ABSTRACT
Spinal dysraphism includes the congenital malformations of the spine and spinal cord. Spinal cord development takes place through successive stages of gastrulation, primary neurulation, and secondary neurulation. Defect in any of these three phases can lead to spinal dysraphism. The embryological classification of spinal dysraphism consists of anomalies of gastrulation, anomalies of primary neurulation, combined anomalies of gastrulation, primary neurulation and anomalies of secondary neurulation. Clinico-radiologic classification of spinal dysraphism consists of open and closed types. Magnetic Resonance Imaging (MRI) is considered as the gold standard for identifying these disorders. By using the clinical, neuroradiological, and development data systematically an accurate diagnosis can be reached. In this article, authors revise the normal development of the spinal cord and spine and discuss the embryologic classification by illustrating the diverse MRI findings of various spinal dysraphism.

PREDISPOSING FACTORS
• Nutritional factors: Cytochalasin ingestion, a metabolite of the fungus Phytophthora infestans (found in blighted potatoes),

INTRODUCTION
Spinal dysraphism includes the congenital abnormalities of the spine and spinal cord. Abnormal midline closure of bony, mesenchymal, and nervous tissue leads to the formation of these heterogeneous groups of anomalies [1]. The usual age at diagnosis is at birth or early infancy but few are detected at a later age due to the absence of clinical manifestations. The inherent advanced soft-tissue resolution and multiparametric imaging capability of MRI allow easier, rapid, and more precise diagnosis of these disorders, thus enabling early detection and case-tailored management [2]. By analysis of the clinical, neuroradiological, and development data systematically, an accurate diagnosis can be reached.

EMBRYOLOGY (A QUICK RECAP OF SPINAL CORD DEVELOPMENT)
Spinal cord development occurs in three basic embryologic steps [3,4]. They include gastrulation (2-3 weeks), primary neurulation (3-4 weeks) and secondary neurulation (5-6 weeks). In gastrulation, the embryonic disc from a bilaminar disc is transformed into a trilaminar disc (composed of ectoderm, mesoderm and endoderm) Table/Fig-1a,b [5]. In primary neurulation, notochord and overlying ectoderm interact to form neural plate. The neural plate then arches, folds and closes in a zipper like manner birectionally to form neural tube. The neural plate then forms the neural tube [Table/Fig-2a,b] [5]. In secondary neurulation, secondary neural tube is formed from caudal cell mass, which is solid initially and subsequently undergoes cavitation. It forms tip of conus medullaris and filum terminale by retrogressive differentiation Table/Fig-3a-c] [5]. Abnormalities in any of the above stages can lead to spine and spinal cord malformations.

Keywords: Congenital malformations, Gastrulation, Magnetic resonance imaging, Primary neurulation, Secondary neurulation

Table/Fig-1: Gastrulation. a) Dorsal view and b) Transverse view of the bilaminar embryonic disk. First ingressing cells at Hensen’s node move anterior to form head processes and notochord. Cells ingressing through primitive streak migrate ventrally and laterally to form mesodermal and endodermal precursors [5].

Table/Fig-2: Primary neurulation. a) Set of transverse views shows evolution from flat neural plate to fused neural tube. Also notice disjunction of the neural ectoderm from the surface ectoderm at the time of neural tube fusion; b) Dorsal view of the embryo on gestational day 21 shows fusion of the neural folds to form a neural tube has begun at the cervical level and proceeds bidirectionally [5].

Table/Fig-3: Secondary neurulation. a) The tail bud forms as a result of coalescence of the neuroectoderm with the lower notochord; b) A secondary neural tube connects cranially with the neural tube formed by primary neurulation; c) Eventually, the tip of the conus medullaris and the filum terminale result from this process. The terminal ventricle is the sole remnant of the secondary neural canal.
deficiency of folic acid or zinc, high nitrates (eg, nitrate-cured meats, bore and ground water), and deficiency or excess vitamin A [6,7].

- Multifactorial with genetic (Chromosomal and single-gene abnormalities) and environmental factors playing a role [8].
- An altered carbohydrate metabolism has been reported in mothers of children with spinal dysraphism, especially those with sacral agenesis [9].
- In consanguineous marriage there is a 3-fold increased incidence and more in monozygotic twins. There is 50% likelihood of 2nd child being affected if the first child is affected and 100% likelihood if two children are affected [10].

**INCIDENCE**

Spinal dysraphism affect approximately 1 per 1000 live-born infants. Open spinal dysraphism occur more frequently than closed and among the open type, myelomeningocele is the most common [8].

**CLASSIFICATION**

Based on studies by Tortori and Caffey, spinal dysraphism is classified according to the embryological events [Table/Fig-4] [4,11,12].

1. **Anomalies of Gastrulation**
   
   A. Disorders of notochord formation
   - Caudal regression syndrome
   - Segmental spinal dysgenesis

   B. Disorders of notochord integration
   - Neurenteric cysts
   - Dorsal enteric fistula
   - Split cord malformations (diaspistomatomyelia)

2. **Anomalies of Primary Neurulation**
   
   A. Premature dysjunction
   - Lipomyelomeningocele
   - Lipomyelocele
   - Intradural lipoma

   B. Nondysjunction
   - Dorsal dermal sinus
   - Myelomeningocele
   - Myelocystocele

3. **Combined Anomalies of Gastrulation and Primary Neurulation**
   
   - Hemimyelocystocele
   - Hemimyelomeningocele

4. **Anomalies of Secondary Neurulation and Retrogressive Differentiation**
   
   - Abnormally long spinal cord
   - Persistent terminal ventricle
   - Tight filum terminale
   - Intraspinal-anterior sacral meningocoele
   - Terminal myelocystocele

[Table/Fig-4]: Embryological classification of spinal dysraphism [4,11,12].

Clinico-radiologically, based on the presence of overlying skin, spinal dysraphism is classified as open and closed types [13-15]. Overlying skin is absent and the neural elements are exposed to the external environment in open type while, in closed type, the skin is intact. Based on the presence of subcutaneous mass closed spinal dysraphism can be further divided [Table/Fig-5,6].

**Open spinal dysraphisms**

- Myelomeningocele
- Myelocystocele
- Hemimyelomeningocele
- Hemimyelocystocele

**Closed spinal dysraphism**

With subcutaneous mass
- Lipomyelomeningocele
- Lipomyelocele
- Terminal myelocystocele
- Meningocele
- Myelocystocele

Without cutaneous mass
- Simple dysraphic states
- Intradural lipoma
- Filum lipoma
- Tight filum terminale
- Persistent terminal ventricle
- Dorsal dermal sinus

**Complex dysraphic states**

- Dorsal enteric fistula
- Neuroenteric cyst
- Diastomatomyelia
- Caudal agenesis
- Segmental spinal dysgenesis

[Table/Fig-5]: Clinico-radiological Classification of spinal dysraphisms.

[Table/Fig-6]: Clinical images of open (a,b) and closed (c) spinal dysraphism.

1. **GASTRULATION RELATED ABNORMALITIES**

The spinal cord and various structures derived from notochord are affected by abnormal gastrulation [16]. Most of these abnormalities are covered by skin and with no subcutaneous mass. Disorders of midline notochordal integration and disorders of notochordal formation come under this category.

**A. Disorders of Notochordal Formation**

Caudal agenesis and segmental spinal dysgenesis are disorders of notochordal formation and occur as a result of abnormal apoptosis [17].

Caudal agenesis (CA): It may lead to total or partial agenesis of the spinal column. Commonly associated other anomalies are the genital anomalies, pulmonary hypoplasia, anal imperforation, renal aplasia or dysplasia, and limb abnormalities. CA is divided into two types:

Type I CA: Caudal cell mass and notochord formation are affected. There are high position and abnormal termination of conus medullaris(most commonly at the level of D12 vertebra). Vertebral aplasia of varying degree is seen.

Type II CA: Only caudal cell mass is affected while notochord formation is unaffected. Hence, only secondary neurulation is defective with normal primary neurulation. Consequently, only the caudal part of conus medullaris is absent. Vertebral dysgenesis is less severe. Patients present with tethered cord syndrome as the conus in these cases is stretched and tethered [18,19].

**Segmental spinal dysgenesis:** It is a rare notochordal abnormality occurring due involvement of the intermediate segment of notochord during gastrulation [Table/Fig-7,8] [17,20]. Characterised by segmental agenesis or dysgenesis of the lumbar or thoracolumbar spine and spinal cord or nerve roots. The child presents with congenital paraparesis or paraplegia with or without associated congenital lower limb deformities.
B. Disorders of Midline Notochordal Integration

Midline notochordal integration is a process where paired notochord anlagen fuse to form a single midline notochord process [3]. Longitudinal splitting of the spinal cord occurs due to abnormality in this step. Neurenteric cyst and diastematomyelia are the common entities of this category.

Neurenteric cyst: Dorsalenteric fistula is a persistent communication between ectoderm (External skin) and endoderm (Intestine). Among disorders of midline notochord integration it is the rare and most severe form. It is a persistent communication between ectoderm (skin surface) and endoderm (bowel). Neuroenteric cysts are trapped remnants of the middle portion of this communication. It is a localised form of dorsal enteric fistula. They are usually intradural and extramedullary in location. Most commonly located in the cervicothoracic region, may be seen in other locations also [21]. They are present anterior to the cervical spinal cord with associated adjacent vertebral anomalies. On T1 and T2 weighted MR images, they appear isointense to hyperintense to CSF (due to high protein content) with absent contrast enhancement [22,23].

Diastematomyelia: Defective midline notochord integration leads to a single midline notochord being replaced by a paired notochordal process which are separated by intervening primitive streak cells. Each “heminotochord” induces a separate “hemi”-neural plate. Each “Hemi”-neural plate, in turn, forms a “Hemi”-neural tube, thus resulting in the formation of two hemicords. The intervening primitive streak tissue, which is a totipotent tissue decides the type of diastematomyelia. In type I diastematomyelia, it differentiates into cartilage and bone, so the two hemicords lie in individual dural sacs separated by osteocartilaginous spur [Table/Fig-9,10]. Whereas in type II diastematomyelia, it is resorbed, so the single dural sac encases the two hemicords [Table/Fig-11,12] [24]. Associated vertebral anomalies and hydromyelia may be present. One of the reliable clinical indicators for underlying diastematomyelia is the presence of a high lying hairy tuft over a child’s back [25].
2. PRIMARY NEURULATION RELATED ABNORMALITIES

A. Premature Dysjunction
Premature dysjunction of the neural tube from the overlying ectoderm leads to the interposition of perineural mesenchyme between the neural tube and ectoderm, which differentiates into fat and prevents complete neural tube closure. The lipomatous malformation spectrum of lipomyelocele, lipomyelomeningocele, and spinal lipomas come under this category [11].

Lipomyelocele and lipomyelomeningocele: Lipomyelocele and lipomyelomeningocele fall under the category of lipomas with a dural defect. As a consequence of premature focal disjunction of the neural tube from the surface ectoderm, the mesenchymal tissue intrudes into the neural tube. The adipomatous tissue is formed from this mesenchymal tissue due to factors not known [26]. Patients present clinically with a subcutaneous swelling above the intergluteal crease. The major distinguishing feature between the lipomyelocele and lipomyelomeningocele is the location of the neural placode-lipoma interface. It is situated within the spinal canal in a lipomyelocele [Table/Fig-13], while in lipomyelomeningocele it is situated outside the spinal canal as a consequence of the expansion of the subarachnoid space [Table/Fig-14,15] [14]. T1 and T2 weighted images show the continuity between the dorsal surface of placode with subcutaneous fat, with signal suppression on the fat-saturated images.

Intradural lipoma: It is a lipoma situated on the midline dorsal aspect of the spinal cord within an unbreached dural sac. The unbreached dural sac distinguishes it from lipomyelocele and lipomyelomeningocele. Lumbosacral region is the most common site of location and tethered cord syndrome is the most common clinical presentation. On MRI, they have a signal intensity similar to subcutaneous fat on all the sequences [13].

Filar lipoma: It is the fibrolipomatous thickening of the filum terminale. It follows the signal intensity of fat on all the MR sequences [12]. It is considered a normal variant unless associated with tethered cord syndrome [27,28].

B. Nondysjunction
Failure of separation of the neural tube from overlying ectoderm results in an ectoderm-neuroectoderm communication that blocks the mesenchymal migration. As a consequence, the open neural tube defect spectrum of the dorsal dermal sinus, myelomeningocele, and meningocele is formed.

Dorsal dermal sinus: It is an epithelium lined fistulous tract connecting neural tissue or meninges with the cutaneous surface. Lumbosacral region is the most common site of location. They are commonly associated with an intraspinal dermoid cyst. Patients present clinically with cutaneous markers like hairy nevus, midline dimple, or capillary hemangioma [29]. Meningitis is the most severe complication due to the presence of external communication.

Myelomeningocele and myelocele: Myelomeningocele and myelocele are the open neural tube defects in which the neural placode is exposed through the midline skin defect on the back. Myelomeningocele constitutes 98% of all the open spinal dysraphism. In myelomeningocele the neural placode extrudes above the skin surface, presenting clinically as a midline reddish mass [3]. Myelocele is a rare anomaly. The major distinguishing feature between myelomeningocele and myelocele is the position of the neural placode. In myelomeningocele, it is flush with the skin surface associated with an intraspinal dermoid cyst. Patients present clinically with cutaneous markers like hairy nevus, midline dimple, or capillary hemangioma [29]. Meningitis is the most severe complication due to the presence of external communication.
3. COMBINED ANOMALIES OF GASTRULATION
AND PRIMARY NEURULATION

Hemimyelomeningocele and hemimyelocele

Hemimyelomeningoceles and hemimyeloceles are remarkably rare anomalies. They occur when a myelomeningocele or myelocele are associated with diastematomyelia and one hemicord fails to neurulate [Table/Fig-21,22].

4. ANOMALIES OF SECONDARY NEURULATION/ANOMALIES OF THE CAUDAL CELL MASS

Low lying cord: Spinal cord position below L2-L3 level after the first month in a term infant is “abnormally low lying”. Axial T1 weighted images are used for knowing the actual position of the conus [31].

Persistent terminal ventricle/fifth ventricle: It is the small ependymal lined cavity within the conus medullaris. It is the remnant of the lumen of the neural tube formed by the secondary neurulation. Absent contrast enhancement and the location just above filum terminale are the characteristic imaging findings and distinguish it from other cystic lesions of conus medullaris [Table/Fig-23] [32].

Tethered Cord Syndrome (TCS): Clinical manifestations included in TCS are gait spasticity, low back pain, leg pain, sensory abnormalities of the lower extremity, and/or bladder abnormalities. A low lying cord with thick filum terminale (>1.5 mm) is the key imaging finding [Table/Fig-24].

Intrasacral-anterior sacral meningocele: It is the arachnoid lined sac located in the enlarged sacral spinal canal. It is connected to the
CONCLUSION(S)
Congenital malformations of the spine and spinal cord have a complex and variable imaging appearance. A meticulous approach with consideration of clinical, developmental data along with the proper interpretation of imaging findings helps in precise diagnosis.

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AUTHOR DECLARATION:

• Financial or Other Competing Interests: None
• Was Ethics Committee Approval obtained for this study? Yes
• Was informed consent obtained from the subjects involved in the study? Yes
• For any images presented appropriate consent has been obtained from the subjects. Yes

PLAGIARISM CHECKING METHODS:

1. Plagiarism X-checker: Sep 29, 2020
3. iThenticate Software: Sep 10, 2021 (21%)

ETYMOLOGY: Author Origin