4D Kinematic CT Angiography for Cerebral Arteriovenous Malformations and Fistulas A Novel Approach to Dynamic Vascular Visualization

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Abstract

Background: Four-dimensional computed tomography angiography (4D-CTA) is an evolving non-invasive imaging technique for the detection and characterization of cerebral arteriovenous malformations (AVMs) and dural arteriovenous fistulas (DAVFs). Although digital subtraction angiography (DSA) remains the gold standard because of its superior temporal and spatial resolution, advances in wide-detector CT technology have enhanced the ability of 4D-CTA to demonstrate dynamic cerebral vascular anatomy and hemodynamics.

Objective: To review the available literature from the past 15 years evaluating the diagnostic performance, clinical applications, advantages, and limitations of 4D-CTA in the assessment and longitudinal management of cerebral AVMs and DAVFs, with particular emphasis on its role as a non-invasive alternative and adjunct to DSA.

Methods: A narrative review of published literature from the past 15 years was undertaken, focusing on studies investigating 4D-CTA for the detection and characterization of intracranial arteriovenous shunts. The review considered diagnostic accuracy, hemodynamic assessment, cerebral circulation time, early venous drainage, treatment planning, and follow-up applications, with DSA serving as the principal reference standard. The reported evidence was synthesized descriptively.

Results: The reviewed literature reported sensitivity values ranging from 77% to 100% and specificity reaching up to 100% for the detection of cerebral arteriovenous shunts. Wide-detector CT systems, particularly 320-detector-row technology, enable dynamic visualization of arterial inflow, nidus opacification, and early venous drainage. These capabilities provide valuable information regarding shunt hemodynamics, cerebral circulation time, and stereotactic radiosurgery planning. However, 4D-CTA remains limited in detecting certain low-flow shunts and delineating small arterial branches because of its comparatively lower spatial and temporal resolution than DSA. Advanced post-processing techniques, including colour-coded perfusion mapping and artificial intelligence-assisted segmentation, may further improve image interpretation and diagnostic utility.

Conclusion: 4D-CTA represents a promising non-invasive imaging modality for the detection, characterization, and follow-up of cerebral AVMs and DAVFs. Its dynamic imaging capabilities and wide anatomical coverage support its use as a screening and complementary diagnostic tool, potentially reducing the need for invasive angiography in selected clinical situations. Nevertheless, DSA remains indispensable when detailed vascular characterization is required or when 4D-CTA findings are inconclusive. Further prospective studies with standardized protocols and larger patient cohorts are needed to establish its diagnostic accuracy and define its optimal role in clinical practice.

Keywords: Four-dimensional computed tomography angiography; cerebral arteriovenous malformation; dural arteriovenous fistula; digital

subtraction angiography; cerebral arteriovenous shunts; wide-detector CT; cerebral hemodynamics; stereotactic radiosurgery.

1. Introduction:

Both cerebral AVMs (Arteriovenous Malformations) and DAVFs (Dural Arteriovenous Fistulas) represent a continuum of shunting disorders characterized by a high incidence of haemorrhagic complications and neurological morbidity as well as increased morbidity and mortality rates. (**32, 36**). AVMs are described as a network of dysplastic vessels linking the feeding arteries and draining veins without the capillary circulations, known as a nidus. DAVFs are characterized by the presence of direct arterial-to-venous dural connections, mostly in the sinuses. (**30,33).** The accurate treatment planning in these cases requires the precise imaging of AVMs and DAVFs. While the spatial resolution of conventional CT angiography (CTA) is outstanding, its one-phased scan fails to visualize shunts as a result of coexistence of arterial and venous enhancements. DSA (Digital Subtraction Angiography) is the standard technique providing high temporal and spatial resolution of imaging, but is rather invasive and involves risks and complications. For this reason, the search of non-invasive alternative continues. 4D-CTA (Four-dimensional CT angiography), also called dynamic or time-resolved CTA, is based on visualization of the contrast bolus passage dynamics. (**28, 38)**. The current review analyses the clinical outcomes, technical issues and diagnostic values of 4D-CTA in assessment of both AVMs and DAVFs, summarizing recent publications from last 15 years.

2. Methods and Technological Approaches

2.1 Scanner Technology and Acquisition Protocols

4D-CTA is essentially contingent upon advancements in wide detector CT scanners. Scanners that have a 320-detector row allow for 16 cm z-axis coverage, thus allowing for whole brain imaging within one rotation of the gantry. (**1, 5, 8)**. This is very important when trying to image the whole cerebral vascular tree, which means imaging everything from the circle of Willis to the cortical surface without table movement. Standard protocol is a dynamic scan after the contrast bolus is injected, which usually involves a volume of 40-70 mL at 4-5 ml. per second. Gantry rotation takes about 0.35 to 1.0 seconds. (**12, 16).** While the temporal resolution varies from 0.275 to 1.0 second and allows for the visualization of arterial, nidus, and venous circulations. (**1, 8, 12).**

Radiation Management: The literature focuses on striking the best balance between image quality and radiation dose, using techniques like individualized cerebral circulation time calculation to limit the number of dynamic acquisitions **(38,18, 2).** Post-Processing and Software Advances: Four-dimensional CTA imaging data is post-processed into various formats to aid interpretation. Time-Resolved MIP displays allow for visualization of the contrast bolus as it passes through the angioarchitecture (1, 8). Colour-Mapping is the Software tools which generate colour-coded maps based on the time-to-peak or arrival time of contrast, which can highlight areas of early venous filling indicative of a shunt (**6, 23).**

4D-DSA Prototypes: Recent software allows for the reconstruction of 4D volumes from 3D rotational angiography data, providing a cine loop viewing angle-independent visualization of flow. (**10, 17, 25).**

Deep Learning and AI: Convolutional neural networks (CNNs) are being deployed to automate the segmentation of arteries and veins, potentially reducing the manual post-processing burden and improving diagnostic accuracy and efficiency (**14, 34).**

3. Diagnostic Performance and Comparative Analysis

3.1 General Diagnostic Accuracy

Performance statistics for 4D-CTA have been uniformly impressive in clinical studies. In one study by Veld et al., the sensitivity and specificity for detection of cerebral arterio-venous shunts were 92.9% and 97.9%, respectively **(1).** Likewise, in a study by Biswas et al., the specificity and positive predictive value for detection of AVM and DAVF were 100% each, albeit with a slightly reduced sensitivity of 77% **(2).** Patients with untreated bAVMs (Brain Arterio-Venous Malformations), 4D-CTA demonstrated a sensitivity of 100% in detecting all 17 cases **(8).**

3.2 Comparison with Digital Subtraction Angiography (DSA)

The 4D-CTA shows high concordance with DSA in the classification of lesions. The Borden and Cognard systems of classification for dural arteriovenous fistulae (DAVFs) are extremely important to determine the requirement for intervention. 4D-CTA has shown excellent correlation with DSA in relation to these classifications, where the Kappa value varies from 0.92 to 1.0**. (5,9,16.)** However, disagreements arise at times. While the 4D-CTA has proven quite efficient in identifying the location of the nidus, its size, and the main draining veins, it could fail to detect some smaller arterial feeders or the distinction of a focal/diffuse fistulous site. **(5, 15)**. Sometimes, deep venous drainage in

AVMs can be missed, resulting in underestimation of Spetzler-Martin grade. 8

3.3 Identification of Specific Vascular Signs

4D-CTA facilitates the assessment of minor vascular abnormalities that are associated with the presence of a shunt, regardless of whether the size of the nidus is tiny or not. They include the following:

Asymmetry of venous opacification characterized by variations in time/intensity of the enhancement process in the internal jugular vein/dural sinus. **(24)**. Shaggy appearance of the dural venous sinus in the CTA scan with a high degree of specificity (100%) for dural arteriovenous fistula (DAVF). **(24)**

Transcalvarial channels and enlargement of foramen spinosum, which are important clues to the presence of DAVF in patients with pulsatile tinnitus. **(24)**

4. Hemodynamic Assessment and Rupture Risk Stratification

4.1 Cerebral Circulation Times and Flow Dynamics

The dynamic nature of 4D-CTA allows quantitative evaluation of cerebral blood flow kinematics. The CCT (Cerebral Circulation Time), which is the time from contrast agent arrival at the I C A (Internal Carotid Artery) to the point of arrival at the S S S (Superior Sagittal Sinus) is the key parameter used for the evaluation. The available literature proves that 4D-CTA provides CCT measurements that do not differ from DSA measurements significantly. (**13).** Thus, 4D-CTA can be successfully used for evaluation of hemodynamics. Shortened CCT is typical for AVM patients with early venous drainage. **(13, 26).**

4.2 Predicting Hemorrhagic Risk

Studies on hemodynamic flow parameters have been done with regards to their potential to be predictors of rupture risk. It has been found that the inflow/outflow ratio in AVMs, as well as venous drainage, is a predictor of a greater tendency towards hemorrhage. **(27).** Shortened circulation time is also associated with the difficulty to obliterate high flow AVMs after stereotactic radiosurgery. **(26).** However, no consensus has been achieved so far, and classic angioarchitectural predictors of rupture (such as intranidal aneurysms and deep venous drainage) still stand**. (4 ,27).**

5. Clinical Utility in Treatment Planning and Follow-up

5.1 Radiosurgery and Surgical Planning

4D-CTA has special importance in SRS (stereotactic radiosurgery) and Gamma Knife treatment planning. It provides temporal information to help physicians differentiate between shunting and non-shunting vessels in order to deliver the correct radiation dose to the nidus **(7, 12).** The use of 4D-dynamic CT scan as a alternate for catheter angiography in the planning of SRS has been found to significantly shorten the frame-on time **(7)**. Also, prototype flat-panel cone-beam CTA has been found to possess Angio architectural characteristics that are equivalent or better than 2D imaging in DSA in most cases **(10).**

5.2 Post-Interventional Monitoring

After the procedure, 4D-CTA acts as a non-invasive surveillance technique. It is used to determine the degree of occlusion following embolization, radiosurgery, or surgical clipping. **(20,21)**. For example, 4D-CTA can measure collaterals as well as the veins' morphology after transarterial embolization. **(11, 22).** Moreover, it can also help detect shunts that are difficult to detect using MRI or conventional CT angiography. (**19,37)**.

5.3 Evaluation of Clinical Symptoms (Tinnitus and Cognitive Impairment)

Utility of 4D-CTA is further seen in terms of assessment of symptoms. Individuals with pulsatile tinnitus utilize 4D-CTA as an effective diagnostic test for detection of DAVFs, with findings such as asymmetric venous collaterals and dilatation of ECA branches revealing high sensitivity and specificity**. (24,35,39).** Also, aggressive DAVFs having cortical venous drainage may result into non-hemorrhagic neurological symptoms, such as cognitive impairment due to DAVF (DAVF-CI). 29. The role of 4D-CTA with its perfusion technique is further seen in identification of venous hypertension and sinus stenosis resulting into these clinical symptoms. **(29).**

6. Limitations of the Evidence

Even with its advanced technology, there are some limitations associated with 4D-CTA. It is not sensitive enough to shunts with low flow and slow perfusion rate, hence providing a possibility of false negatives**. (1,15)**. The spatial resolution of the 4D-CTA, although ideal for an overall brain evaluation, is still not as high as DSA, at below a millimetre, limiting it in detecting tiny feeding vessels**. (38,10,16)**. Its dynamic nature demands more radiation dose as compared to a one-phase CTA. Optimizing the number of frames and the scan duration is a constant challenge **(18).**

Post-Processing Complexity: Detailed analysis, such as segmenting complex AVMs or tracing intranidal vessels, remains time-consuming and requires specialized expertise **10**.

7. Research Gaps and Future Directions

Formulate improved metrics to quantify hemodynamic, including corrected cerebral transit time (CCT) and flow rate parameters to improve consistency and clinical relevance across studies (27).

- AI and Automation: Broaden the scope of AI applications in automating analysis, classification, and segmentation **(14, 34).**

- Ultra-Low-Dose Scans: Develop new reconstruction and acquisition methods to decrease radiation doses while preserving the information about time dynamics necessary for a precise diagnosis.

- Comparison with 4D-MRA: Despite the superior speed provided by 4D-CTA, 4D-MRA represents an alternative approach with comparable spatial and temporal resolutions and no radiation risk. Comparative studies of large groups of patients would highlight the best applications for each type of scan **(19, 31).**

8. Conclusion

4D kinematic CT angiography has proven to be a valuable diagnostic technique in the diagnosis of cerebral AVMs and DAVFs. Through its ability to incorporate temporal resolution in CT angiography, it provides physicians with a complete picture of the vascular shunting and flow dynamics. Despite the fact that it is not fully replacing the invasive DSA, especially in interventional treatments and small-Caliber vessels, its diagnostic precision, usefulness in radiosurgery, and value as a screening technique make it an invaluable tool in neurovascular imaging.

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