Spinal dysraphism illustrated; Embroyology revisited

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Abstract

Spinal cord development occurs through three consecutive periods of gastrulation, primary neurulation and secondary neurulation. Aberration in these stages causes abnormalities of the spine and spinal cord, collectively referred as spinal dysraphism. They can be broadly classified as anomalies of gastrulation (disorders of notochord formation and of integration); anomalies of primary neurulation (premature dysjunction and nondysjunction); combined anomalies of gastrulation and primary neurulation and anomalies of secondary neurulation. Correlation with clinical and embryological data and common imaging findings provides an organized approach in their diagnosis.

Key words: Embryology; illustrated; magnetic resonance imaging; spinal dysraphism

Introduction

Spinal dysraphism refers to the congenital abnormalities of the spine and spinal cord. Clinico-radiological classification of spinal dysraphism has been well established and widely followed. The objective of this article is to illustrate the common magnetic resonance imaging (MRI) findings of various spinal dysraphisms based on embryological events.¹⁻³

Spinal Cord Development

Spinal cord development can be summarized in three basic embryologic stages – gastrulation (2–3 weeks), primary neurulation (3-4 weeks) and secondary neurulation (5–6 weeks).⁴⁻⁵ The rostral spinal cord (to about the level of S2) is formed by primary neurulation and the caudal spinal cord (distal to S2 level) by secondary neurulation, also referred to as canalization and retrogressive differentiation.⁶

Gastrulation

Gastrulation is the process of conversion of bilaminar disc into a trilaminar disc initiated by primitive streak [Figure 1]. Primitive node, a depression at the cranial end of streak, contains cells that are important for organizing the embryonic axes. Epiblast cells migrate toward and through the streak and node, detach and form two new layers ventral to the remaining epiblast. The first cells through the streak displace the original hypoblast to form endoderm, whereas cells migrating slightly later create a middle layer, the mesoderm. Nonmigrating cells of epiblast constitute the ectoderm. Some cells migrate cranially in the midline to form the prechordal plate and notochord, which initiate

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the process of neurulation by inducing the formation of the
neural plate from overlying ectoderm cells. Thus, neural
plate is derived from ectoderm and forms in the central part
of this upper layer. Remainder of the ectoderm surrounding
the neural plate forms the epidermis.[7]

**Primary Neurulation**

Lateral borders of neural plate elevate into neural folds
which later fuse in the midline to form the neural tube
[Figure 2]. The open regions of the neural tube called
the anterior (cranial) and posterior (caudal) neuropores
close by the zippering process. This neurulation process
is called primary neurulation which is responsible for
establishing brain and spinal cord regions down to
the sacral levels (probably up to S2). On neural tube
closure, overlying non-neural epidermal cells form the
ectodermal layer of the skin. Normal neural tube closure
occurs by day 25 to 27.[7] Meanwhile, the neural tube
separates from the overlying ectoderm, a process called
dysjunction.

The neuroepithelial cells (neuroblasts) around the inner
neural tube form the mantle layer, which produces the
spinal cord gray matter. The outermost layer forms
the marginal layer, which subsequently myelinates
to produce the spinal cord white matter. The central
neuroepithelial cells differentiate into ependymal cells
along the central canal. Neural crest cells along each
side of the neural tube form the dorsal root ganglia,
autonomic ganglia, Schwann cells, leptomeninges and
adrenal medulla.[6]

**Secondary Neurulation**

The cord caudal to S2 level is formed by this process.
Totipotent mesodermal cells called caudal cell mass or tail
bud coalesce to form neural tube which then epithelialize,
reorganize around a lumen and finally become continuous
with the cranial part of the tube initially formed by
primary neurulation.[7,8] Part of the caudal cell mass
undergoes both regression and differentiation (a process
called retrogressive differentiation) to form filum
terminale, terminal ventricle, tip of conus medullaris,
and most of the sacrum, coccyx and coccygeal medullary
vestige [Figure 3].[9] By the third gestational month, spinal
cord extends the entire length of the developing spinal
column. Rapid elongation of the vertebral column and
dura relative to the cord produces the apparent ascent of
the cord during the remainder of the gestation and the
conus is at the adult level soon after birth.

Spinal dysraphism can be classified based on embryological
events, as shown in the Table 1, which is formatted based
on studies by Tortori and Caffey.[4,6]
The second is spinal dysraphism with skin-covered back mass, i.e. closed dysraphism, which can be further subcategorized on the basis of the presence or absence of a subcutaneous mass.\cite{11,12}

### Anomalies of Gastrulation

Failure of notochord formation causes complex dysraphic states such as caudal regression syndrome and segmental spinal dysgenesis. Incorrect notochordal induction leads to the incomplete splitting of the neural plate from the notochord, producing the split notochord syndromes (neurenteric cyst and diastematomyelia).

### Anomalies of Notochord Formation

| Disorders of Notochord Formation | Features |
|---------------------------------|----------|
| **1** Caudal Regression Syndrome | Truncated blunt spinal cord terminating above the expected level |
| **b** Segmental Spinal Dysgenesis | Bulky, thickened and low lying cord below the dysgenetic segment |

### Anomalies of Notochord Integration

| Disorders of Notochord Integration | Features |
|-----------------------------------|----------|
| **a** Neurenteric cysts | Separation failure resulting in an abnormal connection between primitive endoderm and ectoderm resulting in trapping of a small piece of primitive gut within the developing spinal canal which may become isolated forming a cyst or may maintain connections with gut or skin (or both); producing the spectrum of dorsal-enteric spinal anomalies |
| **b** Dorsal enteric fistula | Splitting of the spinal cord into two hemicords |
| **c** Split cord malformations (diastematomyelia) | In type 1, the two hemicords are located within individual dural tubes separated by an osseous or cartilaginous septum and in type 2, there is a single dural tube containing two hemi-cords |

### Anomalies of Primary Neurulation

| Disorders of Primary Neurulation | Features |
|---------------------------------|----------|
| **1** Premature Dysjunction | |
| **a** Lipomyelomeningocele | Closed dysraphism with skin-covered lumbosacral masses |
| **b** Lipomyelocele | The placode–lipoma interface lies outside of the spinal canal due to expansion of the sub-arachnoid space |
| **c** Intradural lipoma | Lipoma located along the dorsal midline that is contained within the dural sac |
| **2** Nondysjunction | |
| **a** Dorsal dermal sinus | Tract connecting skin dimple to the dural sac, conus or central spinal cord canal |
| **b** Myelomeningocele | Neural placode protrudes above the skin surface |
| **c** Myelocele | Neural placode is in flush with the skin surface |

### Combined Anomalies of Gastrulation and Primary Neurulation

| Combined Anomalies of Gastrulation and Primary Neurulation | Features |
|-----------------------------------------------------------|----------|
| **1** Hemimyelocele | Extremely rare |
| **2** Hemimyelomeningocele | Diastematomyelia associated with myelomeningocele or myelocele of one of the hemicords |

### Anomalies of Secondary Neurulation and Retrogressive Differentiation

| Anomalies of Secondary Neurulation and Retrogressive Differentiation | Features |
|---------------------------------------------------------------------|----------|
| **1** Abnormally long spinal cord | Persistent cord termination below L2-L3 after the first month of life in a full-gestation infant |
| **2** Persisting terminal verteicle | Location immediately above filum terminale |
| | Lack of contrast enhancement |
| **3** Tight filum terminale | Low-lying cord with thickened filum. |
| **4** Intrascral – anterior sacral meningocele | Intrascral meningocele – sac lined by arachnoid which lies within an enlarged sacral spinal canal attached to the cephalic termination of the dural sac |
| | Large anterior meningocele outpouching that traverses an enlarged sacral foramen and produces a presacral cystic mass. Inherited predisposition within the Currarino triad |
| **5** Terminal myelocystocele | Herniation of large terminal syrinx (syringocele) into a posterior meningocele through a posterior spinal defect which do not usually communicate with each other |

### Table 1: Embryological classification of spinal dysraphism with salient features

| Table 1: Embryological classification of spinal dysraphism with salient features | Features |
|-------------------------------------------------------------------------------|----------|
| **A** Anomalies of Gastrulation | |
| **1** Disorders of Notochord Formation | |
| | |
| | |
| **b** Segmental Spinal Dysgenesis | |
| | Bulky, thickened and low lying cord below the dysgenetic segment |

Anomalies of notochord formation

- **Caudal regression syndrome**
  - Caudal regression syndrome (CRS) is a complex dysraphic state with aberrations in gastrulation, secondary as well as...
primary neurulation.\cite{13,14} Most cases are sporadic, although a dominantly inherited defect in the HLBX9 gene has been described.\cite{14} Mothers of 15–20% of these infants are diabetic, and the offspring of 1% diabetic mothers are afflicted. Associations with other caudal spinal segment anomalies such as vertebral segmentation and formation anomalies and split cord malformations are noted.

Two types are described. Type 1 features a foreshortened terminal vertebral column, high-lying wedge-shaped conus termination and more severe associated visceral and orthopedic anomalies. Type 2 is less severe and has a low-lying tethered spinal cord with milder associated malformations [Figure 6] In general, the higher the cord termination, the more severe is the sacral anomalies. The most severe CRS presentations are lumbosacral agenesis in which the spine terminates at the lower thoracic level and there is severe sacral dysgenesis with fused lower extremities in a “mermaid” configuration (sirenomyelia).\cite{6}

**Segmental spinal dysgenesis**
Segmental spinal dysgenesis (SSD) is a very rare dysraphic anomaly characterized by segmental thoracolumbar or lumbar vertebral and spinal cord dysgenesis or agenesis. Congenital thoracic or lumbar kyphosis is characteristic, with a palpable dorsal bone spur located at the gibbous apex.\cite{15} The upper spinal cord is normal, however, the cord segment below the dysgenetic segment is bulky, thickened and low-lying. The spinal canal proximal and distal to the dysgenetic level is of normal caliber [Figure 7].

**Anomalies of notochord induction**

**Neurenteric cyst and dorsal-enteric spinal anomalies**
Neurenteric cyst (NEC) is a complex dysraphic state and consists of an intraspinal cyst lined by enteric mucosa. It is most common in thoracic spine followed by cervical spine. They arise from an abnormal connection between primitive endoderm and ectoderm that persists beyond the third embryonic week. Normally, the notochord separates ventral endoderm (foregut) and dorsal ectoderm (skin, spinal cord) during embryogenesis, in an NEC, a separation failure “splits” the notochord and hinders the development of mesoderm, which traps a small piece of primitive gut within the developing spinal canal. This gut remnant may become isolated forming a cyst or it may maintain connections with gut or skin (or both); this produces the spectrum of fistulas.

\[\text{Table 2: Classification of cutaneous markers based on index of suspicion of underlying spinal dysraphism}\]

| High Index of Suspicion | Low Index of Suspicion |
|-------------------------|------------------------|
| Hypertrichosis          | Telangiectasia         |
| Dimples (large, >2.5 cm from the anal verge, atypical) | Capillary malformation (port-wine stain) |
| Acrochordons/pseudotails/true tails | Hyperpigmentation |
| Lipomas                 | Melanocytic nevi       |
| Hemangiomas             | Teratomas              |
| Aplasia cutis or scar   |                        |
| Dermoid cyst or sinus   |                        |

\[\text{Figure 4 (A-C): Cutaneous manifestations – (A) Atrophic patch with dermal sinus (arrow); (B) Pseudotail (arrow) with hyperpigmentation (*). (C) Lipoma (black arrow) with dermal sinus (yellow arrow)}\]

\[\text{Figure 5 (A and B): Hypertrichosis – (A) Silky down type – short and fine vellus hairs. (B) Faun tail type – long coarse terminal hairs}\]

\[\text{Figure 6 (A-C): Partial sacral agenesis – Sagittal T1 (A) and Sagittal T2 (B) weighted images of lumbosacral spine showing partial agenesis of sacrum (arrow in A), low lying cord (arrow in B) and lipomatous thickening of filum terminale (*in A). Coronal T2 (C) image demonstrates L5 butterfly vertebra (arrow)}\]
and sinuses that constitute the spectrum of dorsal-enteric spinal anomalies.

Most severe malformations remain in communication through the primitive vertebral osseous canal of Kovalevsky, however, even mild cases usually show some vertebral segmentation anomalies on close inspection [Figure 8].

**Diastematomyelia**

Diastematomyelia is the separation of the spinal cord into two hemicords. Diastematomyelia can present clinically with scoliosis and tethered-cord syndrome. A hairy tuft on the patient’s back can be a distinctive finding on physical examination [Figure 5]. There are two types of diastematomyelia. In type 1, the two hemicords are located within individual dural tubes separated by an osseous or cartilaginous septum [Figure 9]. In type 2, there is a single dural tube containing two hemi-cords, sometimes with an intervening fibrous septum [Figure 10].

**Abnormalities of Primary Neurulation**

**Premature dysjunction**

If dysjunction occurs prematurely, perineural mesenchyme is interposed between neural tube and ectoderm, which may differentiate into fat and prevent complete neural tube closure. It leads to the lipomatous malformation spectrum of lipomyeloecele, lipomyelomeningocele and spinal lipomas.[6]

**Lipomyeloecele (LMC), b) lipomyelomeningocele (LMMC)**

The main differentiating feature between a LMC and LMMC is the position of the placode–lipoma interface.[11] With an LMC, the placode–lipoma interface lies within the spinal canal. With an LMMC, the placode–lipoma interface lies outside of the spinal canal due to expansion of the sub-arachnoid space [Figures 11 and 12].[12] In both cases, syringomyelia is a commonly associated finding. LMC and LMMC account for 20–56% of occult spinal dysraphism and 20% of skin-covered lumbosacral masses. An important imaging point is that the neural placode is frequently rotated; this foreshortens the roots on one side, predisposing them to stretch injury, and lengthens the roots on the other side, rotating them into the surgeon’s field of view and making them more prone to injury.

**The spinal lipoma**

The spinal lipoma is a simple dysraphic state and is subdivided into intradural and terminal (filar) lipomas. An intradural lipoma refers to a lipoma located along the dorsal midline that is contained within the dural sac [Figure 13]. No open spinal dysraphism is present. They are most commonly lumbosacral in location.[17] Fibrolipomatous thickening of the filum terminale is referred to as a filar lipoma [Figure 14]. Filar lipomas can be considered a normal variant if there is no clinical evidence of tethered-cord syndrome.[18,19]

**Nondysjunction**

Nondysjunction results from failure of dissociation of neural tube from adjacent cutaneous tissue. If dysjunction fails to occur, an ectodermal–neuroectodermal tract forms that prevents mesenchymal migration. Nondysjunction results in open neural tube defect spectrum of dorsal dermal sinus, myelomeningocele, and myeloceles.

**Dorsal dermal sinus**

The simplest of these is the dorsal dermal sinus connecting skin dimple to the dural sac, conus, or central spinal cord canal. The most common dermal sinus tract (DST) location
is in the lumbosacral spine, followed by the occiput. In all dermal sinus cases, there is some degree of focal dysraphism, which may be as subtle as a bifid spinous process. The true congenital dorsal DST usually has an atypical dimple at the ostium that is large (>5 mm), often asymmetric, and remote (>2.5 cm) from the anus [Figure 4A]. These
features help distinguish the dermal sinus from its clinically asymptomatic mimic, simple coccygeal dimple.\textsuperscript{[20,21]} The sinus tract/cord is epithelial-cell lined and may or may not be canalized. When patent, it exposes the patient to an elevated risk of meningitis. It is critical to look for this anomaly in all patients with atypical skin dimples, cutaneous back lesions or lipomas. Moreover, 30–50\% of DSTs may have an associated dermoid or epidermoid cyst [Figures 15-17].

**Myelomeningocele and myelocele**

Myelomeningoceles and myeloceles are caused by defective closure of the primary neural tube and are clinically characterized by exposure of the neural placode through a midline skin defect on the back, and hence, classified under open dysraphic states. Myelomeningoceles account for more than 98\% of open spinal dysraphisms. Myeloceles are rare. It is important to note that preoperative imaging of myelomeningocele is usually not done because of the risk of infection. Nevertheless, the main differentiating imaging feature between a myelomeningocele and myelocele is the position of the neural placode relative to the skin surface. The neural placode protrudes above the skin surface with a myelomeningocele [Figure 18] and is flush with the skin.
surface with a myelocele. Myelomeningoceles are almost always seen in the context of a Chiari 2 malformation.[6,17,22]

**Combined Anomalies of Gastrulation and Primary Neurulation**

**Hemimyelomeningocele and hemimyelocele**

Hemimyelomeningoceles and hemimyeloceles can also occur but are extremely rare. These conditions occur when a myelomeningocele or myelocele is associated with diastematomyelia (cord splitting) and one hemicord fails to neururate [Figure 19].

**Anomalies of Secondary Neurulation/Anomalies of the Caudal Cell Mass**

Failure of expected secondary neurulation leads to conditions such as abnormally long spinal cord, tethered cord syndrome, persisting terminal ventricle, terminal myelocystocele, lipoma of filum terminale and intrasacral – anterior sacral meningocele. It is also implicated in pathogenesis of caudal regression syndrome and segmental spinal dysgenesis.[6]

**Low lying cord**

Persistently cord termination below L2–L3 after the first month of life in a full-gestation infant is abnormally low-lying. Axial T1-weighted images are most accurate in determining the conus level [Figure 20].[23,24]

**Persistent terminal ventricle/fifth ventricle**

By day 48, a transient ventriculus terminalis appears in the future conus. According to Coleman et al., evidence of a fifth ventricle not accompanied by other pathologies is a frequent finding that does not have pathological significance during the first 5 years of life.[25] Key imaging features include location immediately above filum terminale and lack of contrast enhancement, which differentiates this entity from other cystic lesions of the conus medullaris.

![Figure 19: Hemimyelomeningocele - axial T2-weighted image shows type 1 diastomatomyelia with the left hemicord (*) seen ending within a myelomeningocele sac (**). Note also malpositioned, malaligned kidneys (arrows)](image1)

![Figure 20 (A-C): Low lying tethered cord - sagittal T1 (A), sagittal T2 (B), and axial T2-weighted (C) images show low lying tethered cord (arrow in A and B) with thickened filum terminale (arrow in C) at S1 level (arrow in C)](image2)

![Figure 21 (A and B): Intrасal meningocele - sagittal T1-weighted (A) and sagittal T2-weighted (B) images show CSF intensity lesion (*) in sacral canal](image3)
Tethered cord syndrome
Tethered cord syndrome (TCS) patients most likely present during periods of rapid somatic growth. It manifests clinically as gait spasticity, low back and leg pain that is worse in the morning, lower extremity sensory abnormalities, and/or bladder difficulties. On imaging, TCS strictly refers to patients with a low-lying cord and thickened filum (>1.5 mm) [Figure 20].

Intrasacral – anterior sacral meningocele
The term “intrasacral meningocele” is used to denote a sac lined by arachnoid which lies within an enlarged sacral spinal canal and is attached to the caudal termination of the dural sac by a pedicle that usually permits cerebrospinal fluid (CSF) flow from the tip of the subarachnoid space into the meningocele. Consistent with the possible congenital origin, intrasacral meningocele may occur in association with other anomalies such as sacral vertebral anomalies, diastematomyelia or TCS [Figure 21].

Anterior meningoceles are usually presacral in location. It has a large anterior meningocele outpouching that traverses an enlarged sacral foramen and produces a presacral cystic mass. Most ASMs are sporadic but a minority show an inherited predisposition within the Currarino triad or in syndromes that feature dural dysplasia, such as neurofibromatosis type 1 (NF1) and Marfan syndrome.

Terminal myelocystocele
Herniation of a large terminal syrinx (syringocele) into a posterior meningocele through a posterior spinal defect is referred to as a terminal myelocystocele. The terminal syrinx component communicates with the central canal, and the meningocele component communicates with the subarachnoid space. The terminal syrinxes and meningocele components do not usually communicate with each other [Figure 22].

Conclusion
Spinal dysraphism includes numerous entities that vary in complexity and imaging appearance. Clinical, embryological and imaging correlation provides an organized approach in their diagnosis.

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