct volume on follow-up imaging [14]. The presence of a proximal vessel occlusion, poor collateral status and large infarcted areas on admission CTA and CTP are strong predictors of poor outcome and can be used to predict long-term clinical outcome, although there is limited additional prognostic value over clinical neurological evaluation and NCCT [15]. Yet, CTP derived parameters cannot reliably identify patients who will benefit from IAT [16]. It has, however, been reported that less experienced observers more accurately identify major ischemic changes on CTP source images than on NCCT [12], and that 4D-CTA reformatting of CTP increases the diagnostic accuracy and certainty in proximal vessel occlusion detection [17].

In this study we investigate whether brain CTP aids in the detection of intracranial vessel occlusion on CTA.

Materials and methods

Study population

We retrospectively identified patients with the suspicion of acute ischemic stroke scanned in our institute with a CTP protocol in the year 2015. Inclusion criteria were age >18 years, onset of symptoms of less than 9 h and a CT scanning protocol which included brain NCCT, CTA and whole-brain CTP. Exclusion criteria were another diagnosis explaining the symptoms (clinical follow-up taken into account) and previous (endovascular) brain surgery. The following patient characteristics were collected: age, gender, time of onset to imaging, stroke severity (NIHSS), treatment given (IV-tPA, IAT), time of onset to IV-tPA and follow-up imaging.

In total, 177 subjects with clinical suspicion of acute ischemic stroke with a CT protocol including whole-brain CTP were scanned at our institution in the year 2015. Fifty patients (28.2%) were excluded because during clinical follow-up a diagnosis other than acute ischemic stroke was made (9 patients with functional disorder, 8 patients with a seizure, 6 patients with vestibular neuritis, 3 patients with a tumor or metastasis, 2 patients with migraine; the remaining 22 patients had a different diagnosis). Seventeen patients (7.9%) were excluded because of previous (endovascular) brain surgery resulting in metal artifacts on CT. The remaining study population consisted of 110 patients. With clinical follow-up taken into account, 98 patients (89.1%) were finally diagnosed with ischemic stroke and 12 patients (10.9%) were diagnosed with transient ischemic attack. Additional baseline characteristics are presented in Table 1.

Table 1
Baseline characteristics of the study population.

Demographics	*n* = 110
Age (y), mean (SD)	64 (13)
Female sex, *n* (%)	45 (40.9%)
NIHSS on onset, mean (SD)	6.31 (6.44)
Time of onset to imaging, hours:min (SD)	2:33 (1:58)
Treatment, *n* (%)	65 (59.1%)
IV-tPA, *n* (%)	64 (58.2%)
IAT, *n* (%)	14 (12.7%)
Onset to needle time, hours:min (SD)	2:10 (1:13)
Follow-up imaging, *n* (%)	45 (40.9%)
CT, *n* (%)	17 (37.8%)
MRI, *n* (%)	28 (62.2%)
Time to follow-up imaging, days mean (SD)	26 (48)

Abbreviations: NIHSS, National Institutes of Health Stroke Scale; IV-tPA, intravenous tissue-type plasminogen activator; IAT, intra-arterial thrombectomy; SD, standard deviation.

The study has been approved by the medical-ethical committee of our hospital and informed consent was waived because of the retrospective collection of the study data. Clinical data and results of imaging analyses were anonymized and stored in a protected database Castor EDC (www.castoredc.com), following Good Clinical Practice (GCP) and European Data Protection Directive guidelines.

Imaging protocol

All patients were scanned on a 320-row detector CT scanner (Aquilion One, ViSION EDITION, Toshiba Medical Systems Corporation, TMSC, Otawara, Japan). For CTA 70 mL and for CTP 50 mL non-ionic contrast agent (300 mg iodine/mL Iomerion® Bracco Imaging, Italy) was injected into an antecubital vein with an injection rate of 5 mL/s followed by a 40 mL saline flush at 5 mL/s. The contrast bolus triggered CTA acquisition included 0.5 mm slice thickness with scan range from the aortic arch to the cranium vertex at 120 kV tube voltage with dose modulation. For CTP, 19 whole brain volumetric acquisitions were performed over a period of 60 s with 16 cm *z*-coverage using 0.5 mm slice thickness, 0.5 s rotation time at 80 kV tube voltage and 100 mAs. Image reconstruction was done using a convolution kernel FC41 and standard adaptive iterative dose reduction in three-dimensions. Axial and coronal CT perfusion maps (CBV, CBF, MTT, TTP) were created on a Vitrea (Toshiba Medical Systems) workstation using a singular value decomposition deconvolution algorithm with automated arterial input and venous output functions selection.

Imaging review

Three observers with different levels of experience evaluated the imaging data blinded to clinical information and patient identity on an Impax 6.6.1.0 2015 PACS system (Agfa Healthcare, Morsel, Belgium). The first observer (FJAM) was a neuroradiologist with 11 years of experience in neurovascular imaging; the second observer (JV) was a resident subspecializing in neuroradiology; the third observer (SP) was a neuroradiologist with 6 years of experience. All observers were blinded to patient identity and clinical outcomes. Sidedness of the neurological deficit was the only clinical information provided.

The observers scored the presence, or absence, of a proximal or distal arterial vessel occlusion comparing two strategies. In the first strategy, only NCCT and CTA were available. NCCT was evaluated for early ischemic signs and hyperdense vessel sign, and CTA was evaluated for intracranial vessel occlusion. In the second strategy, additional CTP maps were provided. CTP was evaluated for the presence of a perfusion deficit, and subsequently CTA was re-evaluated for intracranial vessel occlusion. Multi-planar reformatting and maximum intensity projections were available in both strategies. In order to reflect clinical practice, a time limit of 5 min was set for the evaluation of each subject.

Reference standard and statistical analysis

The reference standard for the presence or absence of an intracranial vessel occlusion was set based on the evaluation by the three observers, and the judgment of an independent neuroradiologist (SCAS) serving as referee in case of discrepancy between the observers. Vascular 4D-CTA reformats of the CTP acquisition, follow-up imaging (when available), anonymized clinical data and follow-up, as well as the evaluation results of all observers were available to the referee.

Proximal vessels were defined as the supraclinoid segment of the internal carotid artery, first segments of the anterior and posterior cerebral arteries, M1 and M2 segments of the middle cerebral artery, the basilar artery and the intradural course of the vertebral artery. Distal vessels included the second and third segments of the anterior and posterior cerebral arteries, third and fourth segments of the middle cerebral arteries, and the cerebellar arteries (SCA, AICA, PICA).

Sensitivity and specificity of vessel occlusion detection were calculated per strategy for each observer. Receiver operating characteristic (ROC) analysis was used for the evaluation of the diagnostic accuracy in intracranial vessel occlusion detection for both strategies. Differences in area under the curve (AUC) between both strategies were tested for statistical significance using a paired t-test [18]. A *P*-value below 0.05 was considered statistically significant. Subgroup analyses were performed for the anterior circulation, posterior circulation, proximal and distal vessel occlusions.

Analyses were performed using SPSS 22.0.0.1 (IBM Corp. Released 2013).

Results

The study population included fifty-four patients (49.1%) with an intracranial vessel occlusion, of which 32 (59.3%) were located in the anterior circulation and 22 (40.7%) in the posterior circulation; 36 concerned proximal vessel occlusions and 24 distal vessel occlusions. Six patients presented with simultaneous proximal and distal intracranial vessel occlusions.

Diagnostic accuracy of intracranial vessel occlusion detection

The accuracy of overall intracranial vessel occlusion detection was comparable between the observers (Table 2), with sensitivity ranging between 91 and 96% and specificity ranging between 86 and 96% for strategy 2. The level of the observers' experience was of no influence on the accuracy of intracranial vessel occlusion detection.

The accuracy of intracranial distal vessel occlusion detection was lower than for proximal vessel occlusion detection, both with and without the availability of brain CTP. The addition of CTP did, however, increase the accuracy of distal and posterior circulation vessel occlusion detection for the different observers (Table 2, supplementary figure). With the results of the observers pooled together (Table 3), a statistical significant increase in AUC for overall intracranial vessel occlusion detection is seen with the aid of CTP (*P* 0.023), based on improved detection of distal and posterior circulation vessel occlusions (*P*-value of 0.032 and 0.003 respectively). The improved performance is explained by an increase in sensitivity while maintaining high specificity. For all observers, brain CTP was not of added value for proximal vessel occlusion detection, with already high accuracy (AUC 0.92–0.97) based on the evaluation of NCCT and CTA alone.

Brain CT perfusion

The identification of brain parenchyma perfusion deficits on CTP in the study population was comparable between the observers (Table 4). Overall, a brain perfusion deficit was scored present in

Table 2
Comparison of diagnostic accuracy between strategy 1 and 2 in detection of intracranial vessel occlusion per observer ($n = 110$).

Strategy 1 versus strategy 2	Sensitivity %	Specificity %	ROC (area under curve)	*P*-value (2-tailed)*
Observer 1 (neuroradiologist)				
Overall	74 vs 93	98 vs 96	0.86 vs 0.95	**0.049**
Anterior circulation	75 vs 88	100 vs 100	0.88 vs 0.94	0.226
Posterior circulation	73 vs 100	99 vs 98	0.86 vs 0.99	**0.017**
Proximal occlusion	94 vs 100	99 vs 99	0.97 vs 0.99	0.245
Distal occlusion	33 vs 67	100 vs 99	0.67 vs 0.83	0.060
Observer 2 (neuroradiologist in training)				
Overall	85 vs 91	86 vs 86	0.85 vs 0.88	0.574
Anterior circulation	88 vs 94	95 vs 95	0.91 vs 0.94	0.504
Posterior circulation	82 vs 86	94 vs 95	0.88 vs 0.91	0.668
Proximal occlusion	89 vs 89	96 vs 97	0.92 vs 0.93	0.874
Distal occlusion	75 vs 88	94 vs 93	0.85 vs 0.90	0.398
Observer 3 (neuroradiologist)				
Overall	83 vs 96	86 vs 88	0.85 vs 0.92	0.116
Anterior circulation	84 vs 97	94 vs 94	0.89 vs 0.95	0.197
Posterior circulation	77 vs 91	97 vs 97	0.87 vs 0.94	0.270
Proximal occlusion	92 vs 94	95 vs 95	0.93 vs 0.95	0.732
Distal occlusion	63 vs 96	95 vs 95	0.79 vs 0.96	**0.011**

Abbreviations: ROC, receiver-operating characteristics.
Strategy 1 includes NCCT and CTA; strategy 2 includes NCCT, CTA and CTP.
* A *P*-value below 0.05 was considered statistically significant. Abbreviations: ROC, receiver-operating characteristic.

Table 3
Comparison of overall diagnostic accuracy between strategy 1 and 2 in detection of intracranial vessel occlusion with pooling of 3 observers.

	Sensitivity %	Specificity %	ROC (area under curve)	*P*-value (2-tailed)
Pooled results ($n = 330$), strategy 1 versus strategy 2				
Overall	81 vs 93	90 vs 90	0.85 vs 0.92	**0.023***
Anterior circulation	82 vs 93	96 vs 96	0.89 vs 0.94	0.065
Posterior circulation	77 vs 92	97 vs 97	0.87 vs 0.95	**0.032***
Proximal occlusion	92 vs 94	96 vs 97	0.94 vs 0.96	0.459
Distal occlusion	57 vs 83	97 vs 96	0.77 vs 0.90	**0.003***

Strategy 1 includes NCCT and CTA; strategy 2 includes NCCT, CTA and CTP.
* A *P*-value below 0.05 was considered statistically significant. *Abbreviations*: ROC, receiver-operating characteristic.

Table 4
Detection of brain parenchyma perfusion deficit on CT perfusion in patients with an intracranial vessel occlusion per observer ($n = 110$).

	Perfusion deficit (CTP)
Observer 1 (neuroradiologist)	
Overall	48/54 (88.9%)
Anterior circulation	30/32 (93.8%)
Posterior circulation	19/22 (86.4%)
Proximal occlusion	30/36 (83.3%)
Distal occlusion	22/24 (91.7%)
Observer 2 (neuroradiologist in training)	
Overall	47/54 (87.0%)
Anterior circulation	30/32 (93.8%)
Posterior circulation	18/22 (81.2%)
Proximal occlusion	30/36 (83.3%)
Distal occlusion	22/24 (91.7%)
Observer 3 (neuroradiologist)	
Overall	47/54 (87.0%)
Anterior circulation	29/32 (90.6%)
Posterior circulation	18/22 (81.2%)
Proximal occlusion	30/36 (83.3%)
Distal occlusion	23/24 (95.8%)

Abbreviations: CTP, CT perfusion.

87–89% of the patients with an intracranial vessel occlusion. A brain perfusion deficit was more frequently seen in the anterior circulation (91–94%), in comparison to the posterior circulation (81–86%).

Discussion

The detection of an intracranial vessel occlusion can be challenging especially for smaller vessel structures as illustrated in Figs. 1 and 2. The identification of an area of disturbed brain perfusion on CTP maps guides the observers' attention to the vascular structures in this area on CTA. In our study, the accuracy of intracranial vessel occlusion detection was increased after adding brain CTP maps to the evaluation of NCCT and CTA, mainly based on increased sensitivity for the detection of distal and posterior circulation vessel occlusions. It can be debated whether the improved detection of a distal or posterior circulation vessel occlusion is of clinical relevance. For all observers, CTP was not of added value for intracranial proximal vessel occlusion detection, based on which patients are selected for IAT. However, the detection of a smaller vessel occlusion improves the understanding of underlying etiology and pathophysiology which can be of relevance for secondary prevention. Possibly, smaller vessel occlusions could become of relevance for patient selection to new acute stroke treatment strategies in the future.

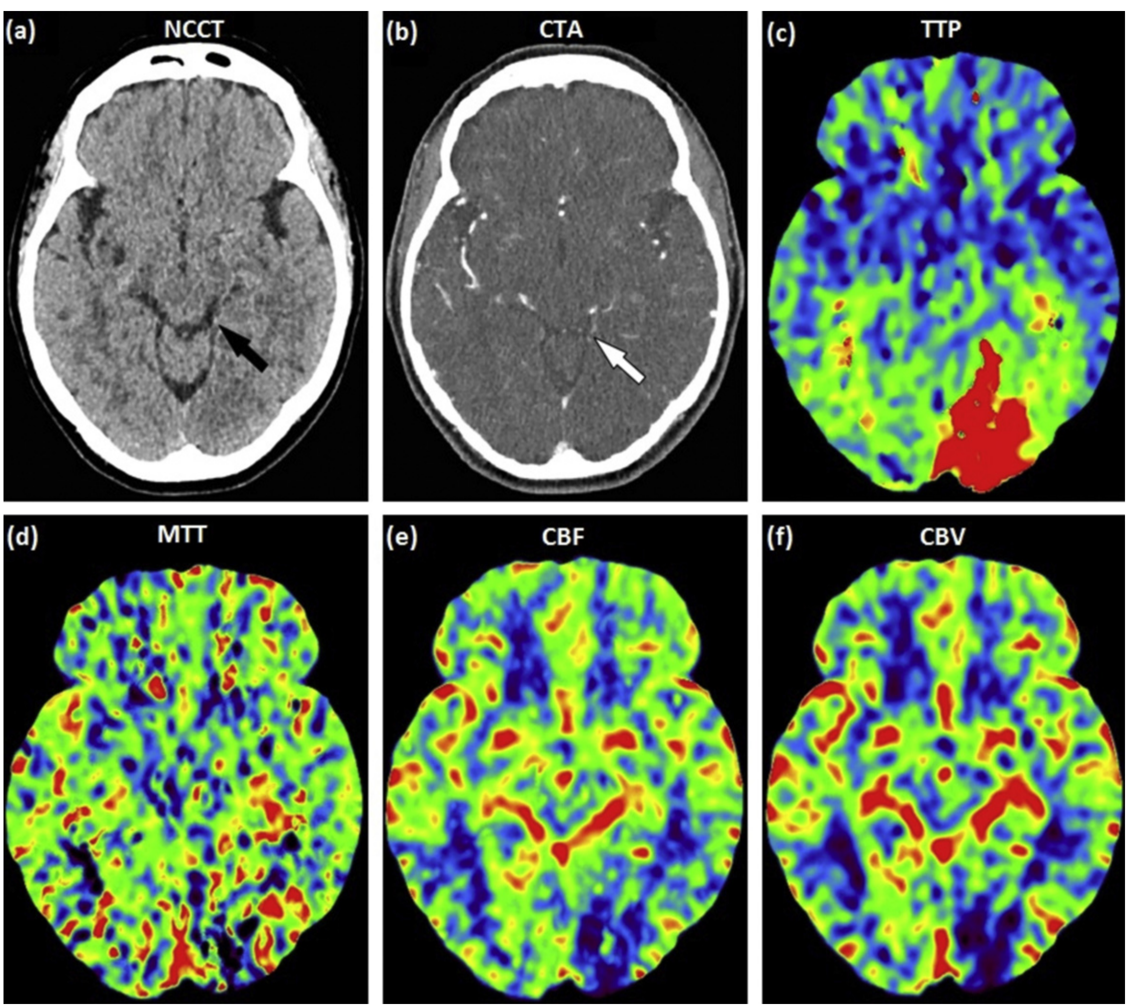

Fig. 1. Case illustration. Head non-contrast CT, CT angiography (CTA) and CT perfusion (CTP) in a patient with acute onset of a unilateral visual deficit. Subtle hyperdense vessel sign on non-contrast CT (a, black arrow) and P3 segment occlusion of the left posterior cerebral artery on CTA, which can easily be overlooked (b, white arrow). Brain CTP maps aid in the detection of this posterior cerebral vessel occlusion by guiding the observers' attention to an area of disturbed perfusion in the left occipital lobe. CTP maps: increased time-to-peak (c), prolonged mean-transit-time (d) and reduction in relative cerebral blood flow (e). Relative cerebral blood volume (f) is reduced in this area, which is indicative of infarct core.

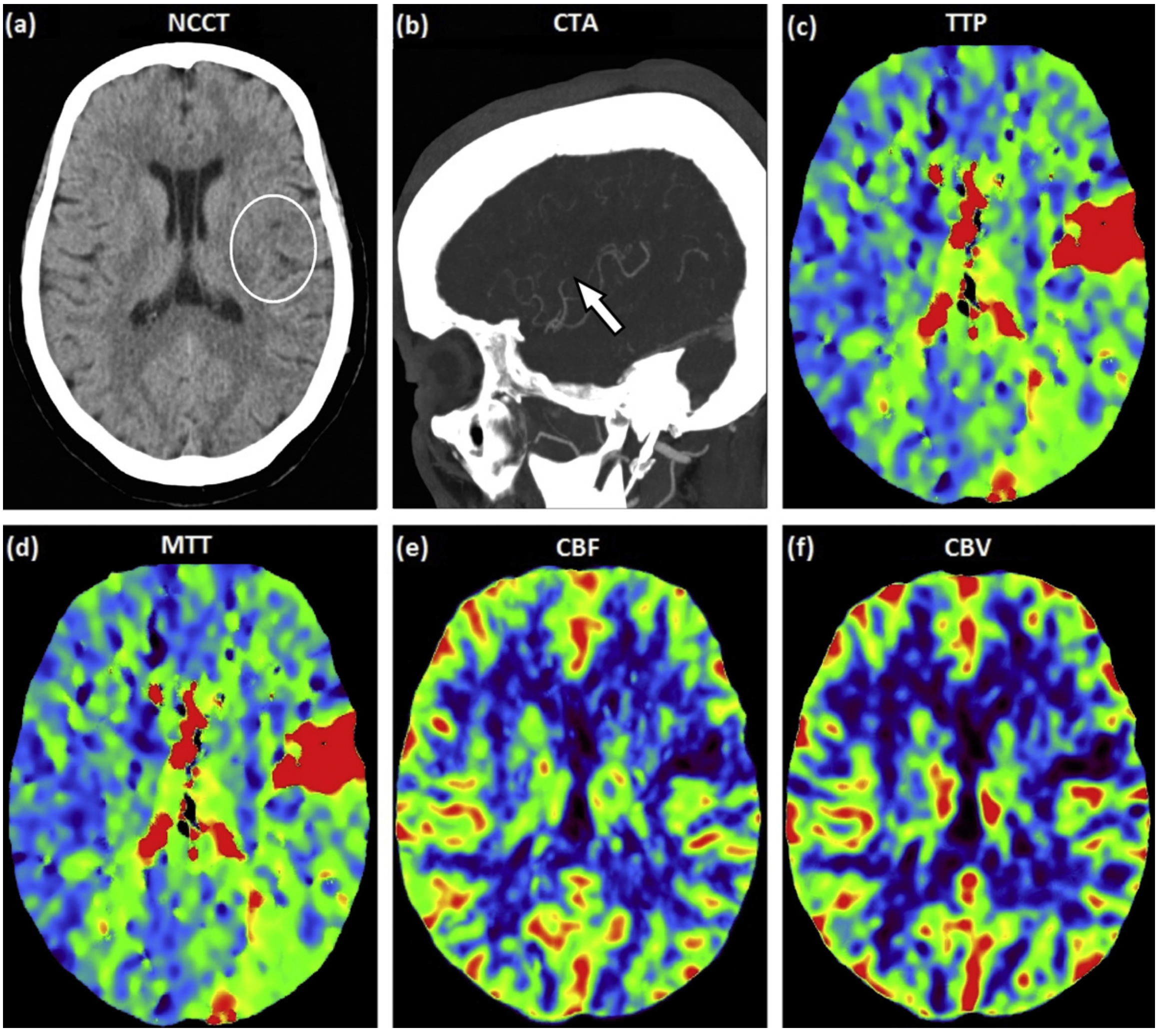

Fig. 2. Case illustration. Head non-contrast CT, sagittal MIP (Maximum Intensity Projection) CT angiography (CTA) and CT perfusion (CTP) in a patient with acute onset of aphasia. Subtle early ischemic changes left operculum region on non-contrast CT (a, white circle), and distal M2 segment occlusion of the left middle cerebral artery on CTA (b, white arrow), which can be easily overlooked. CTP maps: increased time-to-peak (c), prolonged mean-transit-time (d) and reduction in relative cerebral blood flow (e) in the operculum region of the left frontal lobe. Relative cerebral blood volume (f) is reduced in this area, which is indicative of infarct core.

Scanning, reconstruction and interpretation of whole-brain CTP can be done in less than 5 min on recent generation of CT scanners [19,20]. Although vessel occlusions were evaluated on conventional CTA in our study, this conventional CTA could be obviated as a separate acquisition because dynamic CTA can be reconstructed from the CTP acquisition. Several studies have shown that dynamic CTA can replace conventional CTA for the evaluation of the intracranial vessels, with reported improved depiction of thrombus burden and collateral status [21–26]. With the use of a wide detector, a volume neck CTA acquisition combined with dynamic volume acquisitions of the head is technically feasible and this would obviate the need to obtain a separate neck CTA acquisition [27,28]. This saves time and radiation exposure.

Our study has some limitations. First, our study does not fully reflect clinical practice. Only the sidedness of the neurologic deficit was provided to the observers. In the clinical setting, additional clinical information is available, which can aid in the localization of a vessel occlusion, although this can sometimes be misleading. Studies show that predicting infarct location based on clinical information alone is not reliable in up to 6% of the cases [14,29]. It needs to be taken into account that our study population concerns a subgroup of patients in the acute stage of disease with exclusion of subjects with a final diagnosis other than ischemic stroke and exclusion of subjects with previous (endovascular) brain surgery. This explains the relatively high percentage of patients treated with IVT or IAT (59.1%).

Furthermore, the evaluation time of strategies 1 and 2 was due to the sequential nature not evaluated for the observers in our study. Although the accuracy of intracranial vessel occlusion detection was slightly increased for observer 2, distal vessel occlusions were already detected with high accuracy based on scrutinized analyses of NCCT and CTA. A possible explanation is that observer 2 looked more intensively and for a longer time evaluating distal vessel occlusions on NECT and CTA alone, and used CTP for increasing confidence for the presence or absence rather than detection of a distal vessel occlusion. Finally, due to the retrospective collection of the study population only a part of the subjects have had digital subtraction angiography (DSA), CT or MRI during follow-up. In our study the reference standard was defined by the judgment of an independent neuroradiologist serving as referee in case of disagreement between the observers, based on all information available. Vascular 4D-CTA reformats of the CTP acquisition, follow-up imaging when available, clinical follow-up and the evaluation of all observers were taken into account by the referee. Although one can argue that another imaging modality (such as DSA) is needed to serve as the reference standard for all cases, this approach bears the risk of bias due to possible (spontaneous or treatment induced) vessel recanalization in-between the imaging modalities.

Conclusion

The performance for intracranial vessel occlusion detection on CTA was improved with the availability of brain CTP maps, due to improved detection of distal and posterior circulation vessel occlusions.

Disclosure of interest

Two authors (RM, MP) received a grant from Toshiba Medical Systems Corporation (Otawara, Japan). Two authors (RM, ED) received a grant from the Dutch Technology Foundation STW (part of the Netherlands Organization for Scientific Research (NWO), and partly funded by the Ministry of Economic Affairs; project number: 13350).

The other authors declare that they have no competing interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.neurad.2018.03.003.

References

[1] Jauch EC, Saver JL, Adams HP, et al. Guidelines for the early management of patient with acute ischemic stroke: a guideline for healthcare professionals from the American heart association/American stroke association. Stroke 2013;44:870–947.
[2] Sabarudin A, Subramaniam C, Sun Z. Cerebral CT angiography and CT perfusion in acute stroke detection: a systematic review of diagnostic value. Quant Imaging Med Surg 2014;4(4):282–90.
[3] The National Institute of Neurological Disorders and Stroke rt-PA Stroke Study Group. Tissue plasminogen activator for acute ischemic stroke. N Engl J Med 1995;333:1581–7.
[4] Hacke W, Kaste M, Bluhmki E, et al. Thrombolysis with alteplase 3 to 4.5 hours after acute ischemic stroke. N Engl J Med 2008;359(13):1317–29.
[5] Berkhemer OA, Fransen PS, Beumer D, et al. MR CLEAN investigators. A randomized trial of intraarterial treatment for acute ischemic stroke. N Engl J Med 2015;372:11–20.
[6] Campbell BS, Mitchell PJ, Kleinig TJ, et al. EXTEND-IA investigators. Endovascular therapy for ischemic stroke with perfusion-imaging selection. N Engl J Med 2015;372:1009–18.
[7] Goyal M, Demchuk AM, Menon BK, et al. ESCAPE trail investigators. Randomized assessment of rapid endovascular treatment of ischemic stroke. N Engl J Med 2015;372:1019–30.
[8] Goyal M, Menon BK, van Zwam WH, et al. Endovascular thrombectomy after large-vessel ischaemic stroke: a meta-analysis of individual patient data from five randomised trials. Lancet 2016;387(10029):1723–31.
[9] Bracard S, Ducrocq X, Mas JL, et al. THRACE investigators. Mechanical thrombectomy after intravenous alteplase versus alteplase alone after stroke (THRACE): a randomised controlled trial. Lancet Neurol 2016;15(11):1138–47.
[10] Fugate JE, Brinkjikji W, Cloft H, et al. Variability of stroke patients meeting endovascular stroke trial criteria in a non-clinical trial setting. J Neuroradiol 2017, http://dx.doi.org/10.1016/j.neurad.2017.11.003.
[11] Donahue J, Wintermark M. Perfusion CT and acute stroke imaging: foundations, applications, and literature review. J Neuroradiol 2015;42(1):21–9.
[12] Pepper EM, Parsons MW, Bateman GA, et al. CT perfusion source images improve identification of early ischaemic change in hyperacute stroke. J Clin Neurosci 2006;13:199–205.
[13] Abdelgawad EA, Higazi MM, Abdelbaky AO, et al. Diagnostic performance of CT cerebral blood volume colour maps for evaluation of acute infarcts; comparison with diffusion-weighted MRI within 12 h of major stroke onset. J Neuroradiol 2017;44:10–6.
[14] Seeters T, Biessels GJ, Kapelle LJ, et al. DUST investigators. CT angiography and CT perfusion improve prediction of infarct volume in patients with anterior circulation stroke symptoms. Neuroradiology 2016;58(4):327–37.
[15] Seeters T, Biessels GJ, Kapelle LJ, et al. DUST investigators. The prognostic value of CT angiography and CT perfusion in acute ischemic stroke. Cerebrovasc Dis 2015;40:258–69.
[16] Borst J, Berkhemer OA, Roos YBWEM, et al. MR CLEAN investigators. Value of computed tomographic perfusion-based patient selection for intra-arterial acute ischemic stroke treatment. Stroke 2015;46:3375–82.
[17] Wagemans BA, van Zwam WH, Nelemans PJ, van Oostenbrugge RJ, Postma AA. 4D-CTA improves diagnostic certainty and accuracy in the detection of proximal intracranial anterior circulation occlusion in acute ischemic stroke. PLOS ONE 2017;12(2):e0172356.
[18] Hanley JA, McNeil BJ. The meaning and use of the area under a receiver operating characteristic (ROC) curve. Radiology 1982;143:29–36.
[19] Goyal M, Menon BK, Derdeyn CP. Perfusion imaging in acute ischemic stroke: let us improve the science before changing clinical practice. Radiology 2013;266:16–21.
[20] Campbell BCV, Yassi N, Ma H, et al. Imaging selection in ischemic stroke: feasibility of automated CT perfusion analysis. Int J Stroke 2015;10:51–4.
[21] Yang CY, Chen YF, Lee CW, et al. Multiphase CT angiography versus single-phase CT angiography: comparison of image quality and radiation dose. AJNR Am J Neuroradiol 2008;29(7):1288–95.
[22] Siebert E, Bohner G, Dewey M, et al. 320-slice CT neuroimaging: initial clinical experience and image quality evaluation. Br J Radiol 2009;82(979):561–70.
[23] Frolich AM, Psychogios MN, Klotz E, et al. Angiographic reconstructions from whole-brain perfusion CT for the detection of large vessel occlusion in acute stroke. Stroke 2012;43(1):97–102.
[24] Saake M, Goelitz P, Struffert T, et al. Comparison of conventional CTA and volume perfusion CTA in evaluation of cerebral arterial vasculature in acute stroke. AJNR Am J Neuroradiol 2012;33(11):2068–73.
[25] Smit EJ, Vonken EJ, van der Schaaf IC, et al. Timing-invariant reconstruction for deriving high-quality CT angiographic data from cerebral CT perfusion data. Radiology 2012;263(1):216–25.
[26] Frölich AM, Schrader D, Klotz E, et al. 4D CT angiography more closely defines intracranial thrombus burden than single-phase CT angiography. AJNR Am J Neuroradiol 2013;34:1908–13.
[27] Oei MT, Meijer FJ, van der Woude WJ, Smit EJ, van Ginneken B, Prokop M, Manniesing R. Interleaving cerebral CT perfusion with neck CT angiography part I. Proof of concept and accuracy of cerebral perfusion values. Eur Radiol 2016;27(6):2649–56.
[28] Oei MT, Meijer FJ, van der Woude WJ, Smit EJ, van Ginneken B, Manniesing R, Prokop M. Interleaving cerebral CT perfusion with neck CT angiography. Part II: clinical implementation and image quality. Eur Radiol 2016;27(6):2411–8.
[29] Mead GE, Lewis SC, Wardlaw JM, et al. How well does the Oxforshire community stroke project classification predict the site and size of the infarct on brain imaging? J Neurol Neurosurg Psychiatry 2000;68:558–62.