ABSTRACT. Objective. To evaluate the clinical relevance of tetrahydrobiopterin (BH₄) supplementation for pregnant women with phenylketonuria (PKU)/hyperphenylalaninemia (HPA) and the possibility of treating these patients with BH₄ instead of a phenylalanine (Phe)-restricted diet.

Methods. Genotyping was performed on 41 patients with PKU/HPA identified by newborn screening. Evaluating the genotype according to their BH₄ responsiveness is published. Follow-up of 3 patients with mild PKU treated with BH₄ is evaluated. Discussion of the transfer of these experiences to the possibility of treating mothers at risk for maternal PKU is presented.

Results. In 41 patients with PKU/HPA, we found 17 (41%) bearing at least 1 allele with a mutation described as being responsive to BH₄. In 8 of the patients, BH₄ loading had been performed in the newborn period, in 6 of whom the test showed a clear decrease of blood Phe 4 and 8 hours after loading. One of the nonresponders was reinvestigated at 3 years of age, showing a clear response (genotype Y414C/R408W): BH₄ supplementation resulted in a much higher Phe tolerance (500 instead of 250 mg/day) with blood Phe levels <200 μmol/L. Two children (genotype E390G/IVS10–11g>a and L48S/L48S, respectively) were treated with BH₄ only (15–20 mg/kg body weight/day), one from birth, the other from 2 years of age. Blood Phe decreased from >800 μmol/L to a mean of 321.4 and 331.7 μmol/L, respectively (range: 141–718 μmol/L) under a normal diet (total observation time: 4 years). Development was normal with no adverse reactions.

Conclusions. BH₄ supplementation seems to be a promising alternative treatment in some patients with mild PKU. Because blood Phe levels in maternal PKU should be maintained at 120 to 360 μmol/L, clinical relevance may be even greater than for treatment of children with PKU/HPA. BH₄ supplementation may also be combined with a Phe-restricted diet, allowing higher Phe intake and protecting mothers from high Phe blood peaks. However, additional studies are necessary to prove the safety and economy of such an alternative treatment in patients with PKU/HPA, especially during pregnancy. PEDIATRICS 2003;112:1566–1569; maternal PKU, diet, hyperphenylalaninemia, tetrahydrobiopterin.

TREATMENT OF PATIENTS WITH MILD PHENYLKETONURIA

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ABREVIATIONS. PKU, phenylketonuria; Phe, phenylalanine; HPA, hyperphenylalaninemia; BH₄, tetrahydrobiopterin; PAH, phenylalanine hydroxylase.

Treatment of classical and mild phenylketonuria (PKU) involves a restricted phenylalanine (Phe) diet supplemented by a Phe-free amino acid mixture. Recently, it has been shown that in some patients with non-PKU hyperphenylalaninemia (HPA; blood Phe usually <600 μmol/L), blood Phe responded to high dosages of tetrahydrobiopterin (BH₄), the natural co-factor of the Phe hydroxylase (PAH) enzyme. In these patients, BH₄ deficiency had been excluded and mutational analysis of the PAH gene revealed various mild mutations. It was speculated that the mutated enzyme is a Kₘ variant, which in the presence of high BH₄ concentrations increases residual enzyme activity. Because patients with these mild mutations resulting in blood Phe <600 μmol/L usually do not need dietary treatment, the practical relevance of BH₄ responsiveness did not seem to be high. However, in women who are at risk for maternal PKU, this may be different, because the International Maternal PKU Collaborative Study has shown that blood Phe levels >360 μmol/L may be harmful to the fetus. There are also reports showing that patients with mild PKU (blood Phe 360–1200 μmol/L) may respond to BH₄ supplementation.3–8

We investigated the possible treatment of maternal PKU with BH₄ supplementation. We first looked into the frequencies of BH₄-sensitive alleles in a sample of 41 patients with PKU/HPA. In addition, we treated 3 patients with mild PKU with BH₄ supplementation to demonstrate the possibility of this treatment.

METHODS

Genotyping of the PAH gene was performed in 41 patients with persistent HPA (blood Phe >180 μmol/L) found in the newborn screening program. Allele frequencies were determined for mutations of the PAH gene reported in the literature to be responsive to BH₄ loading. Retrospective data for BH₄ loading in the newborn (20 mg/kg body weight; blood Phe measurement at 0, 4, and 8 hours postloading) were available for 8 patients in whom the genotype was indicative of being BH₄ responsive. Response to BH₄ loading was defined as a decrease of blood Phe by at least 30% within 8 hours. Quantitative blood Phe measurements were performed using dried filter spots and tandem mass spectrometry. PKU phenotype was defined as classical PKU (persistent blood Phe >1200 μmol/L), mild PKU (blood Phe between 600 and 1200 μmol/L), and mild HPA (blood Phe <600 μmol/L) under normal nutrition. BH₄ was provided by Schirck’s Laboratories (Jona, Switzerland). In all responders BH₄ deficiency was excluded by urinary analysis of biopterin metabolites.
RESULTS

Table 1 gives an overview of the 15 mutations described to be BH₄ responsive. In 41 patients with PKU/HPA, we found 17 (41%) with at least 1 allele with a mutation described as being responsive to BH₄. In 8 of these, BH₄ loading had been performed in the newborn period, of which 6 showed a clear response of blood Phe and 8 hours after loading and 2 patients showed no response. One of the non-responders (ID 494), who is on a Phe-restricted diet since birth, was reinvestigated at 3.5 years of age and showed a clear Phe decrease even on a more relaxed diet (Fig 1). Details of BH₄ loading in this patient and 2 others in the newborn period are shown in Table 2. Although there was a clear decline of blood Phe in patients ID 230 and 445, patient ID 494 showed no response in the newborn period.

Patient ID 230 was treated from birth with BH₄ supplementation after his favorable response (Fig 2). Blood Phe increased when BH₄ supplementation was stopped at 6 months of age and decreased again when BH₄ was reintroduced at a dosage of 15 mg/kg/day. Since then, the patient is being treated with BH₄ last dosage at 2.5 years of age is 3 times 50 mg/kg body weight/day. Mean blood Phe level was 321.4 μmol/L (range: 141–718 μmol/L; n = 26). Routine clinical examinations and routine blood chemistry were normal. No adverse effects have been observed. The patient is now 2.6 years of age and developing normally.

In Turkish patient ID 445, who is homozygous for the L48S mutation in the regulatory domain of the PAH gene, as recently published, parents had problems giving a Phe-restricted diet in the second year of life and stopped the diet. Because blood Phe levels constantly exceeded 600 μmol/L, we decided to introduce BH₄ at a dosage of 3 times 50 mg/day at 2.5 years of age (~8 mg/kg body weight/day). Since then, blood Phe was monitored 1 to 2 times per month; mean blood Phe was 331.7 μmol/L (range: 183–600 μmol/L; n = 17). Routine clinical examinations and routine blood chemistry were normal. No adverse effects have been observed. The patient is now 3.5 years of age and developing normally.

DISCUSSION

In our sample of 41 patients, 41% are BH₄ responsive according to their genotype, indicating the high frequency of BH₄-responsive mutations in HPA/PKU patients. A similar observation was noted in a large retrospective study indicating that >60% of mild PKU and HPA patients may respond to BH₄ administration. In contrast, Weglage et al. in a sample of 87 patients who underwent a BH₄ loading test in the newborn period, found only 3 responding

<table>
<thead>
<tr>
<th>Allele 1</th>
<th>PAH Enzyme Activity*</th>
<th>Allele 2</th>
<th>PAH Enzyme Activity*</th>
<th>Reference</th>
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<tbody>
<tr>
<td>L48S</td>
<td>39 L48S</td>
<td>39 L48S</td>
<td>Blau and Trefz (3)</td>
<td></td>
</tr>
<tr>
<td>V190A</td>
<td>gd R243X</td>
<td>0</td>
<td>Saapen et al (5)</td>
<td></td>
</tr>
<tr>
<td>A313T</td>
<td>nd 1099insC</td>
<td>0</td>
<td>Saapen et al (5)</td>
<td></td>
</tr>
<tr>
<td>A300C</td>
<td>nd A403V</td>
<td>32</td>
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<td></td>
</tr>
<tr>
<td>R241C</td>
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<td>32</td>
<td>Saapen et al (5)</td>
<td></td>
</tr>
<tr>
<td>E390C</td>
<td>70 IVS10-11g&gt;a</td>
<td>0</td>
<td>Trefz et al (7)</td>
<td></td>
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<tr>
<td>R241C</td>
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<td>0</td>
<td>Kure et al (1)</td>
<td></td>
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<tr>
<td>P407S</td>
<td>nd R252W</td>
<td>&lt;1</td>
<td>Kure et al (1)</td>
<td></td>
</tr>
<tr>
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<td>nd R111X</td>
<td>0</td>
<td>Kure et al (1)</td>
<td></td>
</tr>
<tr>
<td>A373T</td>
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<td>0</td>
<td>Kure et al (1)</td>
<td></td>
</tr>
<tr>
<td>R241C</td>
<td>25 R408W</td>
<td>&lt;3</td>
<td>Kure et al (1)</td>
<td></td>
</tr>
<tr>
<td>Y414C</td>
<td>28 IVS12+1g&gt;a</td>
<td>&lt;3</td>
<td>Lindner et al (4)</td>
<td></td>
</tr>
<tr>
<td>A395F</td>
<td>nd 165I</td>
<td>26</td>
<td>Lässker et al (6)</td>
<td></td>
</tr>
<tr>
<td>R261Q</td>
<td>27 165I</td>
<td>26</td>
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<td></td>
</tr>
<tr>
<td>D129G</td>
<td>nd R408W</td>
<td>0</td>
<td>Hennerman et al (13)</td>
<td></td>
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<tr>
<td>P211T</td>
<td>72 P211T</td>
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<td></td>
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<td>S510C</td>
<td>nd P381E</td>
<td>&lt;1</td>
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<td></td>
</tr>
<tr>
<td>A104D</td>
<td>0 K320N</td>
<td>nd</td>
<td>Steinfeld et al (8)</td>
<td></td>
</tr>
<tr>
<td>Y414C</td>
<td>28 Y414C</td>
<td>28</td>
<td>Steinfeld et al (8)</td>
<td></td>
</tr>
<tr>
<td>IVS3-22G&gt;a</td>
<td>nd Y414C</td>
<td>28</td>
<td>Weglage et al (10)</td>
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<tr>
<td>A104D</td>
<td>nd Y414C</td>
<td>28</td>
<td>Weglage et al (10)</td>
<td></td>
</tr>
</tbody>
</table>

Underlined mutations are proposed to be causative for BH₄ responsiveness.

* of the wild-type activity.
to BH₄. As discussed at a recent BH₄ workshop,¹¹ such retrospective analyses must be interpreted with some caution. In Germany, BH₄ was provided exclusively by Dr Schircks (Jona, Switzerland). Until October 1999, this BH₄ was a mixture of the 6R and 6S forms, thus being only partially biologically active.

Using a dosage of 20 mg of fully active 6R-BH₄ per kg body weight, 63%, 64%, 33%, 15%, and 1% of patients with plasma Phe levels of 200 to 400, 400 to 800, 800 to 1200, 1200 to 1600, and ≈1600 μmol/L, respectively, responded significantly by lowering Phe levels by at least 30%.⁹ In addition, the BH₄ test was performed over a period of only 8 hours because this test was originally designed to exclude BH₄ deficiency. Recently, Blau and Muntau¹¹ reported that in some patients with PAH deficiency, effects of BH₄ on blood Phe levels may be observed only over an observation time of up to 24 hours postloading. Also, in 1 of our patients (ID 494), no response to BH₄ was observed in the newborn period, whereas on the same dosage of 20 mg/kg, a clear drop of blood Phe could be demonstrated (Fig 2).

Our single case studies (now almost 5 treatment years) demonstrated that BH₄ provides an alternative treatment in mild PKU. However, treatment cost may be ~3 to 4 times higher beyond the first year of life than with the conventional Phe-restricted diet with amino acid supplementation.¹¹ Use of BH₄ in the treatment of maternal PKU may be in principle a possibility. However, so far, there is only 1 study available showing that in a case of maternal BH₄ deficiency, BH₄ administration is without any adverse effect on the developing fetus.¹² As demonstrated in patient ID 494, in patients with mild PKU, combining a Phe-restricted diet and BH₄ supplementation is an option. This may increase Phe tolerance to allow an intake of, for example, 500 mg of Phe per day together with 10 to 20 mg/kg/day BH₄ as demonstrated in the above patient. In addition, BH₄ supplementation may “stabilize” the blood Phe profile so that high blood Phe “peaks” (eg, during infections or catabolic status) are avoided. This may play an important role especially during early pregnancy (Trefz et al, this supplement). However, additional studies are necessary to find the optimal dosages in adults, taking into account the high costs of BH₄.

The exact mechanism of how exogenous BH₄ af-

<table>
<thead>
<tr>
<th>Patient ID</th>
<th>Genotype</th>
<th>Phenotype</th>
<th>Ethnic origin</th>
<th>Maximal blood Phe (μmol/L)</th>
<th>Time on BH₄ treatment (10–20 mg/kg/body weight)</th>
<th>Phe-restricted diet</th>
<th>BH₄ loading (newborn)</th>
<th>Phe (μmol/L), 0 h</th>
<th>Phe (μmol/L), 4 h</th>
<th>Phe (μmol/L), 8 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>E390G/VS10-11g&gt;a</td>
<td>Mild PKU</td>
<td>Italian</td>
<td>1132</td>
<td>1 d–3 y</td>
<td>No</td>
<td>20 mg/kg</td>
<td>739</td>
<td>584</td>
<td>178</td>
</tr>
<tr>
<td>445</td>
<td>L485/48S</td>
<td>Mild PKU</td>
<td>Turkish</td>
<td>829</td>
<td>2.6–3.6 y</td>
<td>1st year</td>
<td>250 mg/day</td>
<td>707</td>
<td>522</td>
<td>285</td>
</tr>
<tr>
<td>494</td>
<td>Y414C/R408W</td>
<td>Mild PKU</td>
<td>German</td>
<td>1068</td>
<td>5 d–3.5 y</td>
<td>Yes, 250 mg/day</td>
<td></td>
<td>912</td>
<td>894</td>
<td>1068</td>
</tr>
</tbody>
</table>

Table 2. Summary of Data in 3 Patients With Mild PKU (Blood Phe Levels 600–1200 μmol/L) Treated With BH₄ Supplementation

Fig 2. Profile of blood Phe in a patient with mild PKU (genotype E390G/VS10–11g>a) under BH₄. BH₄ loading after birth and treatment up to 6 months. At 6 months of age, treatment was stopped and reintroduced after 1 week.
ffects blood Phe in some patients with PAH deficiency is under discussion. Possibly BH₄ supplementation influences the promoter activity of the gene rather than enhancing residual enzyme activity by improving affinity for BH₄. Differences of this influence on promoter activity in newborns compared with children might also explain the different effects of BH₄ in the same patient.

There is no doubt that the BH₄ loading test should be performed routinely in the newborn with HPA to exclude BH₄ deficiency. To establish BH₄ responsiveness in PKU/HPA patients, this test should be extended to 15 to 24 hours postloading.

ACKNOWLEDGMENTS

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Blood Phe measurements by tandem mass spectrometry were performed by Dr H. Korall (ZFS Reutlingen, Germany). Mutation analysis of the PAH gene by Dr C. Aulehla Scholz (Stuttgart, Germany).

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Pediatrics 2003;112;1566

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