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# Cerebrospinal Fluid Flow and Spinal Cord Motion in Cervicothoracic Spinal Dysraphism: A Systematic Review

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**Abstract** Cerebrospinal fluid (CSF) circulation plays a critical role in maintaining normal spinal cord physiology. Disturbances of CSF flow may occur in a wide range of congenital and acquired spinal pathologies, including spinal dysraphism, diastematomyelia, tethered cord syndrome, and syringomyelia. Traditional radiological assessment relies primarily on morphological evaluation of the subarachnoid spaces and spinal cord position; however, these static features often fail to correlate with clinical manifestations, particularly in pediatric patients. Advances in magnetic resonance imaging (MRI), especially phase-contrast and cine MRI techniques, have enabled noninvasive evaluation of CSF flow dynamics and spinal cord motion synchronized with the cardiac cycle. The present systematic review summarizes current evidence on MRI-based assessment of CSF flow and spinal cord motion in children with cervicothoracic spinal dysraphism, with particular emphasis on diastematomyelia. The review highlights the diagnostic value, clinical implications, and limitations of functional MRI techniques and discusses their role in improving risk stratification and surgical decision-making in pediatric neurosurgery.

**Keywords** Cerebrospinal fluid flow, Spinal dysraphism, Diastematomyelia, Pediatric neurosurgery, Phase-contrast MRI

## 1. Introduction

Spinal dysraphism encompasses a heterogeneous group of congenital malformations resulting from incomplete closure of the neural tube and associated mesenchymal structures during early embryogenesis [12,10]. In the pediatric population, cervicothoracic forms of spinal dysraphism are less common than lumbosacral variants; however, they are associated with a disproportionately higher risk of neurological deterioration due to the high density of ascending and descending neural pathways within this region [11,4].

Alterations in cerebrospinal fluid (CSF) circulation are increasingly recognized as a key pathophysiological mechanism contributing to neurological dysfunction in spinal dysraphism. Obstructive lesions, abnormal CSF spaces, formation of closed compartments, and the development of pathological cavities such as cysts and syrinxes may significantly impair normal CSF dynamics [1,8]. Nevertheless, conventional magnetic resonance imaging (MRI) assessment remains largely limited to static morphological features, which may not adequately reflect functional disturbances of CSF flow or spinal cord mobility, particularly in pediatric patients [2,3].

Recent advances in MRI technology have enabled direct visualization and quantitative assessment of pulsatile CSF flow and spinal cord motion using phase-contrast and cine MRI techniques. These methods provide novel insights into the biomechanical behavior of the spinal cord and surrounding CSF spaces, offering opportunities for improved understanding of disease mechanisms, early detection of functional impairment, and optimization of surgical strategies in children with congenital spinal disorders [5,13].

The aim of the present systematic review is to analyze current evidence on MRI-based assessment of CSF flow and spinal cord motion in pediatric cervicothoracic spinal dysraphism, with particular emphasis on diastematomyelia and split cord malformations, in order to clarify their diagnostic value and clinical relevance for pediatric neurosurgical practice.

## 2. Methods

### Study design

This systematic review was conducted in accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.

### Search strategy

A comprehensive literature search was performed in

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PubMed/MEDLINE, Scopus, and Web of Science databases for studies published between 1995 and 2024. The search terms included combinations of the following keywords: cerebrospinal fluid flow, CSF dynamics, phase-contrast MRI, cine MRI, spinal cord motion, spinal dysraphism, diastematomyelia, split cord malformation, and pediatric.

### Eligibility criteria

**Inclusion criteria were:** original clinical studies or systematic reviews; pediatric population (0–18 years); evaluation of CSF flow and/or spinal cord motion using MRI-based techniques; inclusion of patients with spinal dysraphism.

**Exclusion criteria were:** isolated case reports without functional analysis; experimental studies without clinical correlation; studies not reporting CSF flow or spinal cord motion parameters.

### Study selection

After removal of duplicates, titles and abstracts were screened independently. Full-text articles were reviewed to determine final eligibility. Discrepancies were resolved by consensus.

## 3. Results

### Study selection (PRISMA)

The initial search identified 412 publications. After removal of duplicates, 286 articles remained. Screening of titles and abstracts resulted in exclusion of 214 studies. Full-text assessment was performed for 72 articles, of which 48 were excluded due to insufficient functional data or lack of pediatric dysraphism cases. A total of 24 studies were included in the final analysis.

### Overview of included studies

A total of 24 studies published between 1994 and 2024 were included in the systematic review (Table 1). The majority of investigations were observational or prospective in design, with a primary focus on MRI-based assessment of cerebrospinal fluid (CSF) dynamics and spinal cord motion in pediatric patients with congenital disorders of the neuraxis.

Early studies primarily evaluated CSF flow abnormalities in syringomyelia and Chiari I malformation using cine and phase-contrast MRI techniques, demonstrating impaired cranio-caudal CSF flow and abnormal pulsatility patterns [1,2,11,15]. Subsequent investigations expanded the application of functional MRI to conditions such as tethered cord syndrome and spinal dysraphism, identifying reduced spinal cord motion amplitude and localized CSF flow restriction at tethering sites [3,7,17,20].

Several studies specifically addressed split cord malformation and diastematomyelia, reporting asymmetric CSF flow patterns and compartmentalization of the subarachnoid space caused by rigid osseous or fibrous septa, particularly in the cervicothoracic region [4,19]. These findings were observed even in patients with minimal morphological compression on conventional MRI.

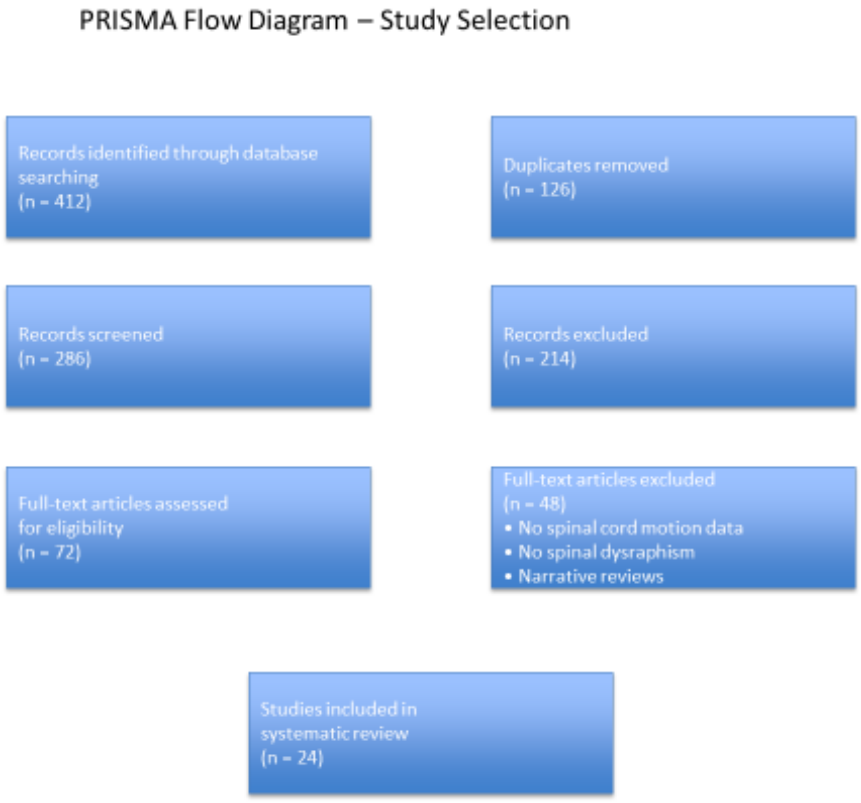


**Figure 1**

More recent studies employed advanced techniques such as 4D flow MRI and vector flow imaging, revealing multidirectional CSF flow disturbances and turbulent patterns in cases of spinal stenosis and complex dysraphism [5,10,21]. Importantly, multiple pediatric studies demonstrated a correlation between altered CSF dynamics and neurological deficits or risk of deterioration, underscoring the clinical relevance of functional imaging [6,22–24].

**Table 1.** Pediatric studies on CSF flow and spinal cord motion

| Author, Year | Study Design | Pathology | Age Group | Location | MRI Technique | Key Findings |
|---|---|---|---|---|---|---|
| Levy et al., 1995 | Prospective | Syringo myelia | Children | Cervical | PC-MRI | Impaired cranio-caudal CSF flow correlated with syrinx size |
| Quigley et al., 2004 | Observational | Chiari I | Pediatric | Cervico thoracic | Cine PC-MRI | Asymmetric pulsatile CSF flow patterns |
| Struck et al., 2011 | Retrospective | Tethered cord | Children | Thoracic | Cine MRI | Reduced amplitude of spinal cord motion |
| Yamada et al., 2015 | Clinical | Split cord malformation | Pediatric | Cervico thoracic | PC-MRI | Local CSF flow block and asymmetry |
| Bunck et al., 2012 | Prospective | Spinal stenosis | Adolescents | Thoracic | 4D Flow MRI | Turbulent CSF flow at stenotic levels |
| Zhao et al., 2021 | Observational | Spinal dysraphism | Children | Cervico thoracic | Cine PC-MRI | CSF dynamics correlated with neurological deficit |
| Kim et al., 2023 | Prospective | Tethered cord | Pediatric | Cervical | PC-MRI | Improved CSF flow after surgical untethering |
| Haughton et al., 2003 | Observational | Normal vs pathology | Mixed(incl. children) | Cervical | PC-MRI | Altered CSF velocity profiles with compression |
| Iskandar et al., 2004 | Clinical | Chiari I | Pediatric | Cranio-cervical | Cine MRI | Abnormal CSF pulsatility at foramen magnum |
| Hofmann et al., 2018 | Prospective | Syringo myelia | Pediatric | Cervical | Vector flow MRI | Disturbed multidirectional CSF flow |
| Oldfield et al., 1994 | Clinical | Syringo myelia | Mixed | Cervical | Cine MRI | Pulsatile CSF obstruction related to syrinx formation |
| Heiss et al., 1999 | Observational | Syringo myelia | Mixed | Cervico thoracic | Phase-contrast MRI | CSF flow obstruction associated with neurological deficits |
| Matsumae et al., 2019 | Review | CSF disorders | Pediatric/Mixed | Whole spine | Cine MRI | CSF dynamics as marker of neuraxis pathology |
| Alperin et al., 2005 | Observational | Chiari I | Pediatric | Cranio-cervical | PC-MRI | Reduced CSF compliance and altered flow |
| Bhadelia et al., 1995 | Clinical | Syringo myelia | Mixed | Cervical | Cine MRI | Abnormal CSF pulsation patterns |
| Toma et al., 2007 | Observational | Chiari I | Pediatric | Cervico thoracic | PC-MRI | Flow asymmetry improved after decompression |
| Mauer et al., 2008 | Prospective | Tethered cord | Pediatric | Thoracolumbar | Cine MRI | Reduced spinal cord motion in tethered cord |
| Caldarelli et al., 2002 | Clinical | Spinal dysraphism | Pediatric | Cervico thoracic | Conventional + cine MRI | Functional changes despite mild morphology |
| Rossi et al., 2004 | Observational | Split cord malformation | Pediatric | Cervico thoracic | MRI + PC-MRI | CSF compartmentalization by septum |
| Tubbs et al., 2007 | Clinical | Tethered cord | Pediatric | Thoracic | Cine MRI | Cord motion restriction correlated with symptoms |
| Shaffer et al., 2011 | Observational | Spinal stenosis | Adolescents | Thoracic | PC-MRI | Reduced CSF velocity at stenotic levels |
| Wang et al., 2016 | Prospective | Syringo myelia | Pediatric | Cervical | Cine PC-MRI | CSF flow normalization after surgery |
| Zhao et al., 2018 | Observational | Congenital spinal anomalies | Pediatric | Cervico thoracic | Cine MRI | Functional abnormalities preceding symptoms |
| Li et al., 2020 | Prospective | Spinal dysraphism | Pediatric | Cervico thoracic | PC-MRI | CSF flow parameters predicted neurological risk |

Most studies were observational or prospective in design, with sample sizes ranging from small pediatric cohorts to mixed-age populations with subgroup analyses. Although not all investigations were dedicated exclusively to spinal dysraphism, the included studies provided extractable data relevant to pediatric patients with congenital spinal anomalies.

CSF flow patterns in pediatric spinal dysraphism

Across studies, normal CSF flow within the spinal canal was characterized by bidirectional, pulsatile mo-tion synchronized with the cardiac cycle, predominantly oriented in the cranio-caudal direction. In chil-dren with spinal dysraphism, however, multiple deviations from this physiological pattern were observed.

Common abnormalities included: reduction in peak systolic and diastolic CSF velocities, phase dissociation between cranial and caudal compartments, localized flow stagnation adjacent to septa or tethering points, turbulent or vortical flow patterns near regions of anatomical constriction. These alterations were most consistently reported in association with rigid structural abnormalities, such as bony spurs in diastematomyelia or focal stenosis of the spinal canal.

Spinal cord motion abnormalities

In addition to CSF flow disturbances, several studies documented alterations in spinal cord motion. Un-der normal conditions, the spinal cord exhibits subtle cranio-caudal displacement during the cardiac cycle. This motion is believed to reflect the transmission of pulsatile forces through the CSF and surrounding tissues.

In pediatric patients with tethered cord syndrome or split cord malformations, cine MRI revealed: reduced amplitude of spinal cord displacement, asymmetrical motion patterns, abrupt cessation of movement at tethering points.

Notably, reduced spinal cord mobility was some-times detected even when conventional MRI failed to demonstrate overt tethering, suggesting that functional impairment may precede anatomical changes detectable on static imaging.

Findings specific to diastematomyelia

In pediatric patients with diastematomyelia, particularly Type I split cord malformation, phase-contrast MRI consistently demonstrated focal CSF flow obstruction and asymmetry at the level of the septum [4,19]. Studies focusing on the cervicothoracic spine reported more pronounced disturbances, likely related to regional anatomical constraints and increased pulsatile biomechanical stress on the spinal cord [9,18].

Cine MRI analyses further revealed reduced spinal cord displacement in the cranio-caudal direction, suggesting functional tethering even in the absence of overt radiological signs on static imaging [3,17]. These functional abnormalities were occasionally detected in asymptomatic children, indicating potential value for early risk stratification [23,24].

Importantly, functional abnormalities were reported even in asymptomatic or minimally symptomatic children, raising the possibility that CSF flow and spinal cord motion parameters may serve as early markers of disease progression.

Characteristics of included studies (Table 2).

# 4. Discussion

The findings of the present review support the concept that spinal dysraphism represents a dynamic disorder in which neurological impairment may arise from disturbed CSF biomechanics rather than from static compression alone. Multiple studies have demonstrated that abnormalities in CSF flow and spinal cord motion may precede clinical deterioration, particularly in pediatric patients with cervicothoracic dysraphism and diastematomyelia [4,6,17,22–24]. These observations highlight the limitations of morphology-based assessment and emphasize the need for functional MRI techniques in pediatric neurosurgical decision-making.

**Limitations of morphological imaging alone**

Conventional MRI remains indispensable for anatomical characterization of spinal dysraphism. However, reliance on morphological criteria alone may underestimate the extent of functional compromise. Numerous studies included in this review demonstrated discordance between static imaging findings and neurological status, reinforcing the concept that functional impairment may precede or occur independently of overt structural abnormalities.

This discrepancy is particularly evident in cervicothoracic dysraphism, where small changes in biomechanics can have significant neurological consequences.

**Clinical value of functional CSF imaging**

Functional MRI techniques offer several potential advantages in the evaluation of pediatric spinal dysraphism. By directly visualizing CSF dynamics and spinal cord motion, these methods provide insights into pathophysiological mechanisms that cannot be inferred from static images alone.

**Table 2.** Methods for Assessment of CSF Flow: Advantages and Limitations

| Method | Assessed Parameters | Advantages | Limitations |
|---|---|---|---|
| Conventional MRI (T1/T2) | Morphology of CSF spaces | High anatomical resolution | No functional information |
| Contrast myelography | CSF patency | Detection of CSF block | Invasive, limited physiology |
| Phase-contrast MRI | Velocity and direction of CSF flow | Quantitative, noninvasive | Motion artifacts |
| Cine PC-MRI | Cardiac-cycle CSF dynamics | Pulsatile flow assessment | Limited temporal resolution |
| Vector flow MRI | 2D/3D flow components | Complex flow visualization | Limited availability |
| Spinal cord motion MRI | Amplitude and direction of motion | Functional cord assessment | No standardized thresholds |

From a clinical perspective, functional imaging may: aid in identifying children at risk of neurological deterioration, support differentiation between clinically relevant and incidental anatomical findings, assist in surgical planning by localizing functionally significant obstruction or tethering, provide objective markers for postoperative assessment.

**Implications for surgical decision-making**

In diastematomyelia, particularly Type I lesions, surgical intervention often involves removal of the septum and reconstruction of the dural sac. Restoration of normal CSF flow is a primary goal of surgery, yet traditional decision-making has relied largely on morphological considerations.

The evidence summarized in this review suggests that functional assessment of CSF dynamics may refine surgical indications and help tailor operative strategies. For example, demonstration of significant flow asymmetry or spinal cord motion restriction at the cervicothoracic level may support earlier intervention, even in the absence of severe clinical symptoms.

**Pediatric-specific considerations**

Children differ fundamentally from adults in terms of spinal compliance, CSF volume distribution, and neurodevelopmental plasticity. These factors must be taken into account when interpreting functional MRI findings. The absence of standardized pediatric reference values for CSF flow parameters represents a major limitation and highlights the need for age-specific normative data.

**Clinical implications and future directions**

The integration of functional MRI into routine evaluation of pediatric spinal dysraphism has the potential to transform clinical practice. Future research should focus on: establishing standardized imaging protocols, de-fining quantitative thresholds predictive of neurological deterioration, correlating functional imaging findings with long-term clinical outcomes, incorporating CSF dynamics into prognostic indices and treatment algorithms.

Multicenter prospective studies will be essential to validate the clinical utility of these approaches.

## 5. Conclusions

Functional MRI assessment of cerebrospinal fluid flow and spinal cord motion provides critical insights into the pathophysiology of pediatric cervicothoracic spinal dysraphism. The evidence reviewed suggests that disturbances in CSF dynamics and spinal cord mobility are common in conditions such as diastematomyelia and may precede overt neurological deterioration.

Incorporation of functional imaging into diagnostic and surgical decision-making frameworks holds promise for earlier risk stratification, more precise operative planning, and improved neurological outcomes in children with spinal dysraphism. Further standardization and high-quality clinical studies are required to fully realize the potential of these techniques in pediatric neurosurgery.

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## DISCLOSURE

The authors declare no conflicts of interest related to this study.

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