Peroxisome biogenesis disorders in the Zellweger spectrum: An overview of current diagnosis, clinical manifestations, and treatment guidelines

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Abstract

Peroxisome biogenesis disorders in the Zellweger spectrum (PBD-ZSD) are a heterogeneous group of genetic disorders caused by mutations in PEX genes responsible for normal peroxisome assembly and functions. As a result of impaired peroxosomal activities, individuals with PBD-ZSD can manifest a complex spectrum of clinical phenotypes that typically result in shortened life spans. The extreme variability in disease manifestation ranging from onset of profound neurologic symptoms in newborns to progressive degenerative disease in adults presents practical challenges in disease diagnosis and medical management. Recent advances in biochemical methods for newborn screening and genetic testing have provided unprecedented opportunities for identifying patients at the earliest possible time and defining the molecular bases for their diseases. Here, we provide an overview of current clinical approaches for the diagnosis of PBD-ZSD and provide broad guidelines for the treatment of disease in its wide variety of forms. Although we anticipate future progress in the development of more effective targeted interventions, the current guidelines are meant to provide a starting point for the management of these complex conditions in the context of personalized health care.
1. Definition, nomenclature, and epidemiology

Peroxisomes are membrane-bound organelles found within almost all eukaryotic cells [1]. They are formed through replication by fission (the major pathway for peroxisome formation) or can originate from the endoplasmic reticulum (ER) through a de novo process [2]. Contained within the peroxisome matrix of mammalian cells are over 70 distinct enzymes required for normal lipid metabolism and a host of other biochemical processes critical for normal health and development [3].

Peroxisome biogenesis disorders (PBDs) are autosomal recessive disorders that are characterized by defective peroxisome biosynthesis, assembly, and biochemical functions [4]. Although it is estimated that 1 in 50,000 births are affected by PBDs in North America [5], these estimates may increase with the introduction of newborn screening [1].

In ZSD, patients with severe disease have a deficiency in the rate limiting enzyme for very long chain fatty acid oxidation, whereas patients with milder disease have a defect in enzymes required for normal lipid metabolism and a host of other biochemical processes critical for normal health and development [3].

We recommend replacing these names with the overall classification of peroxisome biogenesis disorders in the Zellweger spectrum (PBD-ZSD), ranging from severe (ZS), intermediate (NALD), and mild (IRD) phenotypes, respectively. The purpose of this recommendation is to highlight the fact that the individual clinical pictures are along a spectrum of disease severity and often do not fit into the original assigned categories. Additionally, we now also recognize a group of PBD-ZSD patients who do not exhibit the vision and hearing loss usually described in PBD-ZSD, and instead present with peripheral neuropathy and cerebral ataxia [13–15]. Other variant phenotypes continue to be described [16,17]. These patients would be diagnosed as intermediate or mild within the PBD-ZSD spectrum. Table 1 summarizes the clinical features observed in PBD-ZSD based on disease severity and age of symptom appearance. Symptom expression in most patients has an age-dependent component related to disease severity and considerable overlap exists among patients with severe, intermediate and milder phenotypes. Although the relative proportions of certain features were reported in one cohort with a subset of PEX genotypes [18], the prevalence and timing of all outcomes amongst PBD-ZSD patients is not yet adequately described, nor is the risk known for individual patients to develop various postnatal features.

Table 1
Clinical features of PBD-ZSD: severity, age of onset, and suggested treatments.

<table>
<thead>
<tr>
<th>Clinical features</th>
<th>Neonate</th>
<th>1–6 months</th>
<th>6 months–4 years</th>
<th>&gt;4 years</th>
<th>Suggested treatments (if available)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neuronal migration disorder</td>
<td>S</td>
<td></td>
<td></td>
<td></td>
<td>Oxygen support</td>
</tr>
<tr>
<td>Chondrodysplasia punctata</td>
<td>S</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renal cortical microcysts</td>
<td>S</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiratory compromise</td>
<td>S, S</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Craniofacial dysmorphism</td>
<td>S, I, M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct hyperbilirubinemia</td>
<td>S, I, M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liver dysfunction, hepatomegaly</td>
<td>S, I, M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure to thrive, small size, hypotonia and poor feeding</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Feeding therapy, G-tube placement, vitamins A, D, E, and K</td>
</tr>
<tr>
<td>Seizures</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Antiepileptic drugs</td>
</tr>
<tr>
<td>Adrenal insufficiency</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Hydrocortisone (Cortef)</td>
</tr>
<tr>
<td>Cataracts</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Cataract removal</td>
</tr>
<tr>
<td>Retinal degeneration</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Corrective lenses</td>
</tr>
<tr>
<td>Sensorineural hearing loss</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Hearing aid, cochlear implant</td>
</tr>
<tr>
<td>Psychomotor retardation</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Physical/occupational therapy</td>
</tr>
<tr>
<td>Leukodystrophy</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Hydrocortisone (Cortef)</td>
</tr>
<tr>
<td>Osteopenia</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Hydrocortisone (Cortef)</td>
</tr>
<tr>
<td>Calcium oxalate renal stones</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Increased fluid intake, urine alkalinization</td>
</tr>
<tr>
<td>Peripherial neuropathy</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Bonding, repair of permanent teeth</td>
</tr>
<tr>
<td>Cerebellar ataxia</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Bonding, repair of permanent teeth</td>
</tr>
<tr>
<td>Enamel hypoplasia</td>
<td>S, I, M</td>
<td>I, M</td>
<td>M</td>
<td>M</td>
<td>Bonding, repair of permanent teeth</td>
</tr>
</tbody>
</table>

Abbreviations: S, severe; I, intermediate; M, mild; G-tube, gastrostomy tube.
2. Laboratory diagnostic criteria

2.1. Traditional biochemical testing

Since their initial discovery, an increasing number of biochemical functions have been ascribed to peroxisomes including β-oxidation of very long chain fatty acids (VLCFA, 24 carbons or longer) and pristanic acid, phytanic acid α-oxidation, pipecolic acid metabolism, ether glycerolipid (plasmalogen), bile acid biosynthesis, and subcellular localization of catalase (Table 2) [3]. PBDS can be diagnosed by demonstrating abnormalities in several peroxisome biochemical functions that can be monitored in bodily fluids (Fig. 1). The primary step in PBD-ZSD diagnosis generally involves the detection of elevated VLCFA in a fasting plasma sample [19]. Elevations of C26:0 and C26:1 fatty acids and the ratios of C24:0/C22:0 and C26:0/C22:0 are consistent with a peroxisomal fatty acid β-oxidation defect [5]. Although usually abnormal on a blood specimen drawn randomly during the day, equivocal results, for example, in the case of elevated C26:0 with normal or near normal ratios of 24:0/22:0 and 26:0/22:0, and a high total lipid fatty acid content, measurements should be repeated on a plasma sample after overnight fasting. False positive results have rarely been reported, although this can occur if patients are on a ketogenic diet [20,21]. Additional studies demonstrating defects in multiple peroxisome enzyme pathways are necessary to diagnose PBD-ZSD, such as measurement of the methyl-branched fatty acids phytanic and pristanic acids, erthrocyte plasmalogens, pipecolic acid in plasma and/or urine, and the bile acid intermediate dihydroxycholestanolic acid (DHCA) and trihydroxycholestanolic acid (THCA) in plasma and/or urine [11]. Reduced levels of erthrocyte plasmalogens, whose biosynthesis is dependent on peroxisome function, may be observed depending on disease severity [5]. It should be noted that pipecolic acid levels are more likely to be abnormal in urine in the newborn period, and more abnormal in plasma in later ages [22–24]. Additionally, phytanic and pristanic acids may not be elevated in newborn infants who are not consuming dairy products or other dietary sources of these fatty acids [19]. Owing to defective biosynthesis in liver peroxisomes of the final C24 bile acids, cholic and deoxycholic acids, there is elevation of C27 bile acid intermediates, DHCA and THCA, in blood and urine [3].

Biochemical testing of skin fibroblasts is useful to confirm the metabolic abnormalities seen in the blood and urine and clarify questionable results in body fluids. The biochemical assays most frequently used in fibroblasts involve quantifying phytanic and pristanic acid oxidation, VLCFA accumulation and/or oxidation and plasmalogen biosynthesis [19]. Cultured skin fibroblasts are also valuable for establishing the subcellular localization of peroxisomal matrix proteins, such as catalase, which can distinguish PBD-ZSD from phenotypically similar peroxisomal single enzyme deficiencies [25].

Approximately 10–15% of suspected PBD-ZSD patients with elevated VLCFAs will not have PBD-ZSD, but a single β-oxidation enzyme defect in very long chain acyl-CoA oxidase (ACOX1) [26] or D-bifunctional protein (HSD17B4) [27]. The clinical phenotypes of these patients overlap that of PBD-ZSD. Other overlapping phenotypes include single enzyme/protein defects in branched chain fatty acid and bile acid metabolism, including α-methyl-acyl CoA racemase (AMACR) [28], phytanoyl-Coenzyme A hydroxylase (PHYH) [29], PEX7 [30] and sterol carrier protein X (SCPx) [31]. It is important to not rely on VLCFA screening alone for patients who are strongly suspected to have PBD-ZSD. In a small number of cases, mutations in PEX genes such as PEX2, PEX10, PEX12, PEX16 and PEX11B have been identified in patients with mild or absent elevations in VLCFA [9,13,32–35]. Consequently, testing for multiple biochemical functions in patients or obtaining biochemical studies on patient-derived fibroblasts and genetic testing may be necessary for proper diagnosis.

2.2. Genetic diagnostic testing

Next-generation sequencing panels for PEX genes are being used more frequently as a confirmatory test, and may be required for peroxisome disorders that are difficult to resolve by traditional biochemical methods [16,17,34,36–38]. These DNA tests are available on a clinical basis. Identification of mutations may have prognostic value [39]. For example, patients with two PEX null alleles generally have a severe phenotype, and those patients who carry the common PEX1-p.G843D allele are predicted to have a milder phenotype [40]. Homozygosity for PEX1-p.G843D typically predicts a milder phenotype, but even in this category there is a range of intellectual impairment to normal intellect, indicating that modifier genes, as yet to be identified, are influential [16,18]. The outcome of the combination of a PEX null allele with a missense allele can range from intermediate to milder, and this depends on the residual function of the missense allele. In a recent publication [17], certain missense alleles in PEX1 and PEX6, in combination with null alleles, defined a group of PBD-ZSD patients with normal intellect. In addition, patients with mutations in the region encoding the zinc finger domain of PEX2, PEX12 and PEX10, and certain mutations in PEX16 [13–15] exhibit variant phenotypes. In contrast to biochemical tests, mutation analysis will also identify heterozygous carriers, which will allow reliable genetic counseling of families and may assist with eligibility for future clinical trials.

2.3. Newborn screening

The combination of liquid chromatography and tandem mass spectrometry (LC–MS/MS) to detect elevated levels of VLCFAs in newborn blood spots has been validated as a diagnostic approach for X-linked adrenoleukodystrophy (X-ALD), a related peroxisomal disorder [6,41,42]. Legislation for X-ALD newborn screening has passed in New Jersey, Connecticut, Illinois, Tennessee and California and screening has begun in New York; continued legislative efforts are expected to expand through movements initiated by patient families and advocacy organizations to lobby their state legislatures. Recently, the Department of Health and Human Services Advisory Committee for Heritable Disorders for
Newborns and Children voted to propose the addition of X-ALD screening in the Recommend Uniform Screening Panel. The implications of X-ALD newborn screening include the ability to perform clinical surveillance for early detection of symptom onset and treatment for affected males and counseling for carrier females [43]. Newborn screening for X-ALD should also detect the majority of PBD-ZSD cases that feature elevated blood VLCFA levels, thereby permitting early diagnosis and determination of accurate incidence estimates. As newborn screening expands in the future, the diagnostic approach for PBD-ZSDs will necessarily be revised toward more confirmatory testing as seen in other newborn screening diseases. It is anticipated that the clinical phenotype of PBD-ZSD will be expanded as variant patients are identified.

### 2.4. Prenatal diagnosis of PBD-ZSD

Prenatal diagnosis of PBD-ZSD can be accomplished in the first or second trimester using biochemical or genetic testing of chorionic villi cells or cultured amniocytes. Preimplantation genetic diagnosis can also be performed when the PEX gene mutations are known [44].

### 3. Management and treatment guidelines

PBD-ZSD is a multi-organ disease, as peroxisomes are involved in critical metabolic pathways in nearly all the cells of the body from fetal development throughout adult life [4]. The wide variation in clinical severity and rate of disease progression adds complexity to the medical management of the group as a whole. With the recognition that some manifestations of PBD-ZSD arise during fetal development and cannot be reversed, particularly any brain dysplasia, therapeutic expectations for some neurologic symptoms must be tempered. Nevertheless, additional medical issues arise postnatally that can benefit from current therapy. At this time, treatment of any manifestations of PBD-ZSD focuses largely on symptomatic or supportive therapies. The following guidelines are meant as a starting point for management of these complex conditions for personalized medical care.

#### 3.1. Clinical evaluations following initial diagnosis

Table 3 summarizes recommended clinical evaluations at the time of the initial diagnosis of PBD-ZSD to establish the extent of disease and later in life as symptoms appear. It is likely that some of the

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**Table 3**

<table>
<thead>
<tr>
<th>Diagnostic Observations</th>
<th>Evaluation of Biochemical Biomarkers in Body Fluids</th>
<th>Confirmation in Cultured Skin Fibroblasts</th>
<th>Genetic Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identification of clinical features (as described in Table 1)</td>
<td>Elevated very long chain fatty acids in blood</td>
<td>Reduced plasmalogen synthesis</td>
<td>DNA sequencing of PEX and related peroxisomal single enzyme defects genes for mutations</td>
</tr>
<tr>
<td>Elevated VLCFA levels in blood during X-ALD newborn screening</td>
<td>Elevated phytic acid and/or pristanic acid levels in blood</td>
<td>Elevated VLCFA levels and/or reduced VLCFA oxidation.</td>
<td></td>
</tr>
<tr>
<td>Genetic testing for ( \text{ABCD1} ) gene mutations is performed to diagnose and remove X-ALD from subsequent evaluations</td>
<td>Elevated piperolic acid levels in urine/blood</td>
<td>Reduced plasmalogen levels in red blood cell membranes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elevated bile acid intermediates in urine/blood</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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*Fig. 1. Diagnostic criteria flowchart for PBD-ZSD. Given the current availability of next generation sequencing panels, clinicians have moved from evaluation of biochemical markers to genetic analysis future reproductive options, carrier testing in relatives, eligibility purposes in clinical trials and for patients that are difficult to diagnose. In difficult cases, it may still be necessary to evaluate cultured fibroblasts, and this may be important also to ascertain responses of specific mutations for future interventional trials. Abbreviations: PBD-ZSD, peroxisome biogenesis disorder-Zellweger spectrum disorder; X-ALD, X-linked adrenoleukodystrophy; VLCFA, very long chain fatty acids.*
Avoided if respiratory compromise is present. Seizures may be difficult to control despite use of appropriate medication. Feeding difficulties are often prominent, as well as laryngomalacia and aspiration. Patients should be re-evaluated yearly (or more frequently) to detect progression of disease and begin timely therapy.

Severe PBD-ZSD patients present in the neonatal period and have developmental malformations of the brain, kidneys and skeleton (Table 1). They have a more predictable clinical course than milder forms of PBD-ZSD. There is a characteristic craniofacial dysmorphology that includes an enlarged fontanelle, prominent forehead, epicanthal folds, hypertelorism, a broad, flat nasal bridge and mignonathia [5,45]. Neonatal seizures, severe hypotonia and developmental delays are consequent to neuronal migrations defects that characteristically appear as polymicrogyria and heterotopias on brain magnetic resonance imaging [46]. Renal micronodular cortical cysts can be observed by renal ultrasound and are not usually symptomatic. An enlarged liver with dysfunction of the hepatocellular and biliary system is typically present. Due to the severe hypotonia, feeding difficulties are often prominent, as well as laryngomalacia and other respiratory dysfunction [45]. Developmental progress is usually minimal. For seizure control, standard antiepileptic drugs (AED) may be used. No type of AED is contraindicated, although certain medications that have respiratory suppressive effects must be avoided if respiratory compromise is present. Seizures may be difficult to control despite use of appropriate medication. Feeding problems may require the placement of a gastrostomy tube (G-tube). With regards to respiratory therapy, use of nasal cannula for oxygen may be necessary as the disease progresses. The transition to a more aggressive type of respiratory support is a decision that should be discussed between the family and medical care team with informed expectations about survival and quality of life. Overall, for severe PBD-ZSD, seizure control, feeding and respiratory support are often the main focus for management, although additional interventions as described below may also be valuable for quality of life.

For the majority of patients who present with intermediate or milder PBD-ZSD, the details of the management are discussed below.

### 3.2. Feeding and nutrition

Many PBD-ZSD children have significant food selectivity and the involvement of a behavioral feeding program is often indicated in the older PBD-ZSD child. Supplying adequate calorie intake for affected children may entail the placement of a G-tube to allow simpler home management. With many children having some degree of malabsorption due to bile acid deficiency, elemental formulas may be better tolerated.

Currently, there is no specific diet that is recommended for PBD-ZSD patients. Although VLCFA levels are elevated in the tissues and body fluids of PBD-ZSD patients, it is unclear as to whether a reduction in dietary VLCFA will prevent the progression of the disease or its associated symptoms [47]. A reduction in dietary VLCFA alone has not been shown to reduce blood VLCFA levels [48], as the body produces most VLCFA endogenously. Plasma VLCFA levels are decreased only by the combination of dietary reduction of VLCFA and supplementation with Lorenzo’s oil (a 4:1 mixture of glyceryl trioleate and glyceryl trierucate) in X-ALD patients [49], but this does not affect the progression of an already established leukodystrophy [50–52]. Moreover, increased dietary monounsaturated fatty acids in Lorenzo’s oil may be contraindicated in PBD-ZSD patients who already accumulate large amounts of C26:1 due to defective VLCFA oxidation [53]. Finally, the effects of these dietary interventions have not been studied in PBD-ZSD patients.

Phytanic acid is a methyl branched-chain fatty acid exclusively obtained from dietary sources such as ruminant fats, dairy products, and certain fish [54]. As such, it can be eliminated by dietary restriction [54]. There is a minor amount of phytanic acid in human breast milk [55]. Dietary restriction of phytanic acid might be considered, since high phytanic acid levels over time could contribute to disease through mechanisms similar to that observed in adult Refsum disease [56,57]. In contrast to most patients with adult Refsum disease, however, PBD-ZSD patients tend to have normal or lower plasma phytanic acid levels [58] and no studies have demonstrated specific effects of phytanic acid accumulation from other peroxisomal defects in PBD-ZSD patients.

### Table 3

Recommended evaluations for PBD-ZSD patients.

<table>
<thead>
<tr>
<th>Symptoms</th>
<th>Specific examinations</th>
<th>Suspected findings in severe PBD-ZSD</th>
<th>Suspected findings in intermediate/mild PBD-ZSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth failure</td>
<td>Height, weight and head circumference, nutritional evaluation</td>
<td>Poor growth, feeding difficulties, fat soluble vitamin deficiency</td>
<td>Poor growth, feeding difficulties, fat soluble vitamin deficiency</td>
</tr>
<tr>
<td>Deafness</td>
<td>Hearing testing, brainstem auditory evoked responses</td>
<td>Bilateral sensorineural deafness</td>
<td>Progressive bilateral sensorineural hearing loss, deafness</td>
</tr>
<tr>
<td>Visual impairment</td>
<td>Ophthalmologic exam, visual fields, fundus photography, OCT</td>
<td>Cataracts, glaucoma, optic nerve hypoplasia</td>
<td>Progressive retinal dystrophy, blindness, band keratopathy</td>
</tr>
<tr>
<td>Neurological</td>
<td>Brain MRI, EEG, nerve conduction studies</td>
<td>Hypotonia, neural migration defects on MRI, neonatal seizures</td>
<td>Hypotonia, leukodystrophy, cerebellar atrophy on MRI, seizures, peripheral neuropathy, ataxia</td>
</tr>
<tr>
<td>Hepatic dysfunction</td>
<td>AST, ALT, GGT, bilirubin, albumin, alkaline phosphatase, bile acids (intermediate C27 and mature C24 bile acids, PT, PTT, abdominal ultrasound</td>
<td>Hepatomegaly, elevated transaminases, cholestasis, defective synthetic functions, portal hypertension, Renal cortical cysts</td>
<td>Same as severe ZSD, but milder</td>
</tr>
<tr>
<td>Renal insufficiency</td>
<td>Serum creatinine, BUN, abdominal ultrasound, urine oxalate</td>
<td>Progressive adrenal insufficiency</td>
<td>Calcium oxalate renal stones</td>
</tr>
<tr>
<td>Adrenal insufficiency, hypotension, vomiting</td>
<td>Adrenal function tests, early morning (8 am) cortisol and ACTH, ACTH stimulation test</td>
<td>Progressive adrenal insufficiency</td>
<td>Progressive adrenal insufficiency</td>
</tr>
<tr>
<td>Skeletal abnormalities, fractures</td>
<td>X-rays, DXA scan, serum calcium and phosphorous, alkaline phosphatase</td>
<td>Chondrodysplasia punctata, hips and knees</td>
<td>Low bone mineral density, pathological fractures</td>
</tr>
<tr>
<td>Dental</td>
<td>Dental exam, X-rays</td>
<td>Few developmental milestones gained</td>
<td>Enamel hypoplasia of secondary teeth</td>
</tr>
<tr>
<td>Psychomotor retardation</td>
<td>Developmental assessment</td>
<td></td>
<td>Delayed milestones with broad range of achievement from cognitive delay to normal cognition</td>
</tr>
</tbody>
</table>

**Abbreviations:** PBD-ZSD, peroxisome biogenesis disorder-Zellweger spectrum disorder; ERG, electroretinogram; OCT, optical coherence tomography; MRI, magnetic resonance imaging; EEG, electroencephalogram; AST, aspartate aminotransferase; ALT, alanine aminotransferase; GGT, gamma-glutamyltransferase; PT, prothrombin time; PTT, partial thromboplastin time; BUN, blood urea nitrogen; ACTH, adrenocorticotropic hormone; DXA, dual-energy x-ray absorptiometry.
Until definitive studies are conducted, it seems reasonable to monitor plasma phytanic acid levels and consider dietary modification if levels become excessive.

Since PBD-ZSD patients have impaired endogenous synthesis of docosahexaenoic acid (DHA) [59], and DHA is important in brain and retinal development and function, supplementation with DHA, was previously recommended. However, a placebo-controlled study showed no clinical benefit of DHA supplementation in enrolled patients in the PBD-ZSD spectrum. [60] Owing to defective bile acid synthesis, supplements of the fat-soluble vitamins, A, D, E, and K are recommended.

3.3. Liver

To help support liver function, supplementation of vitamin K at a dose of 2.5 mg–5 mg per day is recommended. Bile acid metabolism is altered in PBD-ZSD [61, 62], and primary bile acid therapy (cholic acid and Chenodeoxycholic acid) may improve liver function by reducing the accumulation of abnormal bile acid precursors, such as DHCA and THCA [63, 64]. Recently, cholic acid (Cholbam) has been approved by the United States Food and Drug Administration to treat peroxisomal disorders, including PBD-ZSD [65]. The available studies evaluating the effectiveness of bile acid therapy in PBD-ZSD are limited and may have differential effects depending on the severity of the disease. Coagulation factors and other synthetic liver functions should be monitored. Persons with overt liver dysfunction require more frequent monitoring and may benefit from referral to a gastroenterologist. Liver dysfunction may lead to varices that respond to appropriate therapies.

3.4. Hearing

Many patients with PBD-ZSD have some degree of hearing loss [66]; auditory functions should therefore be evaluated annually in children affected with PBD-ZSD. Hearing aids should be used in children found to have substantive hearing loss. Cochlear implants have been effectively placed in PBD-ZSD children when hearing loss is severe and cannot be compensated by hearing aids. In such instances, improvements in environmental awareness, and in some circumstances, speech, have been frequently noted in other syndromes with congenital deafness [67].

3.5. Vision

Vision loss is commonly seen with PBD-ZSD due to retinal dystrophy and optic nerve abnormalities [16, 68, 69]. Therefore, periodic ophthalmologic evaluations are indicated. Although cataracts are rare, if present, their removal in early infancy may preserve vision with the understanding that retinal dysfunction may later develop. Glasses should be used, as needed, to correct refractive errors. In children with confirmed PBD-ZSD, there appears to be no value in performing multiple electroretinograms (ERG) to assess functional vision. ERG testing has not been demonstrated to be predictive of vision and does not provide an index of progression [60]. Performing optical coherence tomography in children who can cooperate by looking directly at a light source may be useful for defining and monitoring retinal health. For children with both hearing and vision impairment, enrollment in the deaf-blind community is strongly encouraged. Appropriate resources include the National Family Association for Deaf–Blind (http://www.nfadb.org) and the National Center on Deaf-Blindness (https://nationaldb.org), which can provide connections to individual state deaf-blind projects.

3.6. Neurological function

Seizures have been observed in the neonatal period in nearly all severely affected PBD-ZSD patients [70], and have been reported in 23% of less severe patients [18]. EEGs can determine the frequency and duration of seizures and should be performed whenever changes in seizure activity are suspected. Common medications used to control seizures in children affected by PBD-ZSD are levetiracetam, phenobarbital, clonazepam, topiramate, and lamotrigine.

PBD-ZSD patients can also develop a leukodystrophy [18, 64], which can be silent, arrested or progressive. We recommend a baseline MRI of the brain, followed by additional studies if clinically indicated. Identification of white matter changes can have prognostic significance for changes in cognitive, behavioral and/or motor abilities.

Evaluation for early physical, occupational and speech therapy is recommended for all children with PBD-ZSD. Therefore, early intervention services should be provided.

3.7. Bone

Children with severe PBD-ZSD may have chondrodysplasia punctata or stippling seen at the growth plates. Decreased bone mineral density that worsens over time is associated with intermediate and milder forms of PBD-ZSD and pathologic fractures have occurred in some patients with no evidence of trauma. The incidence of bone disease in the course of PBD-ZSD has not been systematically studied. In patients who are older than 1 year and are non-weight bearing, or have had previous fractures, evaluation for bone disease should be considered. This should include dual-energy x-ray absorptiometry (DXA) that has been well-validated in pediatric patients. Evaluation of vitamin D status is also recommended. At the discretion of the clinician, markers of bone turnover such as phosphorus and parathyroid hormone levels may also be evaluated.

Regarding treatment of bone disease in PBD-ZSD, a recent study has reported successful treatment with bisphosphonate medications in a PBD-ZSD patient [71]. Bisphosphonate therapy should be carefully considered in consultation with an experienced metabolic bone specialist. Additionally, weight-bearing physical activity has shown to slow bone loss in children and therefore prevent fractures [72].

3.8. Teeth

Dental examination should be performed every 6 months. Many children with PBD-ZSD have enamel abnormalities of permanent teeth and should receive appropriate dental care [73–75].

3.9. Adrenal insufficiency

As with other peroxisomal disorders, particularly X-ALD, primary adrenal insufficiency has occurred in PBD-ZSD. A recent study reported a high prevalence of primary adrenal insufficiency in a population of 29 PBD-ZSD patients [76]. It is recommended that after one year of age, yearly (or more frequent) adrenal monitoring with adrenocorticotropic hormone (ACTH) and morning cortisol be performed. Treatment with adrenal replacement using standard dosing should be instituted if abnormal. Families and clinicians should be aware of the possibility of adrenal insufficiency and consider stress dosing in periods of sudden severe illness, fever, and major surgical procedures.

3.10. Kidney

Children affected by PBD-ZSD, particularly older children (≥4–6 years), should be monitored for hyperoxaluria, which can lead to kidney stone formation and renal failure [77]. This can be determined by measuring oxalate and creatinine in the urine. Kidney ultrasound may be useful to detect renal stones.

3.11. Other recommendations

It is also recommended that all patients on the PBD-ZSD spectrum should be vaccinated against influenza and respiratory syncytial virus yearly, in addition to the normal course of vaccination for other childhood diseases.
4. Future directions

The treatment guidelines discussed herein provide a starting point for the personalized management of PBD-ZSD based on current medical practice; however, we anticipate these guidelines will evolve over time as emerging therapeutic strategies for PBDs are tested in laboratory settings and eventually in clinical trials. A robust portfolio of in vitro and whole organism models of PBD-ZSD provide the basis for laboratory research. Cultured patient cells, including skin fibroblasts, have provided invaluable for screening and testing drug therapies in vitro [78]. Most recently, PBD-ZSD patient-derived skin fibroblasts have been reprogrammed into induced pluripotent stem cells (iPSCs) that were differentiated into neural and hepatic cell models of disease that could be used in drug screening and testing efforts [79]. There are several genetically engineered mouse models of PEX gene defects [80], including a model of the common PEX1 P.G843D mutation [81]. In addition, a host of invertebrate models of PBD-ZSD exist including genetically engineered worms, fruit flies, and zebrafish [82]. All provide opportunities to screen for and/or test specific therapies on the scale of the whole organism.

The principal strategies being actively pursued include high-content screening of large chemical libraries for compounds that improve peroxisome assembly and function, as well as gene and cellular therapies. Seminal screening studies identified betaine as a potential molecular chaperone that can improve peroxisome assembly in cultured cells from PBD-ZSD patients with PEX1 P.G843D mutations [78]. Candidate drug screens identified arginine as another potential molecular chaperone in patient cell lines [83]. Larger-scale drug screens are currently being conducted at the National Center for Advancing Translational Sciences at the National Institutes of Health (Hacia, personal communication). Advances in gene therapy, including the development of adeno-associated virus (AAV) gene delivery systems, provide hope for the treatment of numerous genetic disorders, including PBD-ZSD. Multiple successful retinal gene augmentation trials for Leber congenital amaurosis (LCA) [84], a rare inherited eye disease, is of special relevance of PBD-ZSD. Currently, AAV9-mediated gene augmentation therapy for vision loss in PBD-ZSD is being developed and will be tested in mouse models of milder forms of PBD-ZSD (Bennett, personal communication). Given that PBD-ZSD is a multisystemic disease, gene therapy aimed at correcting peroxisome assembly in other organs, most notably the central nervous system (CNS) and the liver, is of great interest to the medical research community. Finally, we recognize potential therapeutic opportunities for cellular therapies, including the transplant of cell types and cell lineages affected in PBD-ZSD patients.

5. Concluding remarks

With greater understanding of the full range of severity seen in PBD-ZSD, physicians can transition to a more targeted approach to supportive therapies. Vision and hearing interventions, nutrition provisions, along with monitoring for adrenal insufficiency, renal stones, bone density and dental enamel defects, can all enhance quality of life for PBD-ZSD patients. Further research into all of the variation in PBD-ZSD children is urgently needed in order to provide more evidence-based guidelines. Our established ongoing longitudinal natural history study on PBD-ZSD will help us acquire and disseminate information regarding this disease, and to identify accurate clinical endpoints for future interventional trials (https://clinicaltrials.gov/ct2/show/NCT01668186?term=NCT01668186&rank=1).

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