Original Article

Role of cine phase-contrast magnetic resonance imaging in the management of normal pressure hydrocephalus

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Abstract

Background and Aim: There are several unanswered queries related to normal pressure hydrocephalus (NPH) regarding the diagnostic criteria and selection of appropriate patients for shunt surgery. This study aimed to evaluate the utility of cine phase-contrast (CPC) magnetic resonance imaging (MRI) in the management of patients with NPH.

Patients and Methods: In this prospective study, MRI analysis was done on 1.5 Tesla scanner in 20 patients who presented with clinical features and routine MRI findings which were suggestive of NPH. CPC MRI and clinical assessment were performed before and after a high-volume cerebrospinal fluid (CSF) tap by lumbar puncture. Out of these twenty participants, ten underwent ventriculoperitoneal (VP) shunting. Clinical assessment was also done after VP shunting. CSF flow through the aqueduct was also evaluated in twenty age- and sex-matched controls.

Results: There was a statistically significant difference between aqueductal flow void score in cases and controls. However, no significant difference in flow void was seen after the tap or after the shunt. There was also a statistically significant difference between the values of stroke volume (SV) in cases and controls. Very high SVs (>50 μL) correlated with marked clinical improvement after the tap and after the shunt. Mildly elevated SV did not help in making any interpretation regarding the usefulness of shunt. There was also a statistically significant difference between the values of peak velocity (PV) in cases and controls. Patients with PV >10 cm/s and with a fall of ≥2 cm/s after tap significantly correlated with clinical improvement.

Conclusions: CPC MRI is a useful adjunctive technique to support the diagnosis of NPH as well as in predicting a favorable response to shunt surgery in these patients.

Keywords: Hydrocephalus, imaging, magnetic resonance imaging, normal pressure hydrocephalus, shunt

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INTRODUCTION

Hydrocephalus is described as a hydrodynamic disorder of the cerebrospinal fluid (CSF) that leads to a surge in the volume occupied by it in the central nervous system. Communicating hydrocephalus causes enlargement of all the ventricles including the fourth and may be a consequence of many etiologies such as meningitis, subarachnoid bleed, trauma, and meningeal carcinomatosis or it may be idiopathic.[1,2]

Normal pressure hydrocephalus (NPH) is categorized by the clinical triad of gait disturbance, cognitive decline, and

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urinary incontinence that is accompanied by ventricular enlargement without elevated CSF pressure. This disorder is one of the few treatable causes of dementia, and radiologists are generally engaged in making the diagnosis. Based on etiology, the NPH has been classified as idiopathic normal pressure hydrocephalus or the primary form is seen in patients without known precipitant factors and secondary normal pressure hydrocephalus, i.e., any form of chronic communicating hydrocephalus which is secondary to etiologies such as meningitis and subarachnoid bleed. There are many unresolved problems with this entity concerning the diagnostic criteria and selection of suitable patients for shunt surgery.[3-10]

The different methods which have been used in the diagnosis of communicating hydrocephalus are a high normal opening CSF pressure on lumbar puncture, lumbar puncture and removal of 50 ml of CSF (Miller Fisher test or CSF tap test), ventricular tap test, computed tomography (CT) cisternography, and saline infusion with pressure monitoring. Nonetheless, these tests are invasive and may lead to infection. The earlier radiologic diagnosis was based on the CT finding of the dilated ventricular system out of proportion to cortical sulcal enlargement and periventricular hypodensities. However, it can only show anatomy and not the physiology of CSF flow.[11-13]

The ultimate treatment is typically the placement of a shunt to drain CSF from the ventricles to a body cavity. Ventriculoperitoneal (VP) shunting is the simplest and the most extensively used technique. Conversely, not all patients gain from shunting, and shunt surgery is coupled with a considerable complication rate. The vital issues which are confronted in the management are whether to introduce a shunt at all, how to make sure that the shunt is at a suitable pressure, and how to prevent complications of shunting. Prognostication of surgical outcome has been tried by means of clinical signs and symptoms, results of tests of CSF dynamics (e.g., CSF pressure recordings), response to CSF drainage, results of intrathecal saline infusion, CT, etc. Unfortunately, contradictory reports of the prediction of usefulness with many of these investigations have been published.[14-16]

Magnetic resonance imaging (MRI) findings of communicating hydrocephalus include ventricles enlarged out of proportion to sulcal enlargement, upward bowing of corpus callosum as well as thinning of the corpus callosum on sagittal sequences, flattening of the gyri against the inner table of the skull. MRI also assists in ruling out causes of obstructive hydrocephalus. Transependymal resorption of CSF is visualized on T2W images as areas of the increased periventricular signal. Since white matter changes, i.e., periventricular hyperintensities and deep white matter hyperintensities are related with both periventricular edema and ischemic white matter degeneration, therefore the diagnostic and predictive value of these hyperintensities in NPH is imprecise.

The capability to assess CSF motion has improved through MRI utilizing lack of signal caused by sensitivity to oscillatory motion. CSF motion is demonstrated as a flow void in the narrowest part of the ventricular system, i.e., the aqueduct of Sylvius. In the majority of patients with communicating hydrocephalus, there is a noticeable loss of signal of flowing CSF in the aqueduct as well as in the neighboring third and fourth ventricles on nonflow-compensated axial and sagittal images. However, the more recent MRI sequences such as fast/turbo spin echo are much more inherently flow compensated and do not show the same flow void as was appreciated in the older MR sequences.[17-19]

Lately, cine phase-contrast (CPC) MRI has shown potential for assessing cranial and spinal CSF flow. Phase-contrast imaging delivers data about the phase (or direction) of flow and the velocity (or magnitude) of flow. It involves two measurements that are sensitized to flow in various directions; usually, one measurement is sensitized to flow in one direction and the second is sensitized similarly to flow in the opposite direction. Both measurements are subtracted to remove any influence to image phase that does not occur from flow or motion. Consequently, no signal is perceived from stationary tissue; the signal is obtained only from flowing object. Subtraction of the phase information produces spatial measures of flow velocity [Figure 1]. Phase-contrast technique is susceptible,

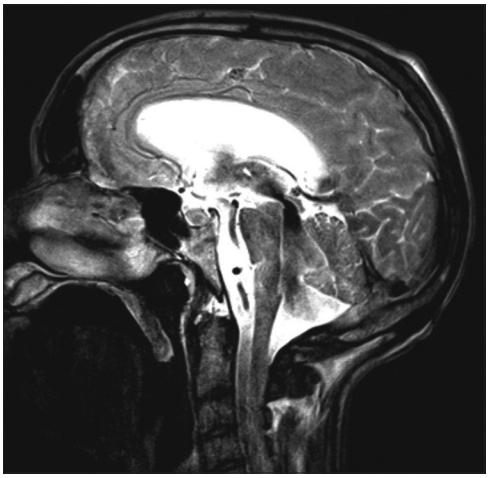

Figure 1: T2-weighted sagittal image showing exaggerated aqueductal flow void extending into the third and fourth ventricles

even to slow flow, and offers the potential for noninvasive flow quantification.[20-23]

This study aimed to determine aqueductal CSF flow rates and velocities in normal and hydrocephalic individuals employing CPC MRI and also aimed to explore associations between clinical outcome and CSF flow rates, as determined with CPC MRI, in patients undergoing lumbar CSF drainage or VP shunting.

PATIENTS AND METHODS

This study was approved by the Institutional Ethics Committee and included 20 patients with NPH, who presented with a triad of gait abnormalities (Grade 2 or 3 on gait scale), urinary incontinence, and memory impairment, along with imaging evidence of ventriculomegaly out of proportion to sulcal enlargement. The following scales were used for the clinical evaluation of the patients: (1) Mini–Mental State Examination (MMSE) for the assessment of cognitive changes (2) and by scrutinizing the gait of patients, which was evaluated by the gait scale comprising 4 grades from 0 to 3: Grade 0 – natural/normal gait; Grade 1 – imbalance when turning with short steps, broadened base, and infrequent falling; Grade 2 – repeated falls and assistance needed for ambulation; and Grade 3 – gait being impossible to achieve.[24] Clinical recovery was considered if there was an improvement in one point or more on the gait scale or >3 points' improvement in the MMSE. The control group included twenty participants who showed no clinical or radiological signs of CSF circulation anomalies and had normal MR scan of the brain. The participants of the control group were age and sex matched with the patients in the study group. Patients omitted from the study were those who had contraindications for performing an MRI and mild gait imbalance (Grade 1) and who had the following findings on MRI scan of the brain: obstructive hydrocephalus and imaging findings that were suggestive of vascular dementia (multi-infarct dementia) and cortical dementia. MRI in all the patients entered in this study was done on Magnetom Avanto 18 Channel 1.5 Tesla MR Machine (Siemens).

All the patients in the study group underwent MR examination before and after CSF tap done on 3 consecutive days (72 h). The findings of clinical examination were evaluated both before and after the tap, and the presence or absence of improvement recorded. In all cases, axial T2-weighted and fluid-attenuated inversion recovery turbo spin-echo (TR/TE/N: 4000/101/2, 5 mm slice thickness) and T1-weighted spin-echo sequences were acquired for assessment of the ventricular system. The presence and degree of ventricular dilatation, periventricular ooze, and CSF flow void in the aqueduct of Sylvius were documented. The flow voids were scored.

CPC imaging employing prospective cardiac gating was then done for the evaluation of CSF flow. For qualitative assessment of CSF flow, midsagittal phase-contrast images were obtained using a FLASH-in-plane sequence with a relaxation time (TR) = 39.55 ms, echo time (TE) = 12, flip angle = 10°, field of view [FOV] = 240, pixel size = 1.3 × 0.98 mm, and matrix = 256 × 192. Quantitative assessment of aqueductal CSF flow parameters was achieved using a FLASH-through-plane sequence with acquisitions in an axial plane at right angles to the main axis of the aqueduct and passing through its midportion. The following parameters were employed: TR = 32.3 ms, TE = 8.36, flip angle = 10°, FOV = 150, pixel size = 0.86 × 0.43 mm, and matrix = 256 × 256. The flow velocity sensitivity (velocity encoding) was set at 20 cm/s. Once the image data had been obtained, a circular region of interest (ROI) was placed in the aqueduct, enclosing its entire area, with the help of a mouse-driven cursor, and a CSF flow waveform was created. The time of the cardiac cycle after the R wave was drawn on X-axis and velocity on Y-axis. The following CSF flow parameters were evaluated: the peak systolic velocity in cm/s and the aqueductal stroke volume (SV in mm^3 or μL). In the present study, SV was the mean of systolic and diastolic volumes passing through the aqueduct.

Quantification of CSF flow on MRI was again done after drainage of 30-ml CSF every day through lumbar route for 3 consecutive days (72 h), mimicking the effect of a shunt. On the basis of improvement in clinical status and positive phase-contrast CSF assessment following CSF tap test, patients were advised for shunt surgery. In the ten patients who underwent surgery, clinical improvement was assessed after 10 days and results were compared with results of phase-contrast imaging. All clinical and MRI findings were documented and analyzed.

Statistical analysis

The following tests were used: McNemar's Chi-square test, paired *t*-test, Mann–Whitney test, and Wilcoxon test. The value of 5% ($P < 0.05$) was fixed as the cutoff for rejecting the null hypothesis with a confidence interval of 95%.

RESULTS

The study consisted of twenty patients who presented with clinical features and routine MRI findings suggestive of communicating hydrocephalus referred from indoor/outdoor departments for MRI. CPC MRI was

performed before and after a high-volume tap in all patients and after the shunt in ten patients who underwent VP shunting. Clinical examination of these patients, including MMSE score and gait assessment, was also performed before and after the tap and after the shunt. CSF flow through the aqueduct was also assessed in 20 age- and sex-matched controls.

The majority of participants included in the study were of geriatric age with the maximum number of patients as well as controls being in the age group of 51–70 years (80% cases and 90% controls). Two participants from each group were in the age group of 71–80 years (20%), and two patients were in the age group of 81–90 years. The youngest case was 55 years old, and the oldest case was of 85 years. The mean age of cases was 66.2 years, and the mean age of controls was 61.9 years. About 70% (n = 14) of the participants included in the study group were males, whereas 30% (n = 6) of the cases were females. About 90% (n = 18) of controls were males and 10% (n = 2) were females [Table 1].

The maximum number of cases (10 out of 20, i.e., 50%) included in our study had idiopathic normal pressure hydrocephalus, i.e., those cases in which no primary cause could be found. A history of head injury was present in 6 (30%) patients. Two patients developed communicating hydrocephalus following subarachnoid hemorrhage secondary to rupture of anterior communicating artery (ACom) aneurysm, and two patients developed it secondary to intracerebral and intraventricular hemorrhage. The control group consisted of those individuals who had complaints (headache, generalized weakness, vertigo, and new-onset seizures) unrelated to abnormalities of CSF circulation. These were age and sex matched with the cases and had normal MRI brain with no imaging abnormality of CSF drainage.

The twenty patients who presented with the clinical features suggestive of communicating hydrocephalus had different duration of symptoms ranging from 20 days to 2–3 years.

Table 1: Pretreatment characteristics of the study population

Characteristics of patients	Number of patients
Female	6
Male	14
Mean age (years)	66.2
Range; age (years)	55–85
Range; duration of symptoms	20 days–3 years
Response to high-volume lumbar puncture (*n*=improved/total)	20/20
Response to shunt placement (*n*=improved/total)	10/10
Aqueductal SV (μL), range; average	20–231; 82.25
Aqueductal CSF flow (cm/s), range; average	3.4–15.8; 11.63

CSF – Cerebrospinal fluid; SV – Stroke volume

Magnetic resonance imaging

All the participants of the study group exhibited disproportionate dilatation of the ventricular system as compared to cortical sulcal prominence. In six patients with secondary normal pressure hydrocephalus, findings of the previous insult to the brain could be seen. Ischemic changes were also seen in 8 (40%) cases. Six out of these patients had long-standing symptoms. In the control group, patients had normal MRI brain except for age-related ischemic changes and atrophy. No abnormal ventricular dilatation was seen.

Aqueductal flow void was evaluated in patients as well controls on routine flow-compensated axial and sagittal T2W turbo spin-echo images [Figure 2]. The flow void was graded as mentioned by Bradley *et al*.[16,18] Ten out of 20 (50%) patients had Grade 4 flow void whereas none of the controls had a Grade 4 flow void. Six patients had Grade 3 flow void as compared to two in the control group. Sixty percent (12 out of 20) of controls had Grade 1 flow void, four controls had Grade 2 flow voids, and two controls had Grade 0 flow void [Figure 3]. The mean flow void score in the patient group was 3.2 with a standard deviation (SD) of 1.03 and that in the control group was 1.3 with a SD of 0.82. The difference was statistically significant (P = 0.03). No statistically significant difference in the change of flow void was seen after high-volume tap or shunting (P > 0.05).

Quantitative assessment

Evaluation of stroke volume and peak velocities

The values of the aqueductal SV had a wide range, both in patients and controls. In controls, the mean SV was 19.3 μL with SD 13.3 and range of 3–46 μL. Patients of communicating hydrocephalus also exhibited a wide range of values varying from 20 to 231 μL with a mean value of 82.25 μL and SD 56.34. The peak velocity (PV) through the aqueduct also showed a wide range, both in cases and controls. Peak systolic velocities in cases ranged from 3.4 to 15.8 cm/s with a mean 11.63 cm/s and SD of 4.24. In

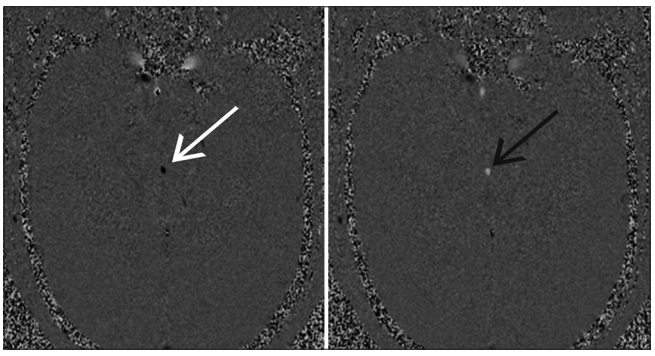

Figure 2: Cranial flow is seen as bright signal while caudal flow is seen as dark signal in this axial phase-contrast image

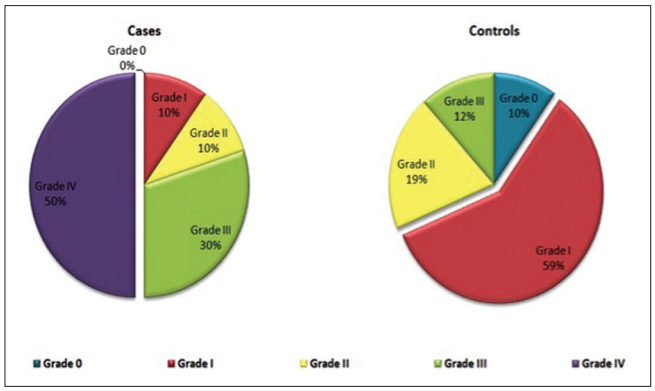

Figure 3: Pie diagram showing grades of flow voids in cases and controls

controls, the range of PV was from 1.4 to 9.5 cm/s with a mean of 4.35 cm/s and SD of 2.30. Both the values of SV and PV were significantly higher than those observed in the control group ($P < 0.05$).

CSF flow quantification was performed in all the 20 patients after high-volume CSF tap. A decrease in SV and PV was seen in all the cases after a high-volume tap which was statistically significant ($P < 0.05$) [Figure 4]. Significant fall in SV and PVs was also observed in the ten patients who underwent shunt ($P = 0.04$). The range of values of SV in patients postshunt was 12–46 μL. Of all the 20 patients who underwent a high-volume tap, 16 patients had high SV (>50 μL) and high PVs (>10 cm/s) at initial evaluation, and all these patients showed good clinical improvement (2 points on gait scale) following high-volume CSF tap. The decrease in PV ≥2 cm/s after tap was found to be significantly associated with clinical improvement ($P = 0.003$). Although the PVs and SVs were significantly higher in the cases than controls, there was a wide range both in cases and controls, and overlap of values was also seen. PVs (>10 cm/s) and SVs (>50 μL) were indicative of hyperdynamic flow and were only seen in the patients. There was a statistically significant association of improvement in gait with a change in the average PV and average SV with $P < 0.05$. The postshunt and posttap PV was <10 cm/s in all ten patients who underwent shunt surgery [Table 2].

Out of rest of the four patients, two patients had low SV of 20 and 25 μL and velocities of 4.4 and 3.4 cm/s, respectively, at presentation, which falls within the range in controls. They had developed communicating hydrocephalus following ruptured aneurysms which were operated. They showed progressively increasing the ventricular size on routine CT and MRI. To assess the usefulness of shunt surgery, high-volume CSF tap was performed for 3 consecutive days. Following this, they

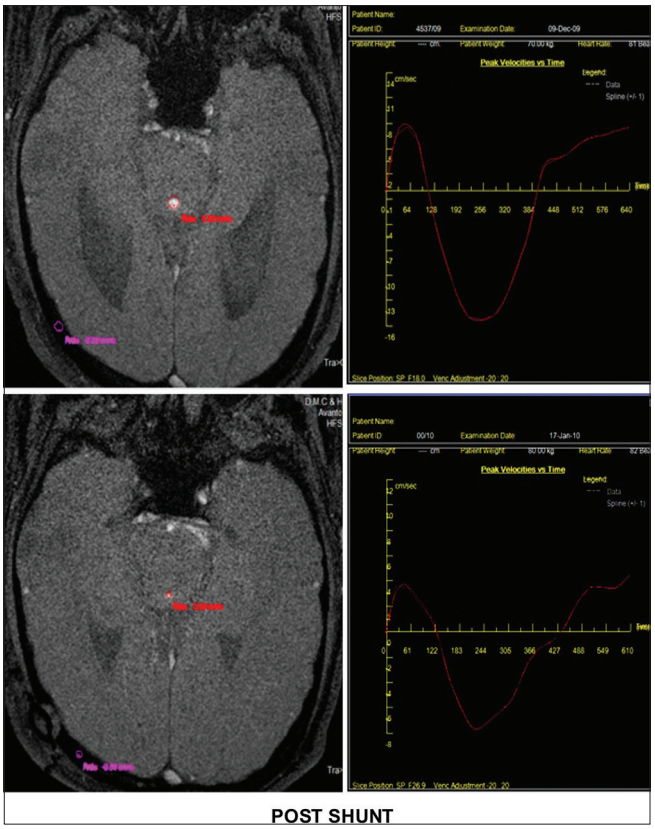

Figure 4: Flow quantification by phase-contrast imaging showing decrease in peak velocity from 15 cm/s to 7.8 cm/s after ventriculoperitoneal shunt

showed mild clinical improvement (one point on gait scale) and an insignificant fall in SV and PVs. These patients subsequently underwent VP shunting with improvement. Two other patients with SVs of 38 μL and 35 μL and PVs of 5 and 10 cm/s respectively were diagnosed as NPH nearly 2 years back on the basis of the findings of ventriculomegaly, exaggerated aqueductal flow void and clinical improvement following high-volume tap. In our hospital, both these patients underwent a high-volume tap, and they showed mild clinical improvement (one point on gait scale) although fall in SVs and PVs was only minimal.

Postoperative complications were seen only in two patients in the form of bilateral subdural hygromas. None of the patients had 3-point improvement in gait scale after interventions.

DISCUSSION

Communicating hydrocephalus signifies one of the few treatable disorders, in which neurologists, neurosurgeons, and neuroradiologists work jointly to make the diagnosis. Communicating hydrocephalus, mainly its idiopathic form is hard to diagnose, because of its inconstant presentation and progression in addition to its overlap and

Table 2: Posttreatment characteristics of the study population along with cutoff values of stroke volume and peak velocity

Gait improvement	Number of patients/ participants	Cut-off values of PV cm/s; SV μL	Change in PV after interventions (cm/s)	*P*
Patients; improved 2 grades	16	>10; >50	>2	<0.05
Patients; improved 1 grade	4	<10; <50	<2	>0.05
Controls	20	<10; <50	NA	NA

SV – Stroke volume; PV – Peak velocity; NA – Not available

superimposition with other neurologic disorders. Once a diagnosis is made, it is still problematic to recognize the patients who are likely to show symptomatic improvement with VPS, the so-called shunt responders. It is vital to precisely identify potential shunt responders because complications associated with VPS occur 13%–50% of the patients and may further degrade the patient's quality of life. To elucidate the cause of NPH, make a precise diagnosis of NPH, and suitably recognize the shunt responders, numerous tests have been suggested, including cisternogram, spinal tap test, resistance measures, external lumbar drainage, and intracranial pressure recording; some of which are invasive.[6-12]

MRI has been shown to have many benefits in the assessment of patients with suspected NPH. The present study was done to define the role of MRI in the assessment of patients with suspected communicating hydrocephalus. The primary objective of any analysis such as this is to establish dependability and validity of the measurements, methods used, and generalizability of the results. Obviously with different imaging factors and quantification methods, distinctive results would be expected. Twenty patients who presented with all the three classic triads of neurologic disorders related with NPH and imaging findings of ventriculomegaly (Evans ratio >0.30) out of proportion to sulcal dilatation were examined. The MR findings were correlated with clinical findings both before and after tap as well as after VP shunt in the ten patients.

The scrutiny of age distribution in this study revealed a narrow range, with all patients above the age of 50 years with a mean age of 66.2 years and age range of 55–85 years. Fifty percent of the cases had a primary or idiopathic form of NPH which is a disease of the elderly population, thus accounting for the above age distribution.

In our study, 40% patients presented <3 months after onset of symptoms and 30% presented after >1 year of symptom onset. The significance of time elapsed between the onset of symptoms and study was emphasized in Scollato *et al*.[24] The authors observed the change in aqueductal SV in unshunted patients with NPH, i.e., in those patients who had declined shunt surgery. They acquired the values of SV in these patients every 6 months over a period of 2 years. Out of total nine patients, seven patients showed high SV >42 μL at presentation, and in the remaining two patients, the SV was <42 μL. These two patients showed an increase in SV on the first follow-up at 6 months, which qualified them as good candidates for shunting. However, over the time, they observed a progressive reduction of the SV in untreated patients with worsening clinical symptoms that may be a sign of a progressive cerebral ischemic injury, which renders the NPH irreversible.

In this study, the evaluation of flow void across the aqueduct provided a subjective assessment of the occurrence of hyperdynamic flow. Sixteen patients showed accentuated flow void. The average flow void score in the patient group was 3.2 and that in the control group was 1.3. The difference of flow void among the study and control groups was statistically significant ($P = 0.03$) which is consistent with the study done by Bradley *et al*. 1991.[18] They evaluated flow void on nonflow-compensated proton-density images and the mean flow void in patients who showed excellent response to surgery was 2.7, and those who showed inadequate response to surgery had a mean flow void score of 0.7.

Consequently, they concluded that the presence of higher score associated well with improvement after the shunt. On the other hand, comparable results were not replicated by other investigators like Bradley *et al*. in 1996[25] and Krauss *et al*. in 1997[26] likely to be due to using of newer fast flow-compensated sequences. In the present study, patients did not display a substantial change in flow void score postsurgery. The use of newer flow-compensated or fast spin-echo sequences tended to rephrase moving spins, thus rendering the "flow void" a less suitable indicator to forecast shunt response.[17-19]

The aqueductal SV is defined as the mean of the volume of CSF moving craniocaudal during systole and that moving caudocranial during diastole. It is resulting from measurements on phase-contrast CSF velocity MR images. Precisely, it is the product of the measured velocity of a pixel (in millimeters per second) and the area of that pixel (in square millimeters) within the cross-sectional area of

the aqueduct over mechanical systole or diastole. The units of the aqueductal CSF SV are, therefore, cubic millimeters or microliters.[25]

Considerable interobserver differences in flow parameters have been seen in many studies both in healthy individuals and in patients with communicating hydrocephalus. These differences are due to the size and anatomy of CSF spaces, heart rate, arterial and venous flow, and amenability of brain tissue. Different observers have computed diverse ranges of SV. In our study, both cases and controls showed some overlap in the values of SVs and PVs; nevertheless, the mean values in the patient group were significantly higher than those seen in the control group ($P = 0.03$).

Elevated values for SV in cases and controls were obtained by Bateman in 2008[6] with the mean SV in controls being 48 μL and in cases being 140 μL with $P = 0.02$. Further higher values were seen by Henry-Feugeas *et al*.[27] with mean SV in healthy participants being 51 ± 25 μL/cycle and in patients with hyperpulsatile flow being 288 ± 124 μL. The different mean values of SV attained in different studies, and our study can be ascribed to different scanners and different imaging parameters used. Although in both these studies, the difference of values among the patients with NPH and controls was statistically significant.

Bradley *et al*. in 1996 did CPC MRI in 18 patients with suspected NPH. Twelve patients who had SV >42 μL responded favorably to shunting, while out of six patients who had SV <42 μL, three patients improved and three did not. Therefore, they concluded that the association between CSF SV >42 μL and positive response to VP shunting was statistically significant ($P < 0.05$), and CSF velocity MRI was valuable in the selection of patients with NPH to undergo shunt formation.[25] In our study, in the patient group, 16 out of 20 patients presented with high SV >50 μL and PVs >10 cm/s and all these patients showed clinical improvement of two grades (gait scale). The patients who had highly elevated values showed more improvement as compared to patients who had a less marked increase in SV.

Out of twenty patients, four presented with lower values of SV and PVs near the range of the control group. Lower values can be explained by the results of the study conducted by Scollato *et al*.[24] in which the SV rises in the first few months and then progressively declines in unshunted patients with NPH. This may be may be a sign of vascular/ischemic injury in patients with long-standing disease. Insignificant correlation between SV and response to shunting was seen in the study conducted by Kahlon *et al*.[28] They studied 38 patients with suspected NPH by means of clinical examination, lumbar infusion and spinal tap tests and the shunt surgery was performed. SV in the not operated patients (mean, 66 ± 53 μl) did not differ significantly from the shunted patients (95 ± 78 μl; $P = 0.335$). Patients were divided into three groups according to SV range: low (0–50 μl), middle (51–100 μl), and high (>100 μl). No statistically significant ($P > 0.05$) improvements in any of the objective tests were found in any of the SV ranges.

In the present study, there is a significant difference in SV in cases and controls, and values >50 μL have been observed in cases only. SV and PV values have not correlated with clinical outcome in 4 out of 20 patients. However, in patients with very high values of SV and PV, there was good correlation between these values and clinical outcomes. In patients with low-to-intermediate values, no particular interpretation could be made.

In all the individuals, we observed greater CSF velocities in the craniocaudal direction (during flow in systole) than in caudocranial direction (in diastole). This was observed in both the study and control groups. Some authors have used peak CSF velocity measurements to characterize CSF dynamics. Peak flow velocity is in the middle of streamline flow; thus, if the FOV is drawn covering the aqueduct by different observers, PV does not show interobserver variation.[29] We observed that peak CSF velocity through the aqueduct of Sylvius also had a wide range, both in cases and controls, and there was a significant difference between PVs in cases and controls.

Our results are in agreement with the results of Giiang *et al*. who showed that the mean maximum CSF flow velocities (Vmax) at the aqueduct were 4.93 ± 0.28 cm/s (mean ± SD) for the control group and 6.22 ± 0.67 and 7.24 ± 1.08 cm/s for the NPH and communicating hydrocephalus groups, respectively.[30] Lee *et al*. obtained a set of reference data of the CSF PV and average flow through the cerebral aqueduct in young healthy volunteers and found that the mean velocity through the ampulla in normal healthy young adults was 3.65 ± 1.59 cm/s.[31]

Sixteen out of 20 patients in our study group had PV ≥10 cm/s indicating hyperdynamic flow. All these patients subsequently improved after the tap. In the study done by Sharma *et al*., the peak CSF flow velocity was used to characterize the CSF flow dynamics because of the hypothesis that peak flow velocity was in the center of the streamline flow, and thus, it was less predisposed to show interobserver variations. Quantification of CSF flow was done at the aqueduct using commercially

Table 3: Important similar studies with pre-/posttreatment patient characteristics, clinical criteria used, and the outcomes

Authors	Study population	Inclusion criteria	Clinical scales used	Evaluation of outcomes	Results
Andrén *et al*.[32]	102 iNPH	"Possible" or "probable" iNPH	Hellstrom's iNPH scale	Improvement of at least 5 points	Significant improvement following shunting with early shunting cohort having a greater degree of improvement
Klinge *et al*.[33]	115 patients with iNPH	Two groups: "Typical"/"questionable" iNPH	mRS, Hellstrom's iNPH scale	Improvement in mRS of at least one point or improvement of at least 5 points on Hellstrom's iNPH scale	64% and 84% of patients were improved at 1 year by mRS and Hellstrom's iNPH scale
Kahlon *et al*.[28]	46 iNPH/8s NPH	Ventriculomegaly, at least one of three symptoms and either positive lumbar infusion test of CSF tap test	Gait assessment, reaction time, memory, and Barthel index	Percentage change in scores of pre- and postoperative tests	>80% of patients exhibited objective improvement and 96% conveyed subjective improvement at 6 months
Anderson *et al*.[34]	20 patients iNPH	Classic triad	CT, CSF tap test, ventricular volumetry	Unified Parkinson's Disease Rating Scale	100% improvement
Kiefer, *et al*.[35]	91 patients iNPH	Clinical presentation and CSF dynamic parameters	KI RI	Nonresponders (RI 0–1) Moderate response (RI 2–4) Good response (RI 5–7) Very good response (RI>7)	88% of patients were shunt responders
Mori[36]	120 patients with iNPH	Ventriculomegaly and presence of full clinical triad	iNPH grading scale	Improvement by at least on point on iNPH scale	80% of patients showed improvement at 3 months
Black[37]	62 patients with iNPH	Ventriculomegaly, dementia and/or gait disturbances, and normal opening pressure	Black scale Stein-Langfitt scale	Excellent, good, fair, or transient outcome on Black Scale or: one point increase in Stein–Langfitt score	46.8% improved by Black scale definition, 33% improved by Stein–Langfitt criteria
Stein and Langfitt[38]	33 patients with iNPH, 10 – secondary NPH	Dementia, ventriculomegaly, normal opening pressure	Stein–Langfitt scale	One point increase in the scale	24% patients showed improvement

NPH – Normal pressure hydrocephalus; iNPH – Idiopathic NPH; mRS – Modified Rankin Scale; KI – Kiefer Index; RI – Recovery Index; CSF – Cerebrospinal fluid; CT – Computed tomography

available software – Argus. Peak flow velocity in healthy participants was reported to vary from 2.03 to 10.14 cm/s with the average of 5.84 cm/s, which is close to the results observed by our study, whereas in NPH patients, it varied from 8.9 to 25.84 cm/s. Sharma *et al*. also observed that there was a significant reduction in the PV after drainage of CSF and the change was >2 cm/s in patients who improved the following tap and subsequently the following shunt.[29] We also observed a decrease of ≥2 cm/s in 16 out of 20 patients after CSF tap, who also showed subsequent clinical improvement. Thus, the fall in PV measurements after tap was correct in 80% cases for predicting clinical response to shunting.

Some studies have shown the usefulness of CPC MRI in the patient selection for shunt surgery for NPH, whereas others found that measurements of CSF flow through the aqueduct did not reliably predict which patients would improve after shunting. The small number of patients limits most studies. On the whole, the velocity ranges found in

the literature are quite broad and overlapping, varying from center to center and from machine to machine [Table 3]. Therefore, we feel that there is no perfect single radiological technique for the management of NPH as there is some overlap between the radiological parameters of NPH. The other limitation is the lack of clinical or radiological gold standard to confirm the clinical diagnosis of NPH. The MRI parameters for CPC imaging and flow analysis software are diverse for different scanners.

Consequently, it would be difficult to apply or reproduce these measurements on other systems and the values obtained cannot be taken as standard by all. Many of the previous studies have not assessed the change in flow dynamics after CSF drainage through lumber tap, so they are less likely to predict a successful surgical outcome in every case. Thus, phase-contrast imaging before and after CSF drainage adds to the clinical evaluation in the patient selection for shunt surgery though the actual gold standard test for the diagnosis of communicating hydrocephalus is the response to shunt surgery.

Our study was limited by the small number of patients evaluated by imaging pre- and postintervention. Although comparison of clinical status, as well as radiological parameters, was done pre- and posttap, the actual follow-up was only available in 10 out of 20 patients who underwent shunting. However, our study has helped to establish values of SV and PV in our MRI machine above which hyperdynamic of aqueductal flow can be considered. Change in PV measurement after tap has also proved to be helpful in predicting response to surgery.

CONCLUSIONS

CPC MRI is a valuable adjunctive tool to support the diagnosis of communicating hydrocephalus. Highly elevated Stroke volumes (>50 μL) and high Peak velocities (>10 cm/s) along with a fall of ≥2 cm/s after intervention helps in predicting a favorable response to shunt surgery.

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Conflicts of interest
There are no conflicts of interest.

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