

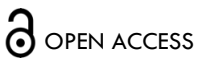


RESEARCH ARTICLE

Diagnostic Accuracy of Phase Contrast MRI Technique in Detecting Cerebrospinal Fluid Flow

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ABSTRACT

Introduction: Cerebrospinal fluid (CSF) dynamics play a critical role in neurological conditions such as normal pressure hydrocephalus (NPH), aqueductal stenosis, and Chiari malformation and also play a crucial role in maintaining the homeostasis of the central nervous system (CNS). The use of phase-contrast magnetic resonance imaging (PC-MRI) to non-invasively quantify cerebro spinal fluid dynamics (CSF) aid in diagnosis and treating such conditions. The aim of the study is to evaluate the diagnostic accuracy of phase contrast MRI technique in detecting cerebrospinal fluid flow.

Methodology: This study was a cross-sectional study and it included 136 participants and was conducted at the Department of Radiodiagnosis, Era's Lucknow Medical College and Hospital, Lucknow, India. All subjects under the inclusion criteria, underwent PC-MRI using a 3T MRI scanner to evaluate CSF flow dynamics, with post-processing performed on a Syngovia workstation.

Results: The majority of participants were male (55.88%), with a mean age of 46.84 years. Normal pressure Hydrocephalus (NPH) was the most prevalent condition (35.29%), followed by diffuse cerebral atrophy (23.53%). The study revealed distinct cerebro spinal fluid flow patterns across neurological conditions. Normal pressure Hydrocephalus (NPH) showed the highest peak systolic velocity (PSV) at 9.24 cm/s and a stroke volume of 65 μ l. Aqueductal stenosis exhibited a lower PSV of 6.53 cm/s but a higher stroke volume of 70 μ l. These findings demonstrate significant variations in CSF dynamics, emphasizing the utility of PC-MRI.

Conclusion: Phase contrast – Magnetic resonance imaging is a valuable tool for assessing cerebro-spinal fluid flow dynamics, providing critical insights into the pathophysiology of neurological conditions. The study highlights the importance of peak velocity as a reliable metric, suggesting its incorporation into routine clinical assessments to enhance diagnostic accuracy and patient outcomes.

Keywords: Cerebrospinal fluid, Phase-contrast MRI, Normal pressure hydrocephalus, Chiari malformation, Aqueductal stenosis, Peak systolic velocity.

Introduction

Cerebrospinal fluid (CSF) flows from the lateral ventricles to the third ventricle via the foramina of Monro, and subsequently enters the fourth ventricle through the aqueduct of Sylvius. From the fourth ventricle, CSF predominantly exits into the subarachnoid space (SAS) through the median foramen of Magendie and the lateral apertures of Luschka, where it circulates around the brain and spinal cord. The spinal SAS is anatomically divided into anterior and posterior sections by dentate ligaments, which provide lateral support to the spinal cord.¹ Although CSF can potentially circulate through both the central canal and the SAS within the spinal canal, the central canal is typically non-functional in adults over the age of 30.¹ CSF also interacts with brain extracellular spaces and mixes with extracellular fluid within Virchow-Robin spaces.² A significant portion of CSF is absorbed through the extracellular matrix and the lymphatic system, including pathways to cervical lymph nodes and the lumbar cistern.³

Early MRI techniques visualized CSF flow in the aqueduct by detecting flow voids—artifacts caused by high flow velocities.⁴ These flow voids were associated with positive outcomes following shunt procedures.⁵ Initial methods for quantifying CSF flow relied on T1 and T2 relaxation times or comparisons of saturation between stationary and flowing tissues.^{5,6} Advances in imaging, such as a modified gradient echo technique using phase shifts from bipolar gradients, improved visualization and facilitated the selection of patients for shunting.⁶ Phase-contrast MRI (PC-MRI) operates on the principle that moving spins acquire phase shifts in a magnetic field gradient, while stationary spins remain unaffected. By employing bipolar gradients, static phase effects are neutralized, and motion is indicated by residual phase shifts.⁶

Non-invasive PC-MRI has become a valuable tool for quantifying CSF dynamics, assisting in the diagnosis, prognosis, and treatment of neurological conditions such as syringomyelia, hydrocephalus, and Chiari malformations.^{6,7,8} Abnormal CSF flow patterns, including increased velocities or flow rates, may signify Chiari malformation and related disorders.⁹ Two principal imaging modalities—4D Flow and 2D PC-MRI—are employed to study CSF dynamics, with 2D PC-MRI being the most widely recognized for both qualitative and quantitative analysis.^{10,11} This study aimed to evaluate CSF flow using phase-contrast MRI.

Methodology

STUDY DESIGN AND SETTING

This cross-sectional study was conducted at the Department of Neurology OPD and Ward, and the Department of Radiodiagnosis at Era's Medical College, Lucknow, India, over a 24-month period. After obtaining ethical clearance and informed consent, 136 subjects were included in the study.

INCLUSION AND EXCLUSION CRITERIA

Participants were recruited based on clinical symptoms, including headache, vomiting, dementia, visual

disturbances, or cognitive impairments, along with conventional MRI findings suggestive of conditions such as normal pressure hydrocephalus (NPH), aqueductal stenosis, Chiari malformation, syringomyelia, or arachnoid cysts. Patients were excluded if they had cardiac arrhythmias or absolute contraindications to MRI, such as claustrophobia, pacemakers, or permanent metallic implants. Written informed consent was obtained from all participants after a thorough explanation of the study. The study received approval from the institutional ethics committee, and strict confidentiality of patient data was maintained.

IMAGING PROCEDURE

All participants underwent Phase Contrast Magnetic Resonance Imaging (PC MRI) using a 3T MRI scanner (Magnetom Vida, Siemens Healthineers). Imaging was conducted with standard head coils, with subjects positioned in a neutral supine posture. To minimize motion artifacts, participants were instructed to avoid deep breathing during the procedure. Routine MRI sequences included axial T1, T2, and FLAIR, sagittal T1, and coronal T2. Additionally, a midsagittal steady-state free precession sequence with thin slices (0.5–1 mm) was performed to evaluate the aqueduct of Sylvius. This sequence, referred to as True FISP in Siemens systems and FIESTA in GE systems, provided detailed visualization of CSF flow.

A two-dimensional cine phase-contrast (2D cine-PC) MRI, synchronized with the cardiac cycle, was used to capture CSF flow during systole and diastole. Imaging parameters for this sequence included a repetition time (TR) of 25 ms, echo time (TE) of 4.3 ms, flip angle of 10°, two acquisitions, a field of view (FOV) of 180 mm, matrix dimensions of 128 × 512, slice thickness of 1 mm, phase encoding velocity (VENC) of 5–10 cm/s, and a total acquisition time of approximately 2.25 minutes.

IMAGE ANALYSIS AND POST-PROCESSING

The images were post-processed using a Syngovia workstation, enabling an in-depth analysis of CSF flow dynamics. Experienced radiologists reviewed all the images, and statistical analyses were conducted to formulate the study's conclusions.

STATISTICAL ANALYSIS:

The data were entered into Microsoft Excel and analyzed using SPSS version 26 (SPSS Inc., Chicago, IL, USA). Continuous variables were summarized as mean with standard deviation or as range values, depending on suitability. Dichotomous variables were reported as frequencies and percentages.

Results

The study found that most participants were between the ages of 51 and 60, comprising 38.24% of the sample, followed by those aged 41 to 50 years (32.35%). The average participant age was 46.84 ± 7.84 years. [Figure-1] Males constituted the majority, accounting for 55.88% of the cohort. [Figure-2]

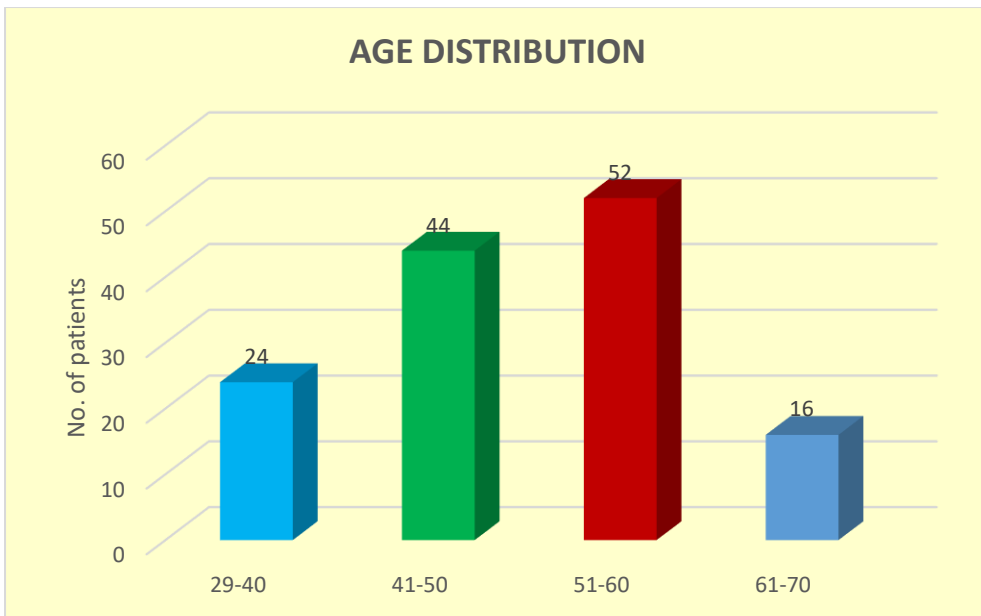


Figure 1: Age distribution of the enrolled patients

The most common diagnosis was Normal Pressure Hydrocephalus (NPH), affecting 35.29% of participants, followed by diffuse cerebral atrophy (23.53%). [Table-

1] Headache was the most frequently reported symptom, affecting 58.82% of the participants. [Table-2]

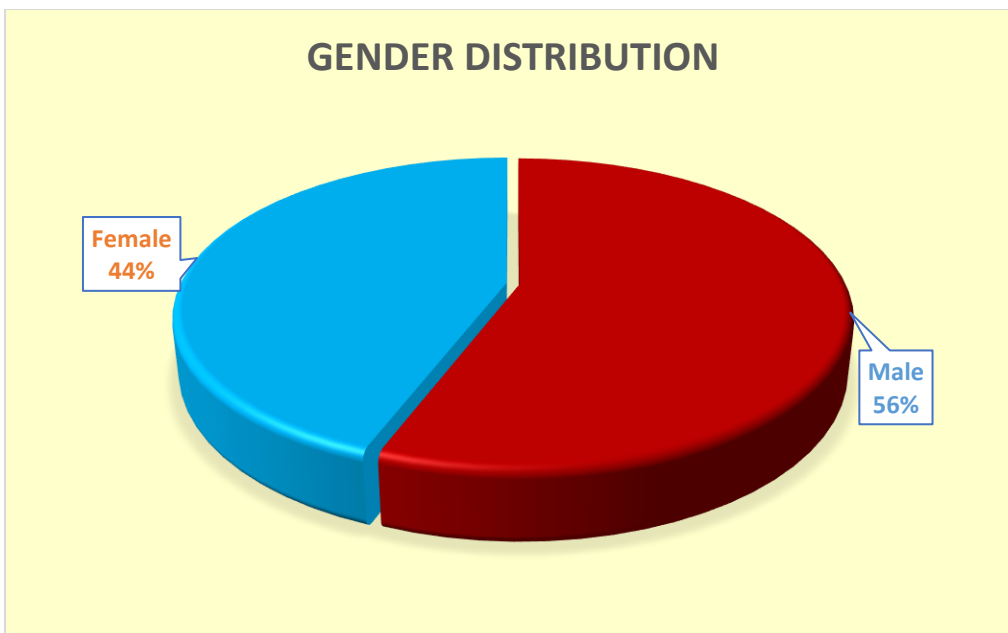


Figure 2: Gender distribution of the enrolled patients

Distinct CSF flow patterns were identified across various neurological conditions. NPH demonstrated the highest PSV (9.24 ± 4.51 cm/s) and a relatively high stroke volume (65 ± 20 μ l). Aqueductal stenosis exhibited lower PSV (6.53 ± 2.25 cm/s) and EDV (2.9 ± 1.5 cm/s) but had a slightly elevated stroke volume (70 ± 25 μ l). Chiari

malformation showed intermediate values for these parameters. Other conditions presented a PSV of 8.16 ± 4.09 cm/s and a stroke volume of 63 ± 15 μ l, representing a range of intermediate measurements. [Table-4]

Table 1: Different Condition among the enrolled patients [N=136]

Condition	Number	Percentage
Diffuse cerebral atrophy	32	23.53%
Aqueductal Stenosis	16	11.76%
Chiari Malformation	12	8.82%
Others (Tumor)	16	11.76%
Arachnoid Cysts	12	8.82%
NPH (Normal Pressure Hydrocephalus)	48	35.29%

Table 2: Symptoms reported by the enrolled patients

Symptoms	Number	Percentage
Headache	80	58.82%
Cognitive Impairment	48	35.29%
Gait Disturbance	40	29.41%
Visual Disturbances	32	23.53%
Nausea/Vomiting	24	17.65%
Neck Pain	20	14.71%
Dizziness	20	14.71%
Numbness/Tingling	16	11.76%
Seizures	12	8.82%
Urinary Incontinence	12	8.82%
Weakness	12	8.82%
Sensory Impairment	8	5.88%

The mean peak systolic velocity (PSV) was 8.58 ± 5.59 cm/s, the mean end-diastolic velocity (EDV) was 3.31 ± 2.21 cm/s, and the mean systolic flow (MSF) was 0.137

± 0.04 ml/s. The mean systolic duration was 454.63 milliseconds, and the mean stroke volume was 60.47 microliters (μ l). [Table-3]

Table 3: MRI characteristics of the enrolled patients

Parameters	Mean \pm SD (cm/s)	Range	Median
Peak Systolic Velocity	8.58 ± 5.59	16.15 (3.92 – 20.07)	5.18
End Diastolic Velocity	3.31 ± 2.21	7.32 (0.93 - 8.26)	2.93
Mean Systolic Flow	0.137 ± 0.04	0.20 (0.09 - 0.26)	0.17
Systolic Duration	454.63 ± 139.94	421 (282 – 701)	502
Stroke Volume	60.47 ± 25.96	127 (31 - 157)	56.65

Table 4: MRI characteristics in various neurological conditions

Neurological Conditions	Peak Systolic Velocity (cm/s)	End Diastolic Velocity (cm/s)	Mean Systolic Flow (ml/s)	Systolic Duration (ms)	Stroke Volume (μ l)
Normal Pressure Hydrocephalus [n=48]	9.24 ± 4.51	3.8 ± 1.9	0.14 ± 0.03	480 ± 120	65 ± 20
Aqueductal Stenosis [n=16]	6.53 ± 2.25	2.9 ± 1.5	0.11 ± 0.02	550 ± 150	70 ± 25
Chiari Malformation [n=12]	7.82 ± 3.67	3.2 ± 1.7	0.13 ± 0.04	510 ± 130	60 ± 18
Diffuse cerebral atrophy [n=32]	2.15 ± 1.81	2.5 ± 1.3	0.10 ± 0.02	600 ± 200	75 ± 30
Arachnoid Cysts [n=12]	6.14 ± 3.17	3.0 ± 1.6	0.12 ± 0.03	490 ± 140	68 ± 22
Others (Tumor) [n=16]	8.16 ± 4.09	3.57 ± 1.83	0.13 ± 0.03	500 ± 110	63 ± 15

These results underscored significant differences in MRI characteristics among neurological disorders, highlighting the utility of phase-contrast MRI in evaluating CSF flow dynamics. This method proved valuable for the diagnosis and management of various neurological conditions.

Discussion

This study included participants aged 29 to 70, with the largest group (38.24%) in the 51–60 age range. In contrast, Ahmad et al.¹² examined 39 patients aged 1 to 65 years and a control group of nine age- and sex-matched individuals. Sakhare et al.¹³ focused on a younger cohort with a mean age of 24.8 ± 3.9 years, significantly younger than our mean age of 46.84 years. Govindarajan et al.¹⁴ reported a broader distribution,

with 25% aged 1–20 years, 22.2% aged 21–40, 25% aged 41–60, and 27.8% aged 61–80 years, highlighting variability in age demographics across studies.

Our study recorded a mean End-Diastolic Velocity (EDV) of 3.31 ± 2.21 cm/s, with values ranging from 0.93 to 8.26 cm/s and a median of 2.93 cm/s. Govindarajan et al.¹⁴ found that NPH patients had significantly higher Peak Systolic Velocity (PSV) and EDV compared to controls (9.96 ± 1.73 vs. 4.80 ± 0.39 , $p < 0.05$; 4.72 ± 0.62 vs. 3.21 ± 0.55 , $p < 0.05$). Conversely, age-related brain atrophy and aqueductal stenosis (AS) showed lower PSV and EDV values. While Elsafty et al.¹⁵ reported lower values for NPH, our findings of increased stroke

volume (SV) align with reports of hyperdynamic circulation by Kahlon et al.¹⁶.

NPH was the most prevalent condition in our study (35.29%), followed by diffuse cerebral atrophy (23.53%). Aqueductal stenosis and other conditions each accounted for 11.76%, with Chiari malformation and arachnoid cysts at 8.82% each. These findings differ slightly from Govindarajan et al.¹⁴, who examined a similar range of conditions with a focus on age-related variations.

Headache was the most common symptom, reported by 58.82% of participants, followed by cognitive impairment (35.29%) and gait disturbances (29.41%). Visual disturbances were observed in 23.53%, while nausea/vomiting, neck pain, and dizziness were less frequent (17.65% and 14.71%, respectively). Other symptoms, such as numbness/tingling, seizures, urinary incontinence, and weakness, were reported in 8.82%, and sensory impairment was the least common (5.88%).

In our study, the mean systolic flow (MSF) was 0.137 ± 0.04 ml/s, ranging from 0.09 to 0.26 ml/s, with a median of 0.17 ml/s. The mean systolic duration was 454.63 ± 139.94 ms, with values ranging from 282 to 701 ms. These findings align with Sakhare et al.¹³, who used 2D cine-PC sequences, while Stankovic et al.¹⁸ highlighted the advancements of 4D flow MRI for volumetric CSF flow analysis.

The mean stroke volume in our study was 60.47 ± 25.96 μ l, ranging from 31 to 157 μ l, and a median of 56.65 μ l. These results align with El Sankari et al.¹⁹, who noted compensatory mechanisms in intracranial pressure regulation, and Stoquart et al.²², who reported lower stroke volumes in older adults. The wide range of stroke volumes in our study suggests varying risks for conditions like hydrocephalus and underscores stroke volume's diagnostic value.

Specific findings in CSF flow dynamics included higher PSV (9.24 ± 4.51 cm/s) and SV (65 ± 20 μ l) in NPH, lower PSV (6.53 ± 2.25 cm/s) and EDV (2.9 ± 1.5 cm/s) but slightly higher SV (70 ± 25 μ l) in aqueductal stenosis, and intermediate values for Chiari malformation. Diffuse cerebral atrophy exhibited the lowest PSV (2.15 ± 1.81 cm/s) but the highest SV (75 ± 30 μ l). These variations demonstrate the diagnostic utility of phase-contrast MRI in differentiating neurological conditions.

Physiological factors, such as respiration, heart rate, and circadian rhythm, as noted by Schrauben et al.²⁷, can influence CSF and cerebral blood flow (CBF) dynamics. Variability in venous flow, especially in the internal

jugular veins, underscores the need to consider these factors during MRI assessments. Establishing normative flow values by age, gender, and pathology can enhance diagnostic accuracy and enable phase-contrast MRI to serve as a non-invasive biomarker for conditions like hydrocephalus and cognitive impairment.

This study highlights the value of phase-contrast MRI in understanding CSF dynamics and its potential in improving diagnosis and management of neurological disorders. Standardization and further research are needed to fully harness its clinical applications.

Conclusion

The findings of this study highlight the value of phase-contrast MRI in evaluating CSF flow dynamics, demonstrating notable variations across neurological conditions and offering valuable insights into their underlying pathophysiology. While peak velocity was initially underemphasized, the research established it as a more accurate and reliable parameter for assessing cerebral hemodynamics. This shift suggests that incorporating peak velocity measurements into routine clinical practice could improve diagnostic accuracy and patient care. Additionally, the study lays the groundwork for exploring the longitudinal effects of cerebral hemodynamics and encourages further neuroimaging research with flexible and adaptive methodologies.

Despite its strengths, the study has limitations. These include a reliance on subjective self-reported symptoms, the absence of a healthy control group, and unreported measurement reliability, which may affect the accuracy and generalizability of the results. Future research should address these limitations by including larger, more diverse sample populations, incorporating healthy controls, using objective symptom assessments, and investigating how CSF dynamics influence treatment outcomes. Such efforts would yield more robust findings and enhance their applicability to clinical practice.

Conflict of Interest: All authors declare no conflict of interest.

Source of Funding: None

Consent: As per international standards or university standards written participant consent has been collected and preserved by the authors.

Ethical Approval: As per international standards or university standards written ethical permission has been collected and preserved by the author(s).

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