Wavelet-Based Angiographic Reconstruction of Computed Tomography Perfusion Data

Diagnostic Value in Cerebral Venous Sinus Thrombosis

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Objective: The aim of this study was to test the diagnostic value of wavelet-based angiographic reconstruction of CT perfusion data (waveletCTA) to detect cerebral venous sinus thrombosis (CVST) in patients who underwent whole-brain CT perfusion imaging (WB-CTP).

Materials and Methods: Datasets were retrospectively selected from an initial cohort of 2863 consecutive patients who had undergone multiparametric CT including WB-CTP. WaveletCTA was reconstructed from WB-CTP: the angiographic signal was generated by voxel-based wavelet transform of time attenuation curves (TACs) from WB-CTP raw data. In a preliminary clinical evaluation, waveletCTA was analyzed by 2 readers with respect to presence and location of CVST. Venous CT and MR angiography (venCTA/venMRA) served as reference standard. Diagnostic confidence for CVST detection and the quality of depiction for venous sections were evaluated on 5-point Likert scales. Thrombus extent was assessed by length measurements. The mean CT attenuation and waveletCTA signal of the thrombus and of flowing blood were quantified.

Results: Sixteen patients were included: 10 patients with venCTA-/venMRA-confirmed CVST and 6 patients with arterial single-phase CT angiography (artCTA)–suspected but follow-up-excluded CVST. The reconstruction of waveletCTA was successful in all patients. Among the patients with confirmed CVST, waveletCTA correctly demonstrated presence, location, and extent of the thrombosis in 10/10 cases. In 6 patients with artCTA-suspected but follow-up–excluded CVST, waveletCTA correctly ruled out CVST in 5 patients. Reading waveletCTA in addition to artCTA significantly increased the diagnostic confidence concerning CVST compared with reading artCTA alone (4.4 vs 3.6, $P = 0.044$). The mean flowing blood-to-thrombus ratio was highest in waveletCTA, followed by venCTA and artCTA (146.2 vs 5.9 vs 2.6, each with $P < 0.001$). In waveletCTA, the venous sections were depicted better compared with artCTA (4.2 vs 2.6, $P < 0.001$), and equally well compared with venCTA/venMRA (4.2 vs 4.1, $P = 0.374$).

Conclusions: WaveletCTA was technically feasible in CVST patients and reliably identified CVST in a preliminary clinical evaluation. WaveletCTA might serve as an additional reconstruction to rule out or incidentally detect CVST in patients who undergo WB-CTP.

Key Words: whole-brain CT perfusion, wavelet transform, cerebral venous sinus thrombosis, stroke

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Cerebral venous sinus thrombosis (CVST) is a rare but important differential diagnosis in patients with suspected ischemic stroke. Cerebral venous sinus thrombosis is detected in 0.5% to 1.0% of acute strokes.[1] It can manifest with a wide variety of clinical symptoms. Depending on the location of the thrombosis, patients can present with signs of intracranial hypertension, headaches, aphasia, hemiparesis, seizures, and disorientation.[2,3]

Most of the CVST symptoms can also be caused by ischemic stroke, which is by far the more frequent diagnosis.[4] Because of this overlap of symptoms, CVST patients may undergo a multiparametric stroke CT protocol including nonenhanced CT (NECT), arterial single-phase CT angiography (artCTA), and dynamic CT perfusion (CTP). Because standardized stroke protocols are generally not tailored to the demonstration of venous vessels, the confirmation or exclusion of CVST is frequently not possible in these examinations.

Abnormalities on NECT can only be seen in approximately 30% of CVST patients,[5] and artCTA can only demonstrate a filling defect in cerebral sinuses when there is venous contamination. A further challenge is the frequency of anatomical variations such as sinus hypoplasia or aplasia.[5] Hence, additional venous CT angiography (venCTA) or MR angiography (venMRA)[6] is often required to confirm or rule out the diagnosis of CVST. Performing these examinations may lead to a significant delay in diagnosis, which has shown to increase the risk of a poor outcome.[7] The additional screening also implies further costs and may require a secondary administration of contrast agents and/or radiation exposure of patients.

Novel postprocessing algorithms, however, can create high-quality CT angiographies from the initially acquired CTP data.[8–12] As CTP is a dynamic examination, it does not only cover the arterial but also the venous phase, which implies the potential of these CTP-derived angiographic techniques to detect CVST better than artCTA.[13] Among these approaches, wavelet-transformed CTA (waveletCTA) has shown an excellent signal-to-noise ratio[14] and the ability to accurately differentiate between arterial and venous vessels.[13] The wavelet transform generates the angiographic signal by voxel-based application on time attenuation curves (TACs) from CTP raw data. Given that CTP is part of the stroke protocol in clinical practice, the assessment of CVST using waveletCTA would be possible in a "1-stop shop" fashion without any additional examinations.

The aim of the present study was to test the technical feasibility and the diagnostic value of waveletCTA in a preliminary clinical analysis in patients with confirmed or suspected CVST.

MATERIALS AND METHODS

Study Design and Population

The institutional review board approved this retrospective study and waived requirement for informed consent. Based on a prospectively collected stroke registry, our initial cohort consisted of 2863 consecutive patients who had undergone multiparametric

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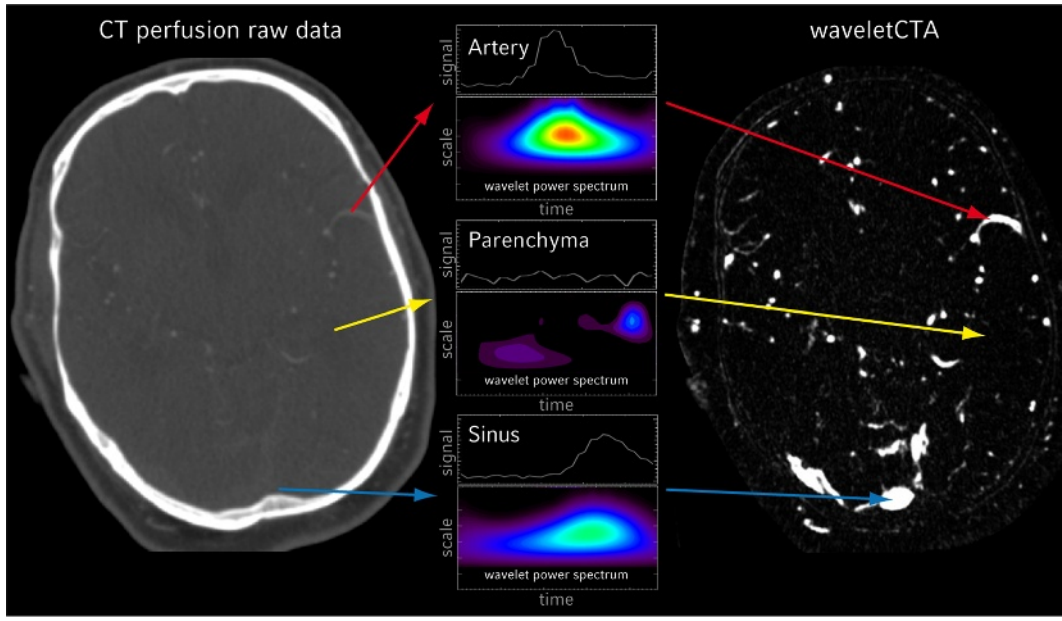

FIGURE 1. Wavelet-based angiographic reconstruction of CT perfusion data. Schematic representation of wavelet-based angiographic reconstruction of WB-CTP data. Voxel-based wavelet transform of TACs produces a flow-sensitive representation of WB-CTP data. The TAC and the generated wavelet power spectrum are depicted for an M3 segment of the middle cerebral artery (red arrow), brain parenchyma (yellow arrow), and the superior sagittal sinus (blue arrow), illustrating the differential signal generation.

CT protocol including whole-brain CT perfusion (WB-CTP) between March 2009 and May 2016.

Of this cohort, we included all subjects with (1) evidence of CVST confirmed by venCTA or venMRA with prior WB-CTP (n = 12) or (2) suspected CVST on artCTA with subsequent negative venCTA or venMRA (n = 7).

We excluded patients with (1) incomplete WB-CTP raw data sets (n = 3) and (2) nondiagnostic quality of CT perfusion or artCTA (n = 0).

As control population, 30 patients with both unremarkable initial multiparametric CT and negative follow-up MRI were selected from the initial cohort in a consecutive fashion.

TABLE 1. Patient Characteristics of the Study Population

Age	Sex	Underlying Disease	Indication for WB-CTP	CVST	Standard of Reference	Time From CTP to Final Diagnosis	Etiology
Follow-up–confirmed CVST							
62	F	Intracranial aneurysms	Hemiparesis	Yes	VenCTA	19 h	Postop
82	F	Acute ischemic stroke	Motor aphasia	Yes	VenMRA	44 h	Unknown
65	F	Intracranial meningioma	Motor aphasia	Yes	VenCTA	47 h	Postop
72	F	Intracranial meningioma	Hemiparesis	Yes	VenCTA	VenCTA added*	Postop
63	F	Metastatic breast cancer	Hemiparesis	Yes	VenCTA	VenCTA added*	Malignant
74	F	Cryptogenic liver cirrhosis	Loss of consciousness	Yes	VenCTA	VenCTA added*	Unknown
69	M	CUP syndrome	Motor aphasia	Yes	VenCTA	216 h	Malignant
77	M	Acute ischemic stroke	Hemiparesis	Yes	VenMRA	32 h	Unknown
46	M	Metastatic melanoma	Loss of consciousness	Yes	VenCTA	VenCTA added*	Malignant
72	M	Acute ischemic stroke	Hemiparesis	Yes	VenCTA	165 h	Unknown
ArtCTA-suspected but follow-up–excluded CVST							
66	M	Acute ischemic stroke	Hemiparesis	No	VenMRA	45 h	NA
61	F	Myocardial infarction	Hemiparesis	No	VenMRA	12 h	NA
64	F	Acute ischemic stroke	Hemiparesis and aphasia	No	VenCTA	24 h	NA
65	F	Intracranial meningioma	Hemiparesis	No	VenMRA	71 h	NA
69	F	Hepatic encephalopathy	Hemiparesis	No	VenCTA	VenCTA added*	NA
60	M	Polytrauma	Hemiparesis	No	VenCTA	63 h	NA

*Additional venCTA imaging was performed right after WB-CTP to evaluate CVST due to clinical suspicion.

WB-CTP indicates whole-brain CT Perfusion; CVST, cerebral venous sinus thrombosis; venCTA/venMRA, venous CT/MR angiography; F, female; M, male; CUP, cancer of unknown primary; artCTA, arterial CT angiography; NA, not applicable.

CT and MRI Examination Protocol

All patients underwent our standardized multiparametric CT stroke imaging protocol consisting of NECT, artCTA, and WB-CTP. All CT examinations were performed using 1 of the following 4 CT scanners: SOMATOM Force, a 2 × 192 slice dual-source CT scanner; SOMATOM Definition Flash, a 2 × 128 slice dual-source CT scanner; and SOMATOM Definition Edge and SOMATOM Definition AS+, both 128 slice CT scanners (all Siemens Healthcare, Forchheim, Germany).

For artCTA, 50 mL of iodinated contrast agent was administered intravenously, followed by a saline chaser of 40 mL, both with a flow rate of 5 mL/s. Arterial CT angiography was performed from the aortic arch to the vertex with 140 and 80 kV tube voltage and attenuation-based tube current modulation (CareDose). Collimation was 0.6 mm. Arterial CT angiography data were read as source images using syngo. via imaging software (Siemens Healthcare, Forchheim, Germany).

Whole-brain CT perfusion imaging was obtained with 0.6 mm collimation and 100 mm scan coverage in the z-axis using adaptive spiral scanning. The data sets were acquired continuously over 48 seconds (32 cycles, sweeps every 1.5 seconds). Tube voltage and current were 80 kV and 200 mA, respectively. CT dose index was 276 mGy. A total of 35 mL of iodinated contrast agent (400 mg/mL) was administered at a flow rate of 5 mL/s, followed by a saline flush of 40 mL at 5 mL/s.

Venous CT angiography was performed with 60 mL of iodinated contrast agent after a delay of 35 seconds using CareDose 4D and attenuation-based tube current modulation (CareDose 4D); the other acquisition parameters were the same as in artCTA. Contrast-enhanced (CE) and time-of-flight (TOF) venMRA were performed on a 1.5 T whole-body scanner (Siemens Aera, Siemens Healthcare, Erlangen, Germany). For CE-venMRA, 0.1 mL of Gadovist per 1 kg body weight (1.0 mmol/mL gadobutrol; Bayer Vital GmbH, Leverkusen, Germany) was administered at a flow rate of 2 mL/s. Scanning was performed at a delay of 35 seconds using a T1-weighted MRA sequence (repetition time, 18.0 milliseconds; echo time, 4.03 milliseconds). Time-of-flight venMRA was performed using axial and coronal planes with a slice thickness of 2.5 mm, a repetition time of 25 milliseconds, and an echo time of 6.92 milliseconds.

Image Postprocessing and Wavelet Transform

The 32 × 99 (phases × slices) CT DICOM images were imported into in-house developed software (PMI, Platform for Medical Imaging v0.4)[15] based on IDL 8.3 (Exelis Visual Information Solutions, Boulder, CO). On each 4-dimensional CT volume, rigid-body motion correction was performed with the elastix toolbox[16] using a binary mask that contained all pixels with density > 0 HU at the first phase.

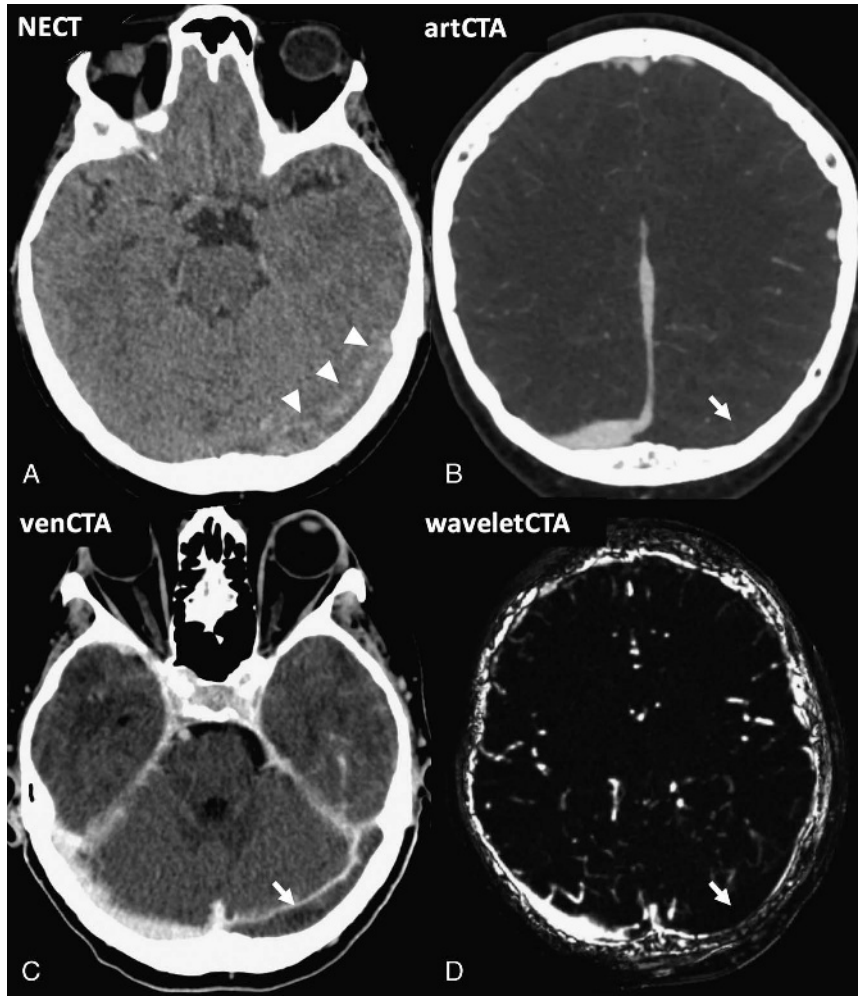

FIGURE 2. Example of waveletCTA-based confirmation of suspected CVST. A 63-year-old female patient with meningeal carcinomatosis from breast cancer evaluated using multiparametric stroke CT for acute right-sided hemiparesis. A, NECT demonstrated a cord sign (arrowheads) along the left transverse sinus. B, On artCTA, the same sinus did not show any contrast enhancement (arrow). C, VenCTA was additionally requested, which confirmed the diagnosis (arrow). D, WaveletCTA reconstruction would have confirmed the diagnosis with equal diagnostic confidence (arrow).

The main principle is to analyze the TAC of each voxel in terms of its similarity to the shape of a generic and idealized contrast agent bolus TAC. According to Havla et al,[14] the complex-valued Paul wavelet $\Psi_0(\eta)$ of order 1 serves the purpose well by visual resemblance between the "analyzer"—the wavelet—and the "analyzed" data—the bolus curves. The degrees of freedom such as translation (parameter t) and scaling (parameter s) result in the "maximization of correlation" between TAC $f(\eta)$ and the basis function ("mother wavelet") at applying the continuous wavelet transform:

$$\Psi_{s,t}(\eta) = |s|^{(-1/2)}\Psi_0\left(\frac{\eta - t}{s}\right)$$

$$\tilde{f}(s,t) = \int f(\eta)\overline{\Psi}_{s,t}(\eta)d\eta \text{ with } \overline{\Psi}_{s,t} := \text{complex conjugate of } \Psi_{s,t}$$

This continuous wavelet transform results in a 2-dimensional function called the wavelet power spectrum, of which the maximal value is interpreted as angiographic signal intensity. The waveletCTA technique provides a significantly improved contrast-to-noise ratio of arterial and venous structures compared with temporal maximum intensity projections and allows for the removal of bone structures such as the calvaria.[14] An illustration of the waveletCTA generation is provided in Figure 1.

Image Analysis of ArtCTA, VenCTA/VenMRA, and WaveletCTA

Two readers, 1 board-certified attending radiologist (W.H.S.) with over 10 years of experience in stroke imaging and one 5th-year radiology resident (K.M.T.) with over 4 years of experience in stroke imaging, independently evaluated initial NECT, artCTA, and WB-CTP of 16 patients of the study population and 30 patients of the control population in a randomized fashion. In case of disagreement, consensus was reached in a separate session. Readers were blinded to clinical information and follow-up imaging. The evaluation was performed (1) in a first session without waveletCTA and (2) in a second session (after 4 weeks) with additional access to waveletCTA.

In each session, the readers were asked to state their degree of confidence in determining the pathology of CVST on a 5-point Likert scale (1, nondiagnostic; 2, poor; 3, fair; 4, good; 5, excellent; rating: "diagnostic confidence"). An artCTA-suspected CVST was defined if the readers raised suspicion of CVST and recommended follow-up to confirm or exclude. The quality of depiction of the dural venous sinuses

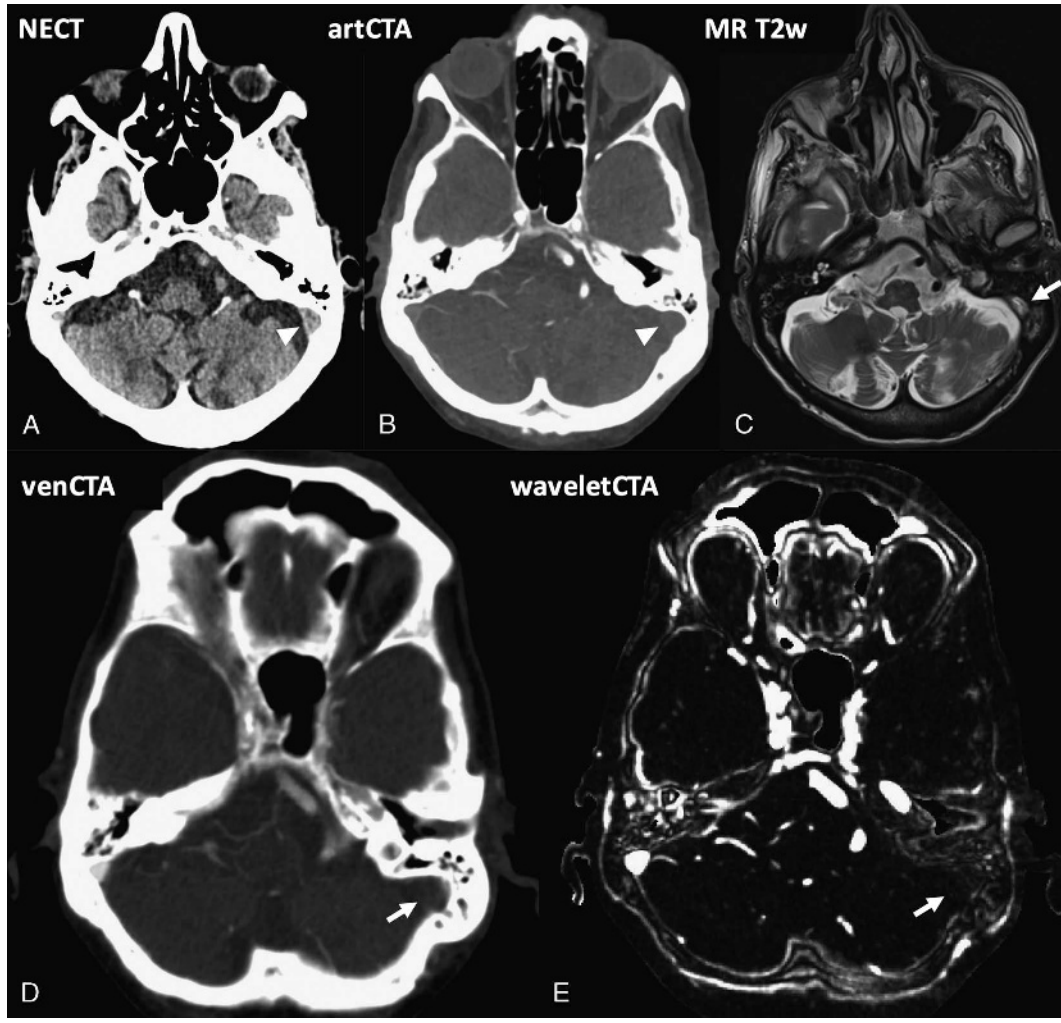

FIGURE 3. Example of waveletCTA-based CVST diagnosis in negative multiparametric CT. A 72-year-old male patient examined for acute right-sided hemiparesis. A and B, NECT and artCTA are unremarkable considering the cerebral veins and sinus (arrowheads). C, On the follow-up T2-weighted MRI scans after 159 hours, incidental note was made of missing flow void (arrow) in the left transverse and sigmoid sinus. D, CVST was confirmed after another 6 hours by venCTA (arrow). E, WaveletCTA would have accurately identified the occluded sinus (arrow) in the initial examination.

as well as the superficial and deep cerebral veins was rated on an analogous 5-point Likert scale. Thrombus length was measured using 3-dimensional reconstructions of data sets on the manufacturer's imaging software (syngo.via CT Vascular; Siemens Healthcare, Erlangen, Germany). In case that the thrombosis showed concomitant extracranial extension, the entry of the jugular foramen was defined as the end point for measurements. Mean CT attenuation (in Hounsfield units) and mean waveletCTA signal (dimensionless) were quantified using circular regions of interest within the thrombus and in the adjacent proximal sinus with normal perfusion ("flowing blood"). Venous CT angiography and venMRA were both considered as standard of reference for the evaluation of CVST.[6] The diagnosis of CVST was made separate using venCTA or venMRA by an independent third researcher (W.G.K.).

Statistical Analysis

We performed all statistical analyses using SPSS Statistics 23 (IBM, Armonk, NY). For the comparison of the ratings of diagnostic confidence and quality of depiction as well as thrombus length measurements, 2-sample *t* tests were performed. Continuous variables are reported as mean and standard deviation (SD) in case of normal distribution and as median and interquartile range (IQR) in case of nonnormal distribution. Normal distribution was assessed using the Kolmogorov-Smirnov test. The Likert scale variables are presented as mean and SD. *P* values below 0.05 were considered to indicate statistical significance.

RESULTS

The study population consisted of 10 patients with confirmed CVST and prior WB-CTP imaging, and 6 patients with suspicion of CVST in the initial artCTA, which was later ruled out by venCTA or venMRA. The reconstruction of waveletCTA was technically successful and yielded diagnostic image quality in all 16 patients of the study population and in all 30 control patients. Detailed patient characteristics of the study population are shown in Table 1. Patient examples are shown in Figures 2 to 4.

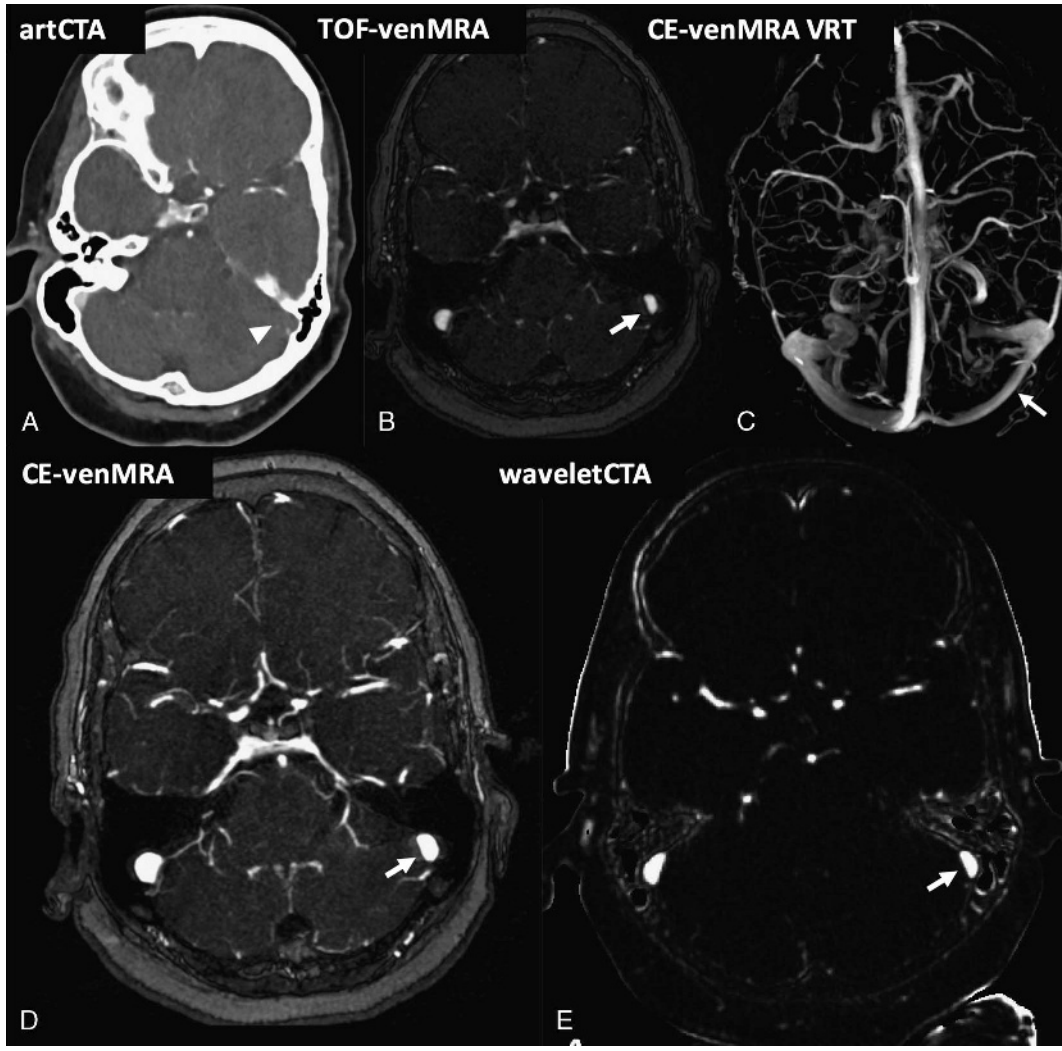

FIGURE 4. Example of waveletCTA-based exclusion of suspected CVST. A 61-year-old female patient with recent myocardial infarction and acute left-sided hemiparesis. A, In the artCTA, a filling defect (arrowheads) in the left sigmoid sinus was detected, raising the suspicion of CVST. B–D, An additional MRI examination was performed 12 hours later with TOF-venMRA and CE-venMRA, which ruled out CVST (arrows). E, WaveletCTA demonstrates angiographic signal (arrow) in the left sigmoid sinus, representing regular blood flow. VRT indicates volume rendering technique.

TABLE 2. Diagnostic Accuracy and Confidence of Multiparametric CT ± WaveletCTA

	NECT		ArtCTA		WaveletCTA			VenCTA/VenMRA		
Location	**Cord Sign**	**Thromb**	**Diag Conf**	**Length, mm**	**Thromb**	**Diag Conf**	**Length, mm**	**Thromb**	**Diag Conf**	**Length, mm**
Follow-up–confirmed CVST										
SSS	No	Yes	5	55	Yes	5	45	Yes	5	43
Left TRAS and SIGS	No	Yes	3	138	Yes	3	123	Yes	5	121
Left TRAS and SIGS	No	Yes	4	110	Yes	4	94	Yes	5	91
Left SIGS	No	No	5	NA	Yes	5	72	Yes	5	75
Left TRAS and SIGS	Yes	Yes	4	157	Yes	5	162	Yes	5	159
Right SIGS	No	No	5	NA	Yes	4	54	Yes	4	51
Right SIGS	No	Yes	3	82	Yes	5	71	Yes	5	69
Right TRAS	No	Yes	3	87	Yes	4	42	Yes	5	44
Right TRAS and SIGS	No	Yes	5	149	Yes	5	146	Yes	5	148
Left TRAS and SIGS	No	No	5	NA	Yes	5	136	Yes	5	133
ArtCTA-suspected but follow-up–excluded CVST										
Right TRAS and SIGS	No	Yes	3	137	No	5	NA	No	5	NA
Left SIGS	No	Yes	4	72	No	5	NA	No	5	NA
Left and right TRAS	No	Yes	2	35	Yes	2	13	No	5	NA
Left cortical vein	No	Yes	2	27	No	3	NA	No	5	NA
Left TRAS	No	Yes	2	46	No	5	NA	No	5	NA
SSS	No	Yes	2	31	No	5	NA	No	5	NA

CT indicates computed tomography; waveletCTA, wavelet-transformed CTA; NECT, nonenhanced CT; artCTA, arterial CT angiography; venCTA/venMRA, venous CT/MR angiography; Thromb, thrombosis; Diag Conf, diagnostic confidence; SSS, superior sagittal sinus; TRAS, transverse sinus; SIGS, sigmoid sinus; CVST, cerebral venous sinus thrombosis; NA, not applicable.

Diagnostic Value of WaveletCTA in Follow-up–Confirmed CVST (n = 10)

Of 10 patients with venCTA- or venMRA-confirmed CVST, the reading of the initial multiparametric CT correctly identified CVST in 7 patients with a mean diagnostic confidence of 3.8/5. The reading together with the waveletCTA correctly identified all 10 patients with a mean diagnostic confidence of 4.5/5 (SD, 0.7; overall sensitivity, 100%). The thrombus length measurements yielded similar results based on waveletCTA compared with venCTA/venMRA (94.5 vs 93.4 mm; SD, 44.3 vs 43.9), indicating that there was no significant overestimation or underestimation of thrombus burden by waveletCTA ($P = 0.956$). The median time delay from initial multiparametric CT imaging to the final diagnosis of CVST in all 10 patients was 26 hours (IQR, 0–46). Immediate additional contrast agent administration for venCTA to rule out CVST was performed in 4 of 10 patients. In the other 6 cases, the median time delay was 46 hours (IQR, 35–136). The detailed results are shown in Table 2. Analysis of the parametric CT perfusion maps revealed minor alterations that corresponded to the territory of venous drainage in 3 patients (see Supplementary Table 1, Supplemental Digital Content 1, http://links.lww.com/RLI/A301).

Diagnostic Value of WaveletCTA in ArtCTA-Suspected but Follow-up–Excluded CVST (n = 6) and in the Control Group Without CVST (n = 30)

Of 6 patients with artCTA-suspected but follow-up–excluded CVST, the additional reading of waveletCTA correctly classified 5 patients as CVST negative with a mean diagnostic confidence of 4.6/5 (SD, 0.8). In the only case in which waveletCTA was not able to rule out CVST, venMRA could identify an atypically appearing arachnoid granulation and thus exclude CVST. The artCTA-suspected diagnoses of CVST were ruled out by follow-up examinations after a median time delay of 35 hours (IQR, 15–59). Detailed results are shown in Table 2. The 30 control patients were all correctly classified as negative by waveletCTA with a mean diagnostic confidence of 4.9/5

TABLE 3. Quantitative Thrombus Attenuation and Signal Measurements in CVST

				P	
Parameter	**ArtCTA**	**WaveletCTA**	**VenCTA***	**WaveletCTA vs ArtCTA**	**WaveletCTA vs VenCTA**
Thrombus, mean HU/signal	83.0	1259.2	66.4	**<0.001**	**<0.001**
Flowing blood, mean HU/signal	201.2	122717.8	382.5	**<0.001**	**<0.001**
Flowing blood-to-thrombus ratio, mean	2.6	146.2	5.9	**<0.001**	**<0.001**

*VenCTA was available in 8 of 10 patients with CVST. A 2-sample *t* test was used to compare the mean HU/signal values. Bold *P* values indicate statistical significance.

CVST indicates cerebral venous sinus thrombosis; artCTA, arterial CT angiography; waveletCTA, wavelet-transformed CTA; venCTA, venous CT angiography; HU, Hounsfield units.

(SD, 0.3). Taken together with the 16 patients of the study population, this results in a patient-based specificity of 97.2%.

Quantitative Thrombus Attenuation and Signal Measurements in CVST

The flowing blood-to-thrombus ratio was significantly higher in waveletCTA compared with venCTA or artCTA (146.2 vs 5.9 vs 2.6, each with $P < 0.001$; measured using mean waveletCTA signal and mean CT attenuation values, respectively). Detailed results are provided in Table 3.

Quality of Depiction of Cerebral Veins and Sinuses

Among the 16 patients of the study population and the 30 control patients, the quality of depiction for all dural venous sinuses as well as superficial and deep cerebral veins was rated significantly higher for waveletCTA compared with artCTA overall (4.2 vs 2.6, $P < 0.001$) as well as for each section individually (each $P < 0.001$). When comparing waveletCTA to venCTA/venMRA, there was no significant difference in the quality of depiction when considering all venous sections together (4.2 vs 4.1, $P = 0.374$). However, the superior sagittal sinus ($P = 0.036$) and the vein of Labbé ($P = 0.004$) were rated significantly higher in waveletCTA. The detailed quality rating results are presented in Table 4.

Diagnostic Confidence

Among the 16 patients of the study population and the 30 control patients, the diagnostic confidence of CVST detection was significantly higher when the readers were additionally provided with waveletCTA compared with merely reading the multiparametric CT (study population, 4.4 vs 3.6, $P = 0.044$; control population, 4.8 vs 3.5, $P = 0.007$).

DISCUSSION

Our study demonstrates the feasibility of wavelet-based postprocessing of WB-CTP data for the evaluation of cerebral veins and sinuses. In a pilot clinical evaluation in patients examined with WB-CTP, the waveletCTA accurately identified all cases of follow-up–confirmed CVST (n = 10) and accurately demonstrated thrombus burden. The quantitative flowing blood-to-thrombus ratio in waveletCTA provided a >50-fold increase in contrast compared with artCTA and an almost 25-fold increase compared with venCTA. WaveletCTA correctly ruled out the diagnosis in 5 of 6 cases with follow-up–excluded CVST, which had been suspected on artCTA (n = 6). The quality of depiction of venous sections in waveletCTA was significantly higher compared with artCTA, and at least equal to venCTA/venMRA.

To our knowledge, this is the first study to assess the value of a CTP-derived angiography in evaluating CVST. A recent retrospective study on confirmed CVST in WB-CTP examinations has detected perfusion abnormalities matching the venous supply territories of the occluded sinus, but has not focused on postprocessing WB-CTP data for depiction of the vessels.[17] Another study focusing on the use of the parametric maps of WB-CTP in CVST patients has demonstrated the predictive value of absolute perfusion parameters like cerebral blood flow or volume for the clinical outcome.[18]

In CVST, the wide spectrum of clinical symptoms often impedes the diagnosis. In a previous study, the median delay between admission to a hospital and diagnosis of CVST was 3 days.[7] Importantly, diagnostic delay was associated with a higher risk of poor outcome.[7] Thus, developing strategies to shorten the time to diagnosis may improve patients' overall outcome. The median time delay from CTP imaging to the final diagnosis of CVST in our study was 26 hours, which could have been avoided by the use of waveletCTA.

The manifold advantages of WB-CTP postprocessing have been demonstrated in precise depiction of the intracranial arteries equivalent to artCTA,[8,12] in timing-invariant imaging of collateral vessels[19] as well as their facilitated color-coded evaluation in acute ischemic stroke.[20] Potentially decision-relevant parameters can be drawn from postprocessed WB-CTP data, for example, the velocity of collateral filling[21] and a close definition of the thrombus burden,[11] potentially supporting the prediction

TABLE 4. Quality of Depiction of Cerebral Veins and Sinuses

				P	
Section (n = 46)	**ArtCTA**	**WaveletCTA**	**VenCTA/VenMRA***	**WaveletCTA vs ArtCTA**	**WaveletCTA vs VenCTA**
Dural venous sinuses					
Superior sagittal sinus	3.3 (±1.0)	4.7 (±0.5)	4.3 (±0.7)	**<0.001**	**0.036**
Inferior sagittal sinus	2.3 (±1.1)	4.3 (±0.6)	4.2 (±1.0)	**<0.001**	0.728
Straight sinus	3.4 (±1.1)	4.6 (±0.6)	4.4 (±0.9)	**<0.001**	0.382
Cavernous sinus	1.7 (±0.5)	2.5 (±0.7)	2.9 (±0.6)	**<0.001**	0.107
Transverse sinus	3.0 (±1.1)	4.5 (±0.6)	4.3 (±0.8)	**<0.001**	0.269
Sigmoid sinus	3.1 (±1.0)	4.6 (±0.7)	4.6 (±0.6)	**<0.001**	0.901
Superficial cerebral veins					
Superior cerebral veins	2.2 (±1.1)	4.2 (±0.6)	4.0 (±0.9)	**<0.001**	0.475
Inferior cerebral veins	1.9 (±1.2)	4.0 (±0.9)	3.8 (±0.8)	**<0.001**	0.389
Vein of Trolard	2.5 (±1.0)	4.4 (±0.6)	4.1 (±0.7)	**<0.001**	0.061
Vein of Labbé	2.4 (±1.2)	4.5 (±0.7)	3.9 (±0.8)	**<0.001**	**0.004**
Deep cerebral veins					
Vein of Galen	3.1 (±0.8)	4.4 (±0.7)	4.5 (±0.5)	**<0.001**	0.658
Basal vein of Rosenthal	2.3 (±1.1)	4.2 (±0.8)	4.1 (±0.9)	**<0.001**	0.838
Internal cerebral veins	3.2 (±1.0)	4.7 (±0.5)	4.5 (±0.5)	**<0.001**	0.289
Overall	2.6 (±1.2)	4.2 (±0.9)	4.1 (±0.9)	**<0.001**	0.374

*VenCTA or venMRA were only available for the 16 patients of the study population. All values shown are mean (±SD). A 2-sample *t* test was used to compare the quality of depiction. Comparison of waveletCTA to venCTA was performed using the available 16 patients. Bold *P* values indicate statistical significance.

ArtCTA indicates arterial CT angiography; waveletCTA, wavelet-transformed CTA; venCTA/MRA, venous CT/MR angiography.

of clinically relevant endpoints such as stent-retriever thrombectomy outcomes.[22] General benefits of CT perfusion-based angiographic techniques as compared with artCTA include higher contrast-to-noise ratios,[8] better depiction of peripheral vessels,[14] and improved differentiation between arterial and venous vessels.[13]

However, WB-CTP is not routinely performed in many institutions because of the implied additional radiation exposure,[23,24] the lack of cross-vendor standardization,[25,26] or a limited scan coverage.[27] This partly implies a limitation as WB-CTP is not utilized on a larger scale. Yet, the added value of various postprocessing techniques including high-quality angiographic techniques may represent an additional reason to implement WB-CTP. In this context, it is important to remember that in acute stroke, CT is the most widely used imaging technique[28] and CT perfusion protocols are generally relatively easy to implement. It should be noted, however, that waveletCTA provides a flow-sensitive representation of the WB-CTP data but anatomical information is partly lost in the process. It should therefore only be used as a supplement after prior study of the morphology that is provided by NECT and artCTA.

There are limitations to this study, which need to be taken into account when interpreting our data. First, this is a very preliminary clinical evaluation of a small number of patients with confirmed or suspected CVST. The small sample size reflects the fact that WB-CTP is generally not performed in patients with a high suspicion of CVST. However, the excellent performance of waveletCTA compared with established venous CTA/MRA protocols and its accurate depiction of thrombus burden in our study sample are encouraging and warrant further evaluation of waveletCTA or other angiographic postprocessing techniques in this respect. Second, our evaluation is prone to selection bias regarding the study population as this is a retrospective single-center study and patients were partially included based on findings on multiparametric CT. Our sample might therefore not represent the average CVST patient, for example, the mean patient age was significantly higher in our study population than the average age of CVST manifestation (68 vs 39 years in the International Study on Cerebral Vein and Dural Sinus Thrombosis).[29]

In conclusion, waveletCTA is a promising technique that expands the value of WB-CTP to the evaluation of the cerebral veins and sinuses. If clinical or radiological suspicion of CVST is raised in patients recently examined by WB-CTP, waveletCTA may shorten time to diagnosis and replace an additional diagnostic workup.

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