Histopathologic Findings Associated with Miller–Dieker Syndrome: An Autopsy Report

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Abstract: Miller–Dieker syndrome (MDS) is a rare genetic disorder characterized by congenital lissencephaly (absent or diminished cerebral gyri), facial dysmorphism, neurodevelopmental retardation, intrauterine fetal demise, and death in early infancy or childhood. We present a case of a 4-year-old girl with MDS (17p13.3p13.2 deletion) who was admitted to the hospital due to fever and increased secretions from her nose, mouth, and tracheostomy tube (as she had been on a ventilator and G-tube dependent since birth). During the course of hospitalization, she developed multiorgan failure, third spacing, and significant lactic acidosis. The patient had a cardiorespiratory arrest and expired after 4 months and 8 days of hospitalization. We provide a synopsis of the main autopsy findings, with a focus on the neuropathologic anomalies.

Keywords: Miller–Dieker syndrome; lissencephaly; sepsis; facial dysmorphism; neuronal heterotopia

1. Introduction

Miller–Dieker syndrome (MDS) (i.e., type 1 lissencephaly), is a rare genetic disorder characterized by congenital lissencephaly (absent or diminished cerebral gyri), facial dysmorphisms, neurodevelopmental retardation, intrauterine fetal demise, and death in early infancy or childhood [1–5]. A prenatal ultrasound can detect abnormal brain development or other signs of MDS during pregnancy, where a genetic amniocentesis can be performed to test amniotic fluid for genetic changes that may indicate MDS. Alternatively, chorionic villus sampling (CVS) can be carried out to test cells from the placenta. If not detected during pregnancy, chromosomal microarray (CMA) testing can be performed after birth, demonstrating the genetic abnormalities associated with MDS.

There are three types of lissencephaly. In type 1 or classical lissencephaly, a defect in neuronal migration leads to abnormal cortical architecture with four layers instead of the normal six layers [6]. A spectrum of clinical features exists within this category of lissencephaly. Four grades of type 1 lissencephaly have been described, and each type results in a different appearance of the cerebral cortex due to varying degrees of abnormal neurodevelopment [7]. The first grade is associated with a “smooth brain” or complete agyria [2]. The isolated lissencephaly sequence (ILS) encompasses grades 2–4. Grades 2 and 3 are characterized by mixed agyria-pachygyria (fewer and abnormally wide gyri), while pachygyria is the predominant phenotype of grade 4 ILS [2]. Due to the total lack of gyri, MDS is the most severe disease in the spectrum of type 1 lissencephaly and is associated with additional findings including extracranial malformations, hypotonia, spasticity, and worse survival [7,8]. In MDS, there is a mutation of the LIS-1 gene that codes for the protein platelet-activating factor acetylhydrolase (PAFAH), which is located in Cajal Retzius cells and neuroepithelium.
We present a case of a 4-year-old girl with a history of MDS (17p13.3p13.2 deletion). She was admitted due to increased secretions from her nose, mouth, and tracheostomy tube (as she had been on a ventilator and G-tube dependent since birth). She was noted to have fever, mildly distended abdomen, and swollen feet. Initial evaluation revealed bacterial tracheitis growing *Enterobacter* and *Pseudomonas aeruginosa*. The patient was put on sepsis protocol, and she was started on multiple antibiotics. During the course of hospitalization, she developed multiorgan failure, third spacing, and significant lactic acidosis. An electroencephalogram (EEG) was performed showing an abnormal background with a pattern of burst suppression and multifocal epileptiform discharges, suggestive of severe encephalopathy of non-specific etiology and higher seizure susceptibility of multifocal onset. The patient had a cardiorespiratory arrest and expired after 4 months and 8 days of hospitalization. An autopsy was performed at Mount Sinai Medical Center.

2. Case Presentation

2.1. Clinical History

This is a case of a 4-year-old girl born via normal vaginal delivery (NVD) to a 34-year-old mother at 38.4 weeks of gestation. The mother had a short cervix with progesterone injections throughout pregnancy, and she was diagnosed with herpes simplex virus (HSV)-2 infection during the first trimester, for which she took antivirals during the last 2 weeks of her pregnancy. Alpha fetoprotein (AFP) was noted to be elevated but further genetic testing was negative for Down syndrome. The mother denied any teratogenic exposures to alcohol, tobacco, prescriptions, or non-prescription drugs.

The patient had a history of Miller–Dieker syndrome. Chromosomal microarray (CMA) testing demonstrated terminal deletion on chromosome 17p13.3p13.2 (pathogenic). There was a loss of 4.8 MB Kb identified in chromosome 17p13.3p13.2. This region contains 77 OMIM genes. Deletion of this region had been identified as pathogenic based on a review of the literature and databases. The clinical manifestations depend upon the size and genes involved. This deletion involves *PAFAH1B1* and *YWHAE* genes. Deletions involving both *PAFAH1B1* and *YWHAE* genes are consistent with Miller–Dieker syndrome, which is the case with our patient. Miller–Dieker syndrome is characterized by facial dysmorphisms and a more severe grade of lissencephaly. The patient’s karyotype analysis showed an abnormal female karyotype showing a terminal deletion in chromosome 17p13.2 identified in five metaphase cells analyzed. This finding is also consistent with the microarray results.

The patient also had microcephaly, patent foramen ovale (PFO) due to atrial septal defect (ASD) secundum, seizure disorder, chronic gastroesophageal reflux disease (GERD), prolonged complicated hospitalizations for recurrent infections (including recurrent episodes of tracheitis, most grew multidrug-resistant *Pseudomonas aeruginosa*), pulmonary hypertension (resolved after patent ductus arteriosus closure via percutaneous transcatheter plug occlusion at 1 year of age), chronic respiratory failure, bronchiectasis, pneumonia intestinalis, global developmental delay, and ventilator and G-tube dependence. Surgical history was significant for esophagogastric fundoplasty with fundic patch (Thal–Nissen fundoplication procedure) at 15 months of age, chemodenervation of bilateral parotid and submandibular salivary glands, and percutaneous gastrostomy and gastro-jejunostomy tube placement. She had known allergies to contrast dye, cow’s milk protein, and tape. Family history was significant for a father with epilepsy secondary to a motor vehicle accident at 15 years of age (gelastic seizures), maternal half-brother with asthma (born at 29 weeks), and maternal half-sister born at 33 weeks. There was no family history of congenital seizures, mental retardation, hearing loss, still birth, migraine, neurocutaneous syndrome stigmata, or metabolic disease. Vaccines were not up-to-date due to the patient’s immunocompromised status.

The patient was in her usual state of health until approximately 3 days prior to presentation at which time she was noted to have increased secretions from her nose, mouth, and tracheostomy tube. She also experienced fever (reaching 103 °F; 39.4 °C) and had a mildly distended abdomen and swollen feet. She was admitted to the hospital and was found to
have bacterial tracheitis growing *Enterobacter* and *Pseudomonas aeruginosa*. Abdominal examination revealed a positive fluid wave test. Vital signs showed a temperature of 102.5 °F (rectal), heart rate of 179 beats per minute, blood pressure of 86/54 mmHg, and respiratory rate of 30 breaths/min. Laboratory results are summarized in Table 1. SARS-CoV-2 test was negative.

**Table 1.** Patient’s relevant laboratory results on admission.

| Laboratory Values          | Reference Range           |
|----------------------------|---------------------------|
| White blood cell (WBC) count | 14.5 × 10^3/µL *         | 4.8–10.8 × 10^3/µL         |
| Segmented neutrophils       | 92.3% *                  | 42–75%                     |
| Red blood cell (RBC) count  | 2.94 × 10^6/µL *         | 3.93–5.22 × 10^6/µL        |
| Hemoglobin                  | 9.0 g/dL *               | 11.0–14.9 g/dL             |
| Hematocrit                  | 27.8% *                  | 32.0–42.0%                 |
| MCV                        | 94.6 fl *                | 75.0–87.0 fl               |
| MCH                         | 30.6 pg                   | 24.0–30.0 pg               |
| Platelet count              | 244 × 10^3/µL            | 150–500 × 10^3/µL          |
| Sodium                      | 142 mMol/L               | 132–143 mMol/L             |
| Potassium                   | 2.4 mMol/L *             | 3.2–5.7 mMol/L             |
| Chloride                    | 99 mMol/L                | 98–116 mMol/L              |
| CO₂                         | 35 mMol/L *              | 18.0–29.0 mMol/L           |
| pH                          | 7.44                      | 7.35–7.45                  |
| Glucose                     | 196 mg/dL *              | 76–115 mg/dL               |
| Serum creatinine            | <0.15 mg/dL *            | 0.3–1.0 mg/dL              |
| Calcium                     | 7.7 mg/dL *              | 9.0–10.9 mg/dL             |
| C-reactive protein          | 4.8 mg/dL *              | 0.0–1.0 mg/dL              |
| Lactate level               | 2.39 mMol/L *            | 0.50–2.20 mMol/L           |
| Albumin                     | 2.6 g/dL *               | 3.1–4.8 g/dL               |

* Abnormal values.

The patient was admitted to the pediatric intensive care unit (PICU) and placed on the sepsis protocol. She was started on multiple antibiotics (Sulfamethoxazole-Trimethoprim, Erythromycin, Linezolid and Tobramycin, aside from her home medications) for a diagnosis of acute on top of chronic respiratory failure in the setting of bacterial tracheitis, pneumonia (due to multidrug resistant *Mycobacterium abscessus*), and acute respiratory distress syndrome (ARDS). Mechanical ventilation was continued with above normal ventilator settings. Chest X-ray (CXR) revealed left central interstitial infiltrates as well as decreased aeration and partially confluent airspace disease in the right upper lobe. Subsequent CXRs showed significant worsening of aeration bilaterally and persistent bilateral pulmonary opacities. During hospitalization, she developed migratory patchy erythema. Hip X-rays revealed subluxation of both femoral heads with bilateral coxa valga, and venous doppler ultrasound of bilateral lower extremities revealed occlusive thrombus of the right external iliac, common femoral, and proximal superficial femoral veins. Fifteen days after admission, the patient began to spike fevers again. She was pan-cultured and started on Meropenem. Gastrointestinal PCR panel showed astrovirus.

The patient’s condition deteriorated with hemodynamic instability, and she had a cardiopulmonary arrest after two months of admission with return of spontaneous circulation (ROSC) after 20 min. The patient developed multiorgan failure, third spacing, significant lactic acidosis, and continued to require multiple vasoactive medications. After four months of hospitalization, neurology was consulted due to acute pulmonary and cardiac decompensation and fixed pupils. An electroencephalogram (EEG) was performed showing an abnormal background with a pattern of burst suppression and multifocal epileptiform discharges, suggestive of severe encephalopathy of non-specific etiology and higher seizure susceptibility of multifocal onset. The patient had a cardiorespiratory arrest and was pronounced dead after 4 months and 8 days of hospitalization.
2.2. Autopsy Findings
2.2.1. External Examination

On external examination, the patient’s body was well developed and well nourished, appearing to be the stated age of 4 years, weighing 19.05 kg and measuring 92 cm from crown to heel, 57 cm from crown to rump, and 35 cm from rump to heel. The skin was pale pink with abrasions at the neck and upper chest. The occipito-frontal head circumference was 45 cm. The chest circumference was 71 cm, and the abdominal circumference was 75 cm. Hand length was 9.5 cm and foot length was 11.5 cm. These anthropometric measurements were within the normal reference range for age [9]. The skull was symmetric and showed no evidence of trauma. The anterior and posterior fontanelles were closed. The pupil with iris measured approximately 0.5 cm on each side. The sclera and conjunctivae were unremarkable.

The external genitalia were those of a female and were unremarkable. The anus was patent. A sacral dimple was present. Livor mortis was appreciated but rigor mortis was absent.

The nasal choanae and mouth were probe-patent. The neck was symmetric and short, and the trachea was in the midline with a tracheostomy in place. The thorax was unremarkable. The areolae were devoid of fat. The abdomen was distended with a vertical, linear, midline, supra-umbilical, abdominal scar (9 cm in length). There were no hernias. Ten fingers and ten toes were present. Finger and toenails were unremarkable (Figure 2). The external genitalia were those of a female and were unremarkable. The anus was probe patent. A sacral dimple was present. Livor mortis was appreciated but rigor mortis was absent.

**Figure 1.** Syndromic facial features associated with Miller–Dieker syndrome. Images of the patient’s face showing (a) small and upturned nose with anteverted nares, (b) hypertelorism (abnormally increased distance between eyes) with wide nasal bridge (inner-canthal distance 2.8 cm), (e) low-set and posteriorly-rotated ears, (d) upslanted palpebral fissures with epicanthus supraciliaris (referring to a vertical fold of skin that extends from just below the brow to an area just over the infraorbital rim, usually obscuring the caruncle [10]), (e) thick upper lip with a thin, downward facing vermilion upper border and short philtrum, and (f) micrognathia.

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Figure 2. Images of the hands and feet showing ten fingers and ten toes with single transverse palmar creases bilaterally and no plantar creases.

2.2.2. Cardiovascular, Respiratory, and Gastrointestinal Systems

Examination of the cardiovascular system revealed an 81.6 g heart (reference mean 73 g [9]) and a ductus arteriosus with a black metallic plug device in place (status post closure of PDA). An ASD was also noted. Cardiac valves and chambers were unremarkable (Figure 3). No pericardial or pleural effusions were present. The lungs were normally lobated and congested (right lung weighed 157.0 g and left lung weighed 140.0 g; reference mean: right: 90.0 g; left: 85.0 g [9]) with diffuse bronchopneumonia and abundant intra-alveolar macrophages and fibrotic septa. The tracheobronchial mucosa showed hyperemia and focal ulcerations. The esophageal mucosa also showed focal hyperemia. The peritoneum was dry, and the small and large intestines were normally rotated with the appendix located in the right lower quadrant. The liver was congested (1250 g; reference mean: 516 g [9]) with clearing of hepatocytes and bile stasis.
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Figure 3. Gross images of the heart. A ductus arteriosus with black metallic plug device in place (status post closure of patent ductus arteriosus) is noted (a). An atrial septal defect was also noted (b).

2.2.3. Genitourinary, Hematopoietic, and Endocrine Systems

Kidneys showed extensive autolysis with no significant gross or microscopic findings. The right kidney weighed 60.1 g and the left kidney 55.7 g (reference: right: 58 g, left: 56 g [9]). The remainder of the urinary system and internal and external genitalia were unremarkable.

The spleen was congested (122.5 g; reference: 39 g [9]). The bone marrow was normocellular. The thyroid and adrenal glands appeared unremarkable and showed autolysis.

2.2.4. Cultures

Postmortem blood and right lung tissue cultures grew *Pseudomonas Aeruginosa*.

2.2.5. Central Nervous System

The patient’s brain weight in the fresh state was 560 g. The expected brain weight for the chronological age of 4 years is 1191 g [9]. The dura was tan in color, and there were no differences between the epi and the subdural spaces. There were no masses, hemorrhages, or discrete lesions. The sagittal sinus was probe patent. There were no hemorrhages in either surface of the brain. The interhemispheric fissure disclosed partial absence of the corpus callosum (Figure 4).

The undersurface of the brain disclosed the presence of cranial nerves I, II, and III on both sides. Cranial nerve IV was only present on the left side. Cranial nerve V was not observed at the time of dissection. Cranial nerves VI as well as VII through X were present bilaterally. The brainstem and cerebellum disclosed the presence of mid brain, pons, medulla oblongata, and superior segment of the cervical spinal cord, which were preserved and were small in size when compared to the cerebrum. The cerebellum had two hemispheres and a vermis, and there were no areas of softening or cavitations. There was no evidence of uncal or cerebellar tonsillar herniation. The vasculature included both vertebral arteries, the basilar artery, and all components of the circle of Willis, which failed to show any aneurysms or vascular malformation. The brainstem and cerebellum
were detached at the level of the mid brain. The coronal sections of the cerebrum were approximately 1 cm apart. The cross sections revealed a very thick cortex with very narrow white matter component, and there were no gyri. The gyri that were present were, for the most part, extremely large, (i.e., pachygyria) and only a few smaller gyri with smaller sulci were identified toward the midline, in the frontal lobe, primarily, where the olfactory sulcus is. The extent of the white matter diminishing was seen in all cerebral hemispheres. The ventricular system was significantly dilated, and the pillars of the fornix did not fuse, were fully separated, leaving a large cavum of the septum pellucidum (Figure 5). The dilatation of the ventricular system involved all cerebral ventricles, whereas the aqueduct of Sylvius was only mildly dilated, and the fourth ventricle was of adequate caliber. There was no delineation of the line of Gennari in the occipital lobe.

Figure 4. Gross images of the fresh brain. The cerebrum was remarkable for the presence of smooth cerebral hemispheres where primary gyri were definitely present and only mild linear crevices were seen for the secondary gyri that showed delayed development for the stage and age of this patient. Most secondary gyri and tertiary gyri were absent. The surfaces of both cerebral hemispheres were covered by finely vascularized leptomeninges that were more congested over the parietal lobes.

The basal ganglia were partially formed anteriorly. The thalamus was visualized posteriorly. The subthalamus nucleus was also noted; however, the hippocampi were remarkably small bilaterally. The brainstem and cerebellum were sectioned from superior to inferior to reveal adequate gross features of the mid brain, pons, and cerebellum. No pigmentation of the substantia nigra or the locus ceruleus was noted, as suspected for chronological age. The anterior posterior dimension of the midbrain, pons, and medulla was small compared to the remainder cerebrum. The cerebral hemispheres showed folia that were full, and the dentate nucleus was observed bilaterally. There were no masses, hemorrhages, or discrete lesions in the mid brain, pons, or cerebellar hemisphere. The medulla oblongata was flattened anterior to posterior but otherwise unremarkable and so were the superior segments of the cervical spinal cord.
Histopathologic examination of the brain showed leptomeninges with vascular congestion and mildly thick-walled blood vessels. Focal leptomeningeal thickening was noted. The gray matter was incomplete, as demonstrated by a four-layered cortex replacing the normal six-layered ribbon (Figure 6). The small hippocampus showed abnormally layered gray matter and a fragment of the posterior hippocampus demonstrated adequate cellularity (Figure 7). The basal ganglia showed extensive diffuse vacuolation of the white matter within the internal capsule; there was a marked decrease in white matter fibers in the external capsule (the extreme capsule was absent). Seen also in the internal capsule were either scattered or small clusters of displaced (heterotopic) neurons (Figure 8). The thalamus showed vacuolar change of the neuropil in the area beneath the ventricular lining. There were also clusters of neurons in what corresponded to the tail of the caudate nucleus. The rostral midbrain including the red nuclei was remarkable for prominent bilateral vacuolation of both red nuclei; the neurons within the midline were decreased anteriorly and appeared asymmetrically disposed posteriorly. The substantia nigra at this level was not visualized. A section of pons demonstrated narrowing of the anterior–posterior diameter of the brainstem. The colliculi were cellular and showed vascular congestion; only posteriorly, there were pontine nuclei separated by narrow bands of white matter. Even at this lower level, there was microscopic evidence of the red nucleus (which is not expected at this caudal level of the brainstem). A cross section of the rostral medulla oblongata disclosed a flattened gross appearance with a significant decrease in the anterior to posterior diameter. The anterior columns were preserved; however, the olives were small and fragmented bilaterally; the neuropil in between was largely vacuolated. The cerebellum showed multifocal loss of Purkinje cells in the folia; there was diffuse and prominent vacuolation of the white matter. Within the dentate nucleus, there were a few, scattered neurons showing cytoplasmic eosinophilia and nuclear pyknosis alongside vascular congestion. The superior segment of the spinal cord sections showed overall preservation of the architecture.
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**Figure 6.** Microscopic images of the cerebrum with immunohistochemical stain for neurofilament showing a 4-layered gray matter. The superficial layer (layer 1) was paucicellular and contained few primarily small neurons. This outermost layer is the molecular layer that contains Cajal-Retzius neurons. The axonal density was reduced, and axons ran in a haphazard manner. The second layer (layer 2) was more adequately populated; however, the neurons were disorganized and displayed small and large pyramidal neurons with bland nuclear morphology. Most axons ran perpendicular to the surface. The third appreciable layer (layer 3) was again hypocellular; neuroepithelial cells were present and neurons were sparse. The fourth layer (layer 4) displayed diffuse vacuolation and was more densely cellular albeit disorganized. It showed axons organized in groups and separated by neuropil, which were either faintly or darkly stained. No heterotopic neurons were seen in the underlying pale and decreased white matter (Neurofilament IHC stain; 100× and 200× magnification).

**Figure 7.** Microscopic image of the hippocampus. The hippocampus showed abnormally layered gray matter (Right panel) compared to a normal 4-year-old child’s hippocampus (Left panel) (H&E; 100× magnification).

**Figure 8.** Microscopic images of the basal ganglia. Section of the basal ganglia stained with H&E showed extensive diffuse vacuolation of the white matter within the internal capsule (Left panel) compared to a normal 4-year-old child’s basal ganglia (Right panel). A Luxol Fast Blue (LFB) stain for myelin is accentuated in the vacuolated areas of the gray and white matter portions (Right panel) (200× magnification).

**Hippocampus**

| Normal 4-year-old Child | Our patient (Miller-Dieker Syndrome) |
|-------------------------|-------------------------------------|
| ![Normal Hippocampus](image1) | ![Hippocampus with Abnormalities](image2) |

**Figure 8.** Microscopic images of the basal ganglia. The cerebral cortex, there was myelin that concentrated in the third layer of the cortex with discrete axonal (linear) staining, but mostly neuropil (diffuse) staining. Within the basal ganglia,
Figure 7. Microscopic image of the hippocampus. The hippocampus showed abnormally layered gray matter (Right panel) compared to a normal 4-year-old child’s hippocampus (Left panel) (H&E; 100x magnification).

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A Luxol Fast Blue (LFB) stain for myelin was performed to reveal that in the cerebral cortex, there was myelin that concentrated in the third layer of the cortex with discrete axonal (linear) staining, but mostly neuropil (diffuse) staining. Within the basal ganglia, the LFB stain accentuated in the vacuolated areas in the gray and white matter portions. As noted previously, there was also some axonal staining and some diffuse staining. In the rostral midbrain, the red nuclei that were vacuolated were strongly LFB positive and so were the peduncles, as expected. The cerebellum showed extensive FB staining in the diffusely vacuolated white matter. Overall, the rostral spinal cord showed adequate myelin presence. In addition, an immunohistochemical stain for neurofilaments showed a superficial layer where the axonal density was reduced, and axons ran in a haphazard manner; the second layer was more densely packed, and most axons ran perpendicular to the surface; the third layer was disorganized and showed different axonal lengths; and the fourth layer showed axons organized in groups and separated by neuropil, which were either faintly or darkly stained. The underlying reduced white matter showed strong axonal staining.

3. Discussion

The disordered neurodevelopment characteristic of Miller-Dieker syndrome (MDS) typically starts between 10 and 14 weeks of gestation [2]. Often, diagnostic evidence of MDS can be seen on prenatal ultrasound as early as 23 weeks of gestation [11]. Early findings can include sylvian fissure abnormalities and mild ventriculomegaly [11]. Later signs arise around the 31st week of gestation and include a widespread smooth gyral pattern, a large subarachnoid space, polyhydramnios, and symmetrical intrauterine growth restriction [11,12].

Characteristic dysmorphic facies including prominent forehead, microcephaly, low set ears, microphthalmia, micрогnathia, short nose, round philtrum, and thin vermilion border [3,5,7,13,14], many of which were demonstrated in our patient. At birth, patients typically display hypotonia, but this subsequently progresses to spasticity [7]. Additionally, affected children often go on to develop gross motor and intellectual delay, difficulty feeding, and epilepsy in the postnatal period. A total of 90% percent of patients develop seizures by age 1 [7], which our patient had. Less commonly, patients present with extracranial manifestations such as congenital heart disease, genitourinary malformations,
and omphalocele [11]. In our case, no gastrointestinal or genitourinary malformations were present. However, congenital heart anomalies were present including patent ductus arteriosus and atrial septal defect.

MDS is exceedingly rare and is generally not inherited. It is estimated to affect one in 100,000 live births [2]. Miller and Dieker contributed to the identification of MDS in 1963 and 1969, respectively, resulting in the nomenclature of the disease [15–17]. The genetic basis of the disorder has primarily been attributed to microdeletions along chromosome 17p13.3 [2,18]. However, in a minority of cases, balanced translocations involving chromosome 17p from unaffected parents have been implicated. Microdeletions in chromosome 17p13.3 can result in either isolated lissencephaly sequence (ILS) or MDS [2]. The determining factor typically relates to the size of the microdeletion, with MDS patients having larger deletions [19]. Phenomena involving an aberrant chromosomal formation known as a “ring chromosome disorder” may also be involved in the development of MDS [2,5]. In ring chromosome disorders, the short and long arms of the chromosome are fused, which leads to increased susceptibility to deletions of chromosomal material.

As previously stated, the major deficit leading to the impaired cortical development in these patients is defective neuronal migration. There are multiple prominent loci in the 17p13.3 region, which are associated with neuronal migration [13,18]. For example, mutations involving the PAFAH1B1 gene have been implicated in multiple syndromes that result in lissencephaly including MDS [18]. Co-occurring damage to the YWHAE gene has been associated with increased severity of lissencephaly and is typically present in all patients with MDS [18]. Defects in YWHAE are thought to be responsible for the severe abnormalities seen in the disorder. Both PAFAH1B1 and YWHAE are genes found on the short arm of chromosome 17. Both are involved in an evolutionarily conserved pathway that regulates cytoplasmic dynein heavy chain function [18]. PAFAH1B1 codes for LIS1, which normally phosphorylates cytoplasmic dynein in a process that is essential for neuronal migration [4,14]. YWHAE is located telomeric to PAFAH1B1 and codes for 14-3-3ε, a protein with many regulatory functions within the cell such as signal transduction, cell death, and cell cycle progression [14,18,20]. 14-3-3ε is also involved in the dynein motor arm pathway downstream of LIS1; thus, it also plays a significant role in neuronal migration [18].

The treatment options for MDS mainly involve multidisciplinary care for symptomatic control. The rarity of MDS has limited the amount of research related to the disease, therefore most of what is known about MDS is based on case reports [2]. Features of MDS such as the absence of the corpus callosum and cerebral malformation can be detected in-utero via routine pelvic ultrasound [21]. After the antenatal period, treatment is usually supportive and begins with a NICU admission to diagnose MDS via genetic testing and brain imaging. After birth, the common complications associated with MDS can be managed once they present in the patient. For instance, the onset of seizures can be treated with antiepileptic drugs after undergoing video-EEG to characterize the seizures [21].

Recent genetic advancements may aid in the development of chromosome-targeted therapy. For instance, the discovery of ring chromosome disorders and their connection to the development of MDS serve as potential therapeutic targets [2]. A study by Bershteyn et al. in 2014 found that reprogramming of the ring chromatides led to resolution of their aberrant formation [22]. This allowed the chromosomal material involved in MDS to be duplicated via uniparental disomy, thus preventing the development of MDS. Gene therapy treatment options are still limited, but with ongoing technological advancements, chromosome-targeted therapy may be a possibility.

The prognosis of MDS is seen as universally poor due to the irreversible neurologic effects such as severe intellectual disability and treatment-refractory epilepsy [21]. The life expectancy of individuals affected by MDS is greatly impacted by the degree of lissencephaly. Most patients with MDS have the most-severe form of lissencephaly, classified as grade 1 [22]. In a study by de Wit et al. in 2011, 24 patients with lissencephaly grade 1 were followed long-term (average of 14 years) and only eleven patients were
living at the time of evaluation. The survival rate was found to be associated with the severity of lissencephaly [23]. As MDS patients age, however, their functionality is greatly impacted by their neurologic conditions. Based on the investigation conducted by de Wit et al., all patients had a severe degree of psychomotor disability ranging from absent eye contact or purposeful movement to minor purposeful movements [23]. Some patients may demonstrate early motor development including proper head control and belly crawling, but this functionality is typically lost after the onset of seizure activity. Although life expectancy is limited, patients can reach adulthood if they receive treatment focused on preventing infections or scoliosis [23]. Increased life expectancy may be attributable to medical advancements such as the development of antiepileptics for enhanced seizure control or gastrostomy tube placements for patients with hypotonia/impaired swallowing mechanisms. Ultimately, the current treatment options are supportive to aid in prolonging the patient’s life, but most cases, typically result in death within the first year [2].

4. Conclusions

In conclusion, the early detection of MDS is imperative for appropriate counseling and obstetric management. However, prognosis remains universally poor due to the irreversible neurologic deficits that the patients have. Ultimately, the current treatment options are supportive to aid in prolonging the patients’ lives, but most cases, typically result in death within the first year.

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