

Original Article

Radiological Differentiation of Normal Variants vs. Pathologies in Cranial Venous Anatomy Using 3D MR Venography

Hasan Imam ^{1*}, Md. Mizanur Rahman Khan ²

1. Department of Internal Medicine, Bangladesh Medical University, Dhaka, Bangladesh.
2. Department of Internal Medicine, Bangladesh Medical University, Dhaka, Bangladesh.

* Correspondence: hasanimam5267@bsmmu.edu.bd

Abstract: Differentiating normal anatomical variants from pathological conditions in cranial venous anatomy is crucial to avoid misdiagnosis and ensure appropriate management. This study aimed to evaluate the spectrum of venous findings on three-dimensional magnetic resonance venography (3D MRV), assess its diagnostic performance, and determine interobserver agreement in identifying normal variants and pathologies. A cross-sectional study was conducted on 120 patients undergoing 3D MRV for suspected venous pathology or incidental evaluation. Findings were categorized as normal anatomical variants, pathological abnormalities, or normal venous anatomy. Diagnostic accuracy was determined by comparing 3D MRV results with a reference standard in 33 pathologically confirmed cases. Interobserver agreement between two radiologists was measured using Cohen's kappa (κ). The mean age of participants was 44.8 ± 15.6 years (range: 18–78), with a slight female predominance (51.7%). Clinical suspicion accounted for 70.8% of indications. Common normal variants included transverse sinus hypoplasia (23.3%), arachnoid granulations (10%), and intrasinus septations (6.7%), while acute cerebral venous thrombosis (15%) was the most frequent pathology. 3D MRV demonstrated a sensitivity of 93.9%, specificity of 95.0%, positive predictive value of 91.2%, negative predictive value of 96.6%, and overall accuracy of 94.6%. Interobserver agreement was excellent for both normal variants ($\kappa = 0.87$) and pathological findings ($\kappa = 0.90$). 3D MRV offers high diagnostic accuracy and excellent interobserver reliability in differentiating normal venous variants from pathological conditions. Its precise characterization of cranial venous anatomy supports its role as a non-invasive, reliable tool in routine clinical practice, reducing the risk of misinterpretation and guiding appropriate patient management.

Keywords: 3D MR venography, cerebral venous anatomy, normal variants, cerebral venous thrombosis

1. INTRODUCTION

Accurate imaging of the intracranial venous system is essential for distinguishing benign anatomical variants from true pathology such as cerebral venous thrombosis (CVT), dural sinus stenosis, or venous malformations. The dural venous sinuses and cortical veins show wide inter-individual variability—for example, asymmetric or hypoplastic transverse sinuses are common—and these normal variants can closely mimic disease on venous imaging if the reader is unaware of modality-specific pitfalls [1,2]. Radiologists increasingly rely on high-resolution, three-dimensional magnetic resonance venography (3D-MRV) techniques (both non-contrast and contrast-enhanced) to map venous anatomy, evaluate flow, and reduce false-positive interpretations [3,4]. Contrast-enhanced, time-resolved, and high-resolution 3D sequences provide superior depiction of sinus morphology and dynamic filling patterns compared with older 2D or single-phase techniques, aiding discrimination between slow flow or

hypoplasia and occlusive thrombus [5,6]. Phase-contrast and contrast-enhanced 3D MRV techniques each have characteristic strengths and artifacts; recognizing these differences is key to correct interpretation [7,8]. Despite improved acquisition methods, interpretation pitfalls persist. Normal asymmetric drainage (e.g., unilateral transverse sinus hypoplasia or aplasia), intra sinus septations, arachnoid granulations, and prominent emissary veins may appear as filling defects or signal loss and be misinterpreted as thrombosis on MRV [9,10]. Comprehensive interpretation thus requires correlation with conventional MRI signal characteristics (e.g., T1/T2 signal of subacute thrombus), evaluation of flow on time-resolved imaging, and—when ambiguity persists—ancillary techniques such as CT venography, catheter angiography, or vessel-wall imaging [11,12]. Recent advances in vessel-wall and “black-blood” MRI sequences, and direct thrombus imaging, show promise for improving specificity by directly characterizing thrombus composition and vessel wall changes instead of relying solely on luminal filling [13,14]. These techniques may help differentiate collapsed or hypoplastic sinuses and chronic thrombosis from acute occlusion when conventional MRV is equivocal [15,16]. Given the clinical importance of timely and accurate diagnosis—cerebral venous thrombosis can be neurologically devastating yet potentially treatable—radiologists must combine anatomic knowledge of common venous variants with an understanding of 3D-MRV protocol-dependent appearances and complementary MRI sequences. This review examines how 3D-MRV protocols, recognized normal variants, and adjunctive MRI tools can be applied pragmatically to reduce mis-classification of normal variants as pathology and improve diagnostic confidence [17,18]. Many benign variants—such as transverse sinus hypoplasia, intra sinus septations, or prominent arachnoid granulations—can mimic serious pathologies like cerebral venous thrombosis (CVT) or dural sinus stenosis on magnetic resonance venography (MRV). Misinterpretation of these findings may lead to unnecessary anticoagulation, delayed diagnosis, or unwarranted invasive procedures. Three-dimensional MR venography (3D MRV) offers higher spatial resolution, multiplanar reconstructions, and better depiction of venous morphology compared to conventional 2D techniques. However, despite these technical advantages, there remains limited consensus on standardized imaging criteria for distinguishing normal variants from true pathological occlusion, especially in cases of asymmetric venous drainage or slow flow. Without such clarity, diagnostic uncertainty persists, affecting patient safety and clinical decision-making. Primary objective of study is to evaluate the effectiveness of 3D MR venography in differentiating normal cranial venous anatomical variants from pathological conditions such as cerebral venous thrombosis and dural sinus stenosis.

2. MATERIAL AND METHODS

This study employed a retrospective, cross-sectional design to evaluate the ability of 3D magnetic resonance venography (3D MRV) to differentiate normal cranial venous variants from pathological findings. MRI and MRV records of patients who underwent brain imaging at the Department of Radiology, Pakistan, between January 2022 and December 2024. Inclusion criteria consisted of patients who had undergone contrast-enhanced or non-contrast 3D MRV with adequate image quality. Exclusion criteria included patients with incomplete imaging data, severe motion artifacts, or prior neurosurgical interventions altering venous anatomy.

Imaging Protocol

All MR examinations were performed using a 3.0 Tesla MRI scanner (Model, Manufacturer) with a dedicated head coil. The imaging protocol included:

- 3D contrast-enhanced MRV using a time-resolved or high-resolution sequence.

- Complementary sequences such as T1-weighted, T2-weighted, FLAIR, susceptibility-weighted imaging (SWI), and diffusion-weighted imaging (DWI).
- In selected cases, vessel-wall imaging or black-blood MRI sequences were performed to assess suspected thrombosis.

Image Analysis

Two experienced neuroradiologists independently reviewed the MRV studies. They assessed for:

- Normal anatomical variants (e.g., transverse sinus hypoplasia/aplasia, intrasinus septations, arachnoid granulations, prominent emissary veins).
- Pathological changes suggestive of venous thrombosis or stenosis.
- Imaging features including lumen continuity, signal intensity, flow-related enhancement, and comparison with conventional MRI sequences.

Disagreements were resolved by consensus. Cases with uncertainty underwent correlation with CT venography or catheter angiography, when available, for confirmation. We recorded demographic data, clinical presentation, imaging findings, and final diagnoses. The diagnostic performance of 3D MRV was calculated using sensitivity, specificity, positive predictive value, and negative predictive value, with reference standards determined by combined imaging and clinical follow-up. Statistical analyses were performed using SPSS version 26. Categorical variables were summarized as frequencies and percentages, while continuous variables were presented as mean $\pm$ standard deviation.

3. RESULTS AND DISCUSSION

The study population comprised 120 patients with a mean age of 44.8 ± 15.6 years (range: 18–78 years) and an almost equal gender distribution (48.3% male, 51.7% female). A majority of patients (70.8%) underwent imaging for clinical suspicion of cerebral venous thrombosis, while 29.2% were imaged for other neurological indications (Table 01). On 3D MR venography, normal anatomical variants were frequent, with transverse sinus hypoplasia being the most prevalent (23.3%), followed by arachnoid granulations (10.0%), intra sinus septations (6.7%), transverse sinus aplasia (5.0%), and prominent emissary veins (4.2%). Pathological findings were less common, with acute cerebral venous thrombosis observed in 15.0% of cases, chronic thrombosis in 5.8%, and dural sinus stenosis in 6.7%. Additionally, 23.3% of patients demonstrated completely normal venous anatomy (Table 02). When compared with the reference standard in 33 pathologically confirmed cases, 3D MRV exhibited high diagnostic performance, achieving a sensitivity of 93.9%, specificity of 95.0%, positive predictive value of 91.2%, negative predictive value of 96.6%, and an overall accuracy of 94.6% (Table 03). Interobserver agreement between neuroradiologists was almost perfect for both normal variant recognition ($\kappa = 0.87$) and pathological diagnosis ($\kappa = 0.90$), with an overall agreement score of $\kappa = 0.88$, reflecting the strong reliability and reproducibility of 3D MRV interpretation in differentiating normal variants from pathological conditions (Table 4).

Table 01: Demographic Characteristics of the Study Population

Characteristic	Value	Percentage (%)
Mean Age (Years $\pm$ Sd)	44.8 ± 15.6	—
Age Range (Years)	18–78	—
Sex – Male	58	48.3
Sex – Female	62	51.7
Clinical Suspicion	85	70.8

Imaging For Other Indications	35	29.2
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Table 02: Distribution of Findings on 3D MR Venography

Category	No. of Cases	Percentage (%)
Normal anatomical variant		
– Transverse Sinus Hypoplasia	28	23.3
– Transverse Sinus Aplasia	6	5.0
– Intrasinus Septations	8	6.7
– Arachnoid Granulations	12	10.0
– Prominent Emissary Veins	5	4.2
Pathological		
– Acute Cerebral Venous Thrombosis	18	15.0
– Chronic Venous Thrombosis	7	5.8
– Dural Sinus Stenosis	8	6.7
Normal Venous Anatomy	28	23.3

Table 03: Diagnostic Performance of 3D MRV Compared to Reference Standard

Parameter	Value (%)
Sensitivity	93.9
Specificity	95.0
Positive Predictive Value	91.2
Negative Predictive Value	96.6
Overall Accuracy	94.6

Table 04: Agreement Between Radiologists in Identifying Variants vs. Pathology

Finding Category	Cohen's κ (kappa)
Normal Variants	0.87
Pathological Findings	0.90
Overall Interpretation	0.88

In this retrospective cohort of 120 patients imaged with 3D MR venography (3D-MRV), we observed that normal anatomical variants of the dural sinuses were common and, in some cases, outnumbered frank pathological findings. Transverse sinus hypoplasia was the single most frequent variant in our series (23.3%), a figure that is within the lower–mid range of prevalences reported in prior imaging studies (reported ranges vary widely from ~20% up to >40% depending on population and technique) [19–21]. Our transverse sinus aplasia rate (5.0%) and frequency of intrasinus septations and arachnoid granulations (6.7% and 10.0%, respectively) are also concordant with prior MR-based series that emphasized both the high prevalence of arachnoid granulations and the substantial variability across cohorts and imaging methods [22,23]. Regarding diagnostic performance for thrombotic disease, our calculated sensitivity (93.9%), specificity (95.0%), and overall accuracy (94.6%) for 3D-MRV compared with the chosen reference standard compare favourably with previously reported values. Time-resolved contrast-enhanced MRV and combination (4D/combo) MRV techniques have demonstrated very high sensitivity for dural sinus thrombosis in multiple series (sensitivities reported up to ~97% for dural sinus segments and somewhat lower for cortical veins), and conventional TOF-MRV usually shows somewhat lower sensitivity for small cortical vein involvement [24–26]. Thus, our sensitivity of ~94%

fits well within contemporary expectations for high-resolution, contrast-enhanced 3D techniques and supports the utility of these sequences for ruling in and ruling out clinically significant sinus thrombosis. The positive predictive value (91.2%) and negative predictive value (96.6%) in our cohort are likewise comparable to those reported elsewhere, though predictive values depend heavily on prevalence and on the composition of the tested population (our study had a relatively high pretest probability with 70.8% imaged for suspected CVT). Several comparative studies and meta-analyses emphasize that when prevalence of disease is higher, PPV increases and NPV falls; this nuance helps explain why absolute PPV/NPV numbers vary across reports [27,28]. Interobserver agreement in our study was excellent ($\kappa = 0.87\text{--}0.90$, overall 0.88). This level of concordance is consistent with prior MRV research showing good to excellent inter-rater reliability for major dural sinuses and thrombosis, though agreement is frequently lower for cortical veins and small tributaries. Several studies have documented kappa values in similar ranges for sinus-level interpretation (often 0.7–1.0 depending on segment), while cortical vein assessment remains more variable [29,30]. Our high kappa values likely reflect use of high-resolution 3D sequences, blinded independent reads by experienced neuroradiologists, and consensus arbitration of discordant cases. A practical implication of our findings is that a substantial fraction of abnormal-appearing MRV findings represent benign variants rather than true occlusion, so over-calling thrombosis remains a real risk. Prior reports have highlighted frequent unilateral nonvisualization or “flow gaps” in the non-dominant transverse sinus and have cautioned about pitfalls such as arachnoid granulations, intrasinus septations, and slow flow artifact that mimic thrombus [31–35]. We therefore recommend integrating 3D-MRV appearances with conventional MRI signal characteristics (T1/T2 evolution of thrombus), time-resolved flow information, and—when necessary—CT venography or catheter angiography to avoid false positives; this multimodal approach is supported by several comparative investigations. Limitations of our study mirror those described in the literature: the retrospective design, single-center setting, and potential selection bias toward symptomatic patients (70.8% with suspected CVT) limit generalizability to screening or lower-risk populations. Further, small sample sizes for some subgroups (for example, only seven chronic CVT cases) reduced the precision of subgroup estimates. Finally, differences in MRV sequence parameters and the use (or absence) of venous-timed contrast injections produce interstudy variability in reported prevalence and diagnostic metrics; these technical heterogeneities likely account for some of the spread in values seen across the cited literature [33–35]. In summary, our results corroborate prior work showing that high-resolution 3D-MRV achieves high sensitivity and specificity for dural sinus thrombosis while also revealing that benign venous variants are common. Careful attention to known anatomic variants, combined reading with conventional MRI sequences, and—when required—corroborative imaging modalities are necessary to minimize misclassification and optimize patient care.

4. CONCLUSION

3D MR venography is a highly accurate, non-invasive imaging tool for evaluating cerebral venous anatomy and pathology. In this study, it demonstrated excellent sensitivity, specificity, and interobserver agreement, enabling reliable differentiation between normal anatomical variants and pathological findings. The high prevalence of normal variants, particularly transverse sinus hypoplasia, highlights the need for careful interpretation to avoid misdiagnosis. Our results are consistent with previously published literature, reinforcing the role of 3D MRV as a valuable first-line modality in the assessment of suspected cerebral venous disease.

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