Exhaustive analysis of BH4 and dopamine biosynthesis genes in patients with Dopa-responsive dystonia

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Dopa-responsive dystonia is a childhood-onset dystonic disorder, characterized by a dramatic response to low dose of l-Dopa. Dopa-responsive dystonia is mostly caused by autosomal dominant mutations in the GCH1 gene (GTP cyclohydrolase1) and more rarely by autosomal recessive mutations in the TH (tyrosine hydroxylase) or SPR (sepiapterin reductase) genes. In addition, mutations in the PARK2 gene (parkin) which causes autosomal recessive juvenile parkinsonism may present as Dopa-responsive dystonia. In order to evaluate the relative frequency of the mutations in these genes, but also in the genes involved in the
biosynthesis and recycling of BH4, and to evaluate the associated clinical spectrum, we have studied a large series of index patients (n = 64) with Dopa-responsive dystonia, in whom dystonia improved by at least 50% after L-Dopa treatment. Fifty seven of these patients were classified as pure Dopa-responsive dystonia and seven as Dopa-responsive dystonia-plus syndromes. All patients were screened for point mutations and large rearrangements in the \textit{GCH1} gene, followed by sequencing of the \textit{TH} and \textit{SPR} genes, then \textit{PTS} (pyruvoyl tetrahydropterin synthase), \textit{PCBD} (pterin-4a-carbinolamine dehydratase), \textit{QDPR} (dihydropteridin reductase) and \textit{PARK2} (parkin) genes. We identified 34 different heterozygous point mutations in 40 patients, and six different large deletions in seven patients in the \textit{GCH1} gene. Except for one patient with mental retardation and a large deletion of 2.3 Mb encompassing 10 genes, all patients had stereotyped clinical features, characterized by pure Dopa-responsive dystonia with onset in the lower limbs and an excellent response to low doses of L-Dopa. Dystonia started in the first decade of life in 40 patients (85%) and before the age of 1 year in one patient (2.2%). Three of the 17 negative \textit{GCH1} patients had mutations in the \textit{TH} gene, two in the \textit{SPR} gene and one in the \textit{PARK2} gene. No mutations in the three genes involved in the biosynthesis and recycling of BH4 were identified. The clinical presentations of patients with mutations in \textit{TH} and \textit{SPR} genes were strikingly more complex, characterized by mental retardation, oculogyric crises and parkinsonism and they were all classified as Dopa-responsive dystonia-plus syndromes. Patient with mutation in the \textit{PARK2} gene had Dopa-responsive dystonia with a good improvement with L-Dopa, similar to Dopa-responsive dystonia secondary to \textit{GCH1} mutations. Although the yield of mutations exceeds 80% in pure Dopa-responsive dystonia and Dopa-responsive dystonia-plus syndromes groups, the genes involved are clearly different: \textit{GCH1} in the former and \textit{TH} and \textit{SPR} in the later.

\textbf{Keywords:} Dopa-responsive dystonia; \textit{GCH1} gene; \textit{SPR} gene; \textit{TH} gene; \textit{PARK2} gene

\textbf{Abbreviations:} CRE = cyclic monophosphate response element; CSF = cerebrospinal fluid; DRD = L-Dopa-responsive dystonia; PCR = polymerase chain reaction; PTS = 6-pyruvoyl tetrahydropterin synthase; QDPR = dihydropteridin reductase; SPR = sepiapterin reductase

\section*{Introduction}

L-Dopa-responsive dystonia (DRD) is a disorder characterized by childhood or adolescence onset dystonia sometimes associated with mild parkinsonism (Segawa \textit{et al}., 1976). The motor symptoms usually fluctuate during the day and are improved by sleep. The hallmark of the disease is a dramatic and sustained improvement of the dystonia with a low dose of L-Dopa. DRD can also present in adulthood as focal dystonia or parkinsonism. Women are affected 2.5–4 times more frequently than men (Nygaard, 1995).

Most cases of DRD are caused by heterozygous point mutations or, more rarely, large deletions in GTP cyclohydrolase1 (\textit{GCH1}) gene, located on chromosome 14q and encoding the GTP cyclohydrolase 1 enzyme (GTPCH EC 3.5.4.16) (Ichinose \textit{et al}., 1994). GTPCH is involved in the first and rate-limiting step of the \textit{de novo} biosynthesis of tetrahydrobiopterin (BH4) by catalysing the formation of dihydroneopterin triphosphate from GTP (Fig. 1). BH4 is an essential cofactor required for the activity of various enzymes such as the nitric oxide synthases and phenylalanine-, tryptophane- and tyrosine- hydroxylases (Thony \textit{et al}., 2000). The second and last steps of the \textit{de novo} biosynthesis of BH4 are catalysed by the pyruvoyl tetrahydropterin synthase (PTPS EC 4.6.1.10; gene symbol \textit{PTS}) and the sepiapterin reductase (SR EC 1.1.1.153; gene symbol \textit{SPR}), respectively. Furthermore, two additional enzymes, pterin-4a-carbinolamine dehydratase (PCD EC 4.2.1.96; gene symbol \textit{PCBD}) and dihydropteridin reductase (DHPR EC 1.6.99.7; gene symbol \textit{QDPR}), are required for the regeneration of BH4 from intermediates formed during the hydroxylation of aromatic amino acids.

Deficits in other enzymes involved in the BH4 biosynthesis may be responsible for the DRD phenotypes associated with other biochemical hallmarks such as hyperphenylalaninemia. Mutations in \textit{PTS} gene commonly induce hyperphenylalaninemia, but a DRD phenotype has rarely been described (Hanihara \textit{et al}., 1997) since hyperphenylalaninemia is systematically detected through neonatal screening, leading to early substitutive dopaminergic and BH4 treatment. Mutations in the \textit{SPR} gene are responsible for DRD with more complex clinical syndromes (Bonafe \textit{et al}., 2001; Neville \textit{et al}., 2005, Abeling \textit{et al}., 2006), without hyperphenylalaninemia.

Thus, theoretically, all the enzymes involved in the biosynthesis and recycling of BH4 could induce DRD, especially when hyperphenylalaninemia is mild and is not detected at birth. In addition, mutations in two other genes also cause an autosomal recessive form of DRD: the tyrosine hydroxylase gene (TH EC 1.14.16.2; gene symbol TH) responsible for typical DRD (Ludecke \textit{et al}., 1995; Furukawa \textit{et al}., 2001; Shiller \textit{et al}., 2004) or L-Dopa-responsive parkinsonism (Ludecke \textit{et al}., 1996; van den Heuvel \textit{et al}., 1998) and the parkin gene (Parkin EC 6.3.2; gene symbol \textit{PARK2}) responsible for juvenile parkinsonism and more rarely for typical DRD (Tassin \textit{et al}., 2000).

However, to date, the relative frequency of the mutations in the genes encoding the enzymes involved in the dopamine and BH4 biosynthesis in DRD patients remains unknown. In order to evaluate the respective contributions of these genes and the associated clinical spectrum, we investigated a cohort of 64 index patients with DRD. All patients were screened for point mutations and large rearrangements in the \textit{GCH1} gene, followed by the sequencing of the TH, SPR, PTS, PCBD, QDPR, as well the \textit{PARK2} genes in patients without mutation in \textit{GCH1}.
Patients and Methods

Patients
We selected 64 index patients who were referred to our centre for a molecular diagnosis, and in whom dystonia improved by at least 50% after L-Dopa treatment. Cases with a possible diagnosis of Parkinson’s disease either on the basis of clinical evolution or with proven dopaminergic denervation evidenced by 123I-FP-CIT SPECT or fluorodopa PET were excluded from the analysis. Among these patients, 10 had already known point mutations in the \textit{GCH1} gene (SAL37, SAL426, SAL444, SAL445, SAL424, SAL438, SAL452, MON132, CLE150, SAL439) and were described in a previous study (Tassin et al., 2000). Their clinical features and mutations are not presented in Table 1, but their data were included in the calculation of the mean age at onset and in the analysis of the relative frequencies of the genes involved in DRD. For patients without mutations in the screened genes, we considered the diagnosis of DRD only if the response to L-Dopa was sustained (i.e. confirmed after at least 1 year of follow-up) and uncomplicated.

Most patients were French; the others originated from Ireland, North-Africa, Mali, Senegal or Guatemala. The medical charts of all the patients were carefully reviewed for clinical data, including age and localization of the dystonia at onset, clinical phenotype of the dystonia at the time of diagnosis and additional neurological features. Pure DRD was defined as isolated dystonia with no other neurological manifestations except mild parkinsonism and a sustained response to low doses of L-Dopa. DRD-plus syndromes were defined as DRD associated with other neurological features (including mental retardation, oculogyric crises, psychiatric manifestations, axial hypotonia and dysautonomia symptoms). Of the 64 patients, 57 had pure DRD and 7 had DRD-plus syndromes. Forty-eight were female and 16 were male. Informed written consent was given by all participating members of the family.

Screening for point mutations in the \textit{GCH1}, \textit{PTS}, \textit{SPR}, \textit{TH}, \textit{PCBD}, \textit{QDPR} and \textit{PARK2} genes

Genomic DNA from peripheral white blood cells was obtained by standard extraction methods (phenol/chloroform). Exons and exon–intron junctions were amplified by the polymerase chain reaction (PCR). Furthermore, the cyclic monophosphate response element (CRE) in the promoter region of the \textit{TH} gene, located between residues –67 and –74 directly upstream of the ATG initiation codon, was amplified by PCR. The amplified fragments were sequenced on an ABI 3730 automated sequencer using the Big Dye 3.1 cycle sequencing kit (Applied Biosystems, Foster City, CA), and the sequencing data were analysed using Sequence Navigator or SeqScape 2.5 software (Applied Biosystems, Foster City, CA).

To predict, \textit{in silico}, the effect of splice site mutations and missense mutations, we used the splicing site score program (http://rulai.cshl.edu/cgi-bin/New_Alt_Exon_Db/score.pl) and the Polyphen program (http://www.bork.embl-heidelberg.de/PolyPhen/), respectively.

Multiplex ligation-dependent probe amplification (MLPA) of \textit{GCH1}, \textit{TH} and \textit{PARK2} genes

Two MLPA were performed. The first one in all patients without a point mutation in \textit{GCH1} using the SALSA MLPA kit P099 GCH1-TH...
All of the exons in GCH1, except the small exon 4 (32 bp), were quantified. Only 6 of the 14 TH exons were quantified. One hundred nanograms of DNA were used in the MLPA protocol, according to the manufacturer’s instructions. Reactions were performed on a GeneAmp PCR System 9700 (Applied Biosystems). One micro-litre of the PCR products was analysed by capillary electrophoresis on an ABI 3730 automated sequencer and MLPA data were analysed using the ABI Prism Genemapper 4.0 software (Applied Biosystems, Foster City, CA). Relative ratios were calculated for each peak using the formula \( r = \frac{\text{mean (peak area patient/control area patient)}}{\text{mean (peak area control individual/control area control)}} \).

### Table 1 Clinical features of 37 carriers of GCH1 mutations

<table>
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<th>Fam No./Sex</th>
<th>Predicted protein alteration</th>
<th>Nucleotide change</th>
<th>Exon</th>
<th>Age of onset (years)</th>
<th>Age at examination</th>
<th>Type of dystonia</th>
<th>Site of onset</th>
<th>Response to L-dopa (%)</th>
<th>Family history</th>
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<td>UF222/2</td>
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<td>del exon 2-4</td>
<td>2–3</td>
<td>7</td>
<td>34</td>
<td>Segmental</td>
<td>LL, UL</td>
<td>80</td>
<td>No</td>
</tr>
<tr>
<td>ITD677/2</td>
<td>Absence of transcript</td>
<td>del exon 4-6</td>
<td>5–6</td>
<td>2</td>
<td>27</td>
<td>Generalized</td>
<td>LL</td>
<td>90</td>
<td>Yes</td>
</tr>
<tr>
<td>ITD566/2</td>
<td>Absence of transcript</td>
<td>del exon 6</td>
<td>6</td>
<td>6</td>
<td>37</td>
<td>Generalized</td>
<td>LL</td>
<td>100</td>
<td>No</td>
</tr>
</tbody>
</table>

*a de novo mutation.

b Patient with DRD plus syndromes. New mutations are indicated in bold. The ten GCH1 mutations of the paper of Tassin et al., 2001 are not described here. Large deletions were analysed by MLPA.

Sexe: 1 = male and 2 = female; NK = not known; LL = lower limbs; UL = upper limbs.
Quantitative real-time PCR

Exon 4 of GCH1 was quantified by quantitative real-time PCR (q-PCR) in all patients without point mutations. The primer pairs were designed using Primer Express 1.5 software. The sequence of the forward and reverse primers was TGAGGCTGACTAAAGCAATTTTTC and ACAGATTGTAACCTGACAGGATCTTC, respectively. Real-time PCR was performed on the ABI PRISM 7500 Sequence Detection system (Applied Biosystems), in a total volume of 25 μL, containing 10 ng of genomic DNA, 1× SYBR Green PCR master mix (Applied Biosystems, Foster City, California, USA), and 250 nM of the forward and reverse primers. The standard amplification protocol was used: 50°C for 2 min, 95°C for 10 min, followed by 40 cycles of 95°C for 15 s and 60°C for 1 min. To normalize the amount of target DNA, exon 8 of albumin gene was amplified in a separate reaction well under identical thermal cycling conditions. Each reaction was run in triplicate. Copy number values between 0.8 and 1.2 were considered as normal; values ≤0.6 evidenced a deletion.

We also quantified exons 2 and 3 of the SPR gene by Q-PCR. The sequences of the forward and reverse primers for exon 2 were ACAGTTTGGCTACTAAGTCAAGAAA and TGCAAGGCACAGAGGA, respectively, and the sequences of the forward and reverse primers for exon 3 were GTGAGCTTCAGGTACAGTGG and GCACAGCAGACTCTTAGA, respectively.

PCR amplification was performed as above.

Deletion mapping by infinium HD DNA analysis BeadChip

Patient ITD612 was analysed using Illumina’s Human CNV 370-Quad BeadChip (Illumina Inc, San Diego, CA, USA). We used 200 ng of patient DNA and followed the protocol as described by the manufacturer (Illumina Inc., San Diego, CA, USA).

Statistical analysis

Age at onset was compared using the Mann-Whitney test. Statistical significance was defined as P<0.05.

Results

GCH1 mutation carriers and their clinical characteristics

Direct sequencing of the GCH1 gene was performed in 64 unrelated index patients. We identified 38 index patients with heterozygous point mutations in GCH1, two index patients with compound heterozygous mutations and seven index patients with heterozygous large deletions. We found 34 different point mutations (6 nonsense, 15 missense, 6 splice site mutations, 6 small deletions and 1 mutation in the 5’ untranslated region). Twenty of them were new mutations (Table 1).

The two patients with compound heterozygous mutations carried a common missense variant (c.68C>T, p.Pro23Leu) located in exon 1. This substitution was previously described as a mutation or a variant in 8 different families (Jarman et al., 1997; de la Fuente-Fernandez 1997; Steinberger et al., 2000; Scola et al., 2007; Zim et al., 2008) and it was found in 1/210 control chromosomes by Jarman et al. (1997). We found the p.Pro23Leu variant in 1/174 control chromosomes. The two mutations combined with the p.Pro23Leu variant were a 2-base deletion (c.137_138delGC, p.Ser46SerfsX18) and a missense mutation (c.206 C>T, p.Pro69Leu), both located in exon 1, in patients ITD588 and ITD625, respectively. In patient ITD588, the p.Pro23Leu variant was inherited from the mother and the deletion (c.137_138delGC) occurred de novo (segment analysis of 8 informative polymorphic markers excluded non-paternity).

The p.Pro69Leu mutation was found in 1/174 control chromosomes in the same control individual that had the p.Pro23Leu mutation. The parental DNA of the patient and the control were not available, so we could not define whether the mutations were in the cis- or in the trans- position. The p.Pro23Leu mutation was considered by Polyphen to be benign and the p.Pro69Leu mutation to be deleterious. Moreover, the proline residue at position 23 is not well conserved in other species, in contrast to the proline at position 69. These observations suggest that p.Pro23Leu is a polymorphism and that p.Pro69Leu is a probably causative mutation. All the other missense mutations identified in the present study altered an amino acid that was conserved across mammalian species and were not found on the control chromosomes.

Four splice site mutations (c.453 +1G>A, c.509 +1G>A, c.626 +1G>A and c.626 +1G>T) affected the invariant bases of the consensus splice donor sequence. The previously reported c.626 +1G>A splice site mutation (Hirano et al., 1998) resulted in the skipping of exon 5 and the introduction of a premature stop codon. The three other splice site mutations were novel; however, since RNA from patients was not available, the transcripts could not be analysed. It is highly probable that these mutations cause exon skipping. We also identified two other splice site variants that did not affect the invariant bases of the consensus splice site sequence, but which were located at position -5 of intron 2 (c.344-5T>G) and at position +5 of intron 3 (c.509 +5G>A). The mutations reduced the splice site score from 7.2 to 4.4 for the c.344-5T>G donor and from 11.6 to 8.2 for the c.509 +5G>A donor. However, no RNA was available to validate the in silico predictions that these variants are splice site mutations.

Except for two in frame deletions (p.Leu179del and p.Arg88_Gln90del), all small deletions caused a frameshift in the coding region that introduced a premature stop codon, theoretically resulting in a truncated protein.

Two of the seven patients with large heterozygous deletions of GCH1 (SAL434 and ITD612) had complete gene deletions and five had partial deletions (exon 1, exons 2–4, exons 2–6, exons 4–6 or exon 6). Four of the seven patients were sporadic cases, three were familial. In family SAL434, four individuals (two males and two females) had complete deletions. The index case presented a pure DRD, whereas the other patients had only mild equinism. Analysis of microsatellites and SNP in the region flanking the deletion in this family demonstrated that the deletion encompassed only the GCH1 gene. In patient ITD612 who also had a complete deletion of GCH1, a mental retardation was observed in addition to classical signs of DRD. Several male relatives of this patient had a microphthalmia with mental retardation and several females had...
low intellectual levels variably associated with strabismus. The size
of the deletion was analysed by using Infinium High-Density
BeadChips (Human CNV 370-Quad). We identified a 2.3 Mb
deletion ranging from rs4901534 to rs1189820. This region
contained 10 genes, one of which is the homeobox OTX2 gene,
involved in severe ocular malformations including anopthalmia-
microphthalmia and variable developmental delay (Wyatt et al.,
2008). In family ITD677, three females were affected (the mother
and her two daughters). They all had a partial deletion of GCH1
comprising exons 4–6, with ages at onset ranging from 5 to
8 years. In family ITD435, one female and two males were
affected, but DNA was available only for the index patient who
had an exon 1 deletion.

In the 47 families with a point mutation or a large deletion in
GCH1, there were 63 patients and 16 asymptomatic carriers.
There were 2.5 times more females than males (45 versus 18)
in the patients and 2.2 times more males than females (11 versus 5)
in the asymptomatic carriers. Thirty-five percent of the patients
had a family history of DRD and 65% were isolated (the one
patient for whom the family history was unknown was excluded).
Analysis of the DNA of the parents of the five index cases without
patient for whom the family history was unknown was excluded).

The clinical characteristics of patients with a mutation or a large
deletion in GCH1 were very stereotyped. The mean age of onset
was 7.5 years ± 4.9 (4 months to 27 years) and there was no
significant difference between carriers of point mutations com-
pared to carriers of large deletions (7.8 ± 5.1 years versus
5.8 ± 3.2 years, \( P = 0.39 \)). Dystonia started in the first decade of
life in 40 patients (85%) and before the age of 1 year in one (2%)
(Fig. 2). Onset of the disease after the age of 11 years was
observed in six patients (13%), two of which (ITD625 and
SAL444-194) manifested the disease after the age of 18 years.
Dystonia first appeared in a foot or lower limb in almost all
of the patients. The response to \( \alpha \)-Dopa was always excellent
(70–100% improvement), and the majority of patients experi-
enced diurnal fluctuation of symptoms. Atypical presentations
were noted in only three patients who had been diagnosed as
having tremor, parkinsonism or spastic paraparesis before con-
firmation of DRD. Except for mental retardation in patient
ITD612, no other neurological features were observed.

**Mutations in TH and SPR genes**

We analysed TH in 14 of the 17 index patients without mutations
in GCH1 and onset before the age of 16 years along with SPR in
all of the patients. Five different mutations, four of which were
new, were found in TH in three index patients. Two previously
described mutations in SPR were found in two index patients
(Table 2).

**Patients with mutations in the TH gene**

Patient ITD600, a girl from Guatemala, was examined at the age
of 2 years. She had early motor delay with reduced proximal tone
that contrasted with dystonia and stiffness in the limbs. These
motor symptoms were characterized by marked diurnal fluctua-
tions. However, she had no cognitive dysfunction. Dystonia dra-
matically improved (by nearly 80%) with low doses of \( \alpha \)-Dopa.
Analysis of the cerebrospinal fluid (CSF) revealed low levels of
homovanillic acid (HVA) and normal levels of 5-hydroxyindole
acetic acid (5-HIAA). Detailed clinical and biochemical descriptions
of this patient, consistent with a TH deficiency, was described by
Doummer et al. (2009). This patient had two heterozygous
missense mutations c.1125G>C and c.1399A>G, responsible for
changes in two conserved amino acids, phenylalanine to leucine
at codon 375 (p.Phe375Leu) in exon 10 and serine to glycine at
codon 467 (p.Ser467Gly) in exon 13, respectively. Parental DNA
was not available because the patient had been adopted. Since the
mutations are located in the catalytic domain of the TH protein,
they are expected to alter its enzymatic activity.

Patient ITD736, a female, was examined at the age of 24 years.
Her disease started during early childhood with progressive motor
delay including axial hypotonia and segmental dystonia of
the lower limbs with bilateral equinovarus deformity. When examined,
she had generalized dystonia with bulbar involvement, moderate
parkinsonism, bilateral rest tremor, mild cognitive impairment and
depression. She improved by 80% with low doses of \( \alpha \)-Dopa.
No biochemical data on pterin metabolism were available. Her brother
had similar clinical signs, but the TH gene could not be sequenced
for lack of DNA. Patient ITD736 carried two heterozygous missense
mutations, c.956G>C and c.1240G>A changing two conserved
amino acids: arginine to proline at codon 319 (p.Arg319Pro) in
exon 7 and glycine to arginine at codon 414 (p.Gly414Arg) in
exon 12, respectively. The p.Gly414Arg mutation has already
been described (Giovanniello et al., 2007). The p.Arg319Pro and
p.Gly414Arg mutations were not found on 128 control chromo-
somes and both are located in the catalytic domain of the protein.

Patient ITD797, a girl, was examined at the age of 6 years.
Her parents were consanguineous. Pregnancy, delivery and the
neonatal period were normal. Motor delay was noticed by her
mother at the age of 5 months. Her head control was poor and
she could not sit. Axial and proximal tone was low but dystonia
and spastic stiffness were observed in the extremities. She
also had parkinsonism, including episodes of rest tremor, together
with multifocal myoclonus. Her deep tendon reflexes were very
brisk. Her motor symptoms fluctuated during the day and were
improved by rest. In addition, she had supranuclear gaze palsy
and mild mental retardation. A few weeks after the initiation of \( \alpha \)-dopa
treatment, her motor status improved dramatically, and she could
control her head and sit normally. Reduced levels of HVA and HVA/5-HIAA ratio were found in her CSF. She had a homozygous missense mutation (c.901C>G) that changed a conserved proline to alanine at codon 301 (p.Pro301Ala) in exon 8. This mutation was not found on the 184 control chromosomes and both parents were heterozygous for the mutation.

**Patients with mutations in SPR gene**

Patient ITD498, a girl, was examined at 13 years of age. She was investigated for generalized dystonia with diurnal fluctuations and improved 90% on 50 mg of L-Dopa a day. Her dystonia started in the trunk at the age of 6 years and progressively spread and worsened. Since the onset of her disease, she had episodes, in which her eyes rolled-up, which could last several minutes. Mental retardation was also noted. No biochemical data on pterin metabolism were available. The patient had an affected sister who had the same clinical phenotype since the age of 8 years. The two sisters had homozygous c.596-2A>G mutation in the splice acceptor site of intron 2, and their parents both carried the same mutation in the heterozygous state. This mutation has been described previously (Farrugia et al., 2007) and probably results in the absence of the protein.

Patient ITD613, a male, was examined at age 23 years. His disease started during the first year of life with oculogyric crises. He progressively developed generalized dystonia that was first noted in the lower limbs and progressively spread to the trunk, neck and upper limbs. He also had mild parkinsonism without tremor. His symptoms were characterized by marked diurnal fluctuation. Dystonia was significantly improved by L-Dopa, but some oculogyric crises, brought on by exercise, still occurred despite the treatment. The patient also complained of hypersonsomolence and hyperphagia. Analysis of CSF revealed very low levels of HVA and 5-HIAA and elevated levels of neopterin and biotpterin. This patient had a homozygous missense mutation: c.448A>G in exon 2, changing a conserved arginine to glycine at codon 150 (p.Arg150Gly). The mutation has already been described and results in an inactive protein (Bonafé et al., 2001).

**Mutation in the PARK2 gene**

In the remaining 12 DRD patients with no mutations in **GCH1**, **TH** or **SPR** genes, the **PTS**, **PCBD** and **QDPR** genes were sequenced. No mutations were detected. Following these results, we analysed by sequencing and MLPA the **PARK2** gene in patients in whom the pattern of transmission was compatible with autosomal recessive inheritance. We found a new homozygous missense mutation c.1346G>A in exon 12, changing a conserved cysteine to tyrosine at codon 449 (p.Cys449Tyr) in patient ITD729. This mutation was not found in 340 control chromosomes and both parents were heterozygous for the mutation. The patient was a female examined at 23 years. She had a generalized dystonia which was improved by 150 mg of L-Dopa and a postural and action tremor of the upper limbs. Dystonia started in the upper limbs at 16 years. At seven years follow-up, the L-Dopa was still efficient and no dyskinesia were observed.

**Patients without mutations in any of the genes tested**

Eleven DRD patients were negatives for all of the genes analysed. Five were sporadic cases, three were familial. The family histories...
of the other three patients are unknown. The mean age of the patients at onset was 8.8 ± 8.9 years (3 months to 27 years). Their clinical characteristics are summarized in Table 3. One patient, ITD703, was classified as DRD-plus syndromes because of slight mental retardation. At the latest follow-up evaluation, the improvement under dopaminergic treatment was sustained and uncomplicated for all these patients. No dyskinesia was observed.

**Discussion**

We looked for mutations in all of the genes involved in the biosynthesis of BH4 and in *TH* gene involved in the synthesis of L-Dopa and in the PANK2 gene in 64 index patients with DRD, whose motor symptoms improved by at least 50% after L-Dopa treatment (summary, Fig. 3). We found 40 patients (62.5%) with point mutations and seven patients (11%) with large deletions of *GCH1*. Among these 47 *GCH1*-positive patients, 76.6% were female. These results were consistent with other studies of DRD patients: a frequency of *GCH1* point mutations of 50–60% and a frequency of *GCH1* large deletions of 8% (Hagenah et al., 2005; Zim et al., 2008) with females affected 2.5–4 times more frequently than males (Nygaard, 1995). Fifteen percent of the 47 *GCH1*-positive patients had large deletions, suggesting that MLPA or Q-PCR should be used routinely to search for rearrangements in *GCH1* gene in DRD patients in whom mutations had not been found by sequence analysis. Thus, the redefining of DY14 as DY5 in the paper by Wider et al. (2008) has been made possible by using a dosage method.

Thirty-four different *GCH1* point mutations were identified. They are distributed in all of the exons, and all types of mutations were found: missense mutations (37.5%), nonsense mutations (17.5%), splice site mutations (20%), small deletions (20%) and changes in the 5′ untranslated region (5%). Three mutations (p.Arg216X, c.626 + 1G>T and 5′UTR-22C>T) and one deletion (c.631_632delAT) were found in more than one subject. For the

\[ \text{Table 3 Clinical features of 11 DRD patients without mutations in the genes involved in metabolic pathways of BH4 and L-Dopa and in the PARK2 gene} \]

<table>
<thead>
<tr>
<th>Fam No/Sex</th>
<th>Age of onset (year or month)</th>
<th>Age at examination (years)</th>
<th>Duration of FU with L-Dopa</th>
<th>Type of dystonia</th>
<th>Location of first dystonia</th>
<th>Additional features</th>
<th>Response to L-Dopa</th>
<th>Family history</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITD249/1</td>
<td>3 month</td>
<td>25</td>
<td>16</td>
<td>Generalized</td>
<td>Neck</td>
<td></td>
<td>90</td>
<td>Yes</td>
</tr>
<tr>
<td>ITD328/1</td>
<td>27</td>
<td>30</td>
<td>4</td>
<td>Segmental</td>
<td>UL</td>
<td></td>
<td>50</td>
<td>No</td>
</tr>
<tr>
<td>ITD435/2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>Segmental</td>
<td>LL</td>
<td></td>
<td>100</td>
<td>Yes</td>
</tr>
<tr>
<td>ITD458/2</td>
<td>0.5</td>
<td>41</td>
<td>1</td>
<td>Focal</td>
<td>Neck</td>
<td>Postural tremor of neck and UL</td>
<td>70</td>
<td>No</td>
</tr>
<tr>
<td>ITD478/2</td>
<td>6</td>
<td>27</td>
<td>3</td>
<td>Generalized</td>
<td>NK</td>
<td>Limbs spasticity</td>
<td>100</td>
<td>No</td>
</tr>
<tr>
<td>ITD592/1</td>
<td>1</td>
<td>18</td>
<td>2</td>
<td>Generalized</td>
<td>NK</td>
<td></td>
<td>100</td>
<td>NK</td>
</tr>
<tr>
<td>ITD623/2</td>
<td>8</td>
<td>9</td>
<td>3</td>
<td>Focal</td>
<td>Foot</td>
<td></td>
<td>100</td>
<td>No</td>
</tr>
<tr>
<td>ITD670/2</td>
<td>17</td>
<td>30</td>
<td>4</td>
<td>Focal</td>
<td>Hand</td>
<td></td>
<td>100</td>
<td>Yes</td>
</tr>
<tr>
<td>ITD682/2</td>
<td>12</td>
<td>31</td>
<td>14</td>
<td>Generalized</td>
<td>LL</td>
<td></td>
<td>100</td>
<td>NK</td>
</tr>
<tr>
<td>ITD703/1</td>
<td>5</td>
<td>6</td>
<td>1</td>
<td>Hemi dystonia</td>
<td>NK</td>
<td>Slight mental retardation</td>
<td>90</td>
<td>NK</td>
</tr>
<tr>
<td>UF221/2</td>
<td>19</td>
<td>20</td>
<td>1</td>
<td>Multifocal</td>
<td>LL</td>
<td></td>
<td>90</td>
<td>No</td>
</tr>
</tbody>
</table>

\(a\) All patients had pure DRD except one patient with DRD-plus syndromes.

\(1 = \text{male and 2 = female; NK = not known; LL = lower limbs; UL = upper limbs; FU = follow-up.}\)
In patients with TH mutations, the disease started early, often in the first year of life. To date, 29 patients with TH mutations have been reported in the literature. The clinical presentations of patients with TH deficiency ranged from typical DRD (Ludecke et al., 1995; Furukawa et al., 2001; Shiller et al., 2004) to L-Dopa-responsive infantile parkinsonism (Ludecke et al., 1996, Swaans et al., 2000) or severe progressive encephalopathy (Hoffmann et al., 2004, Ribás et al., 2007). All of our patients, one of whom was mentally retarded, had infantile parkinsonism with a rather good response to L-Dopa therapy which was limited by the occurrence of dyskinesia. Biochemical analyses of the CSF in two patients revealed decreased HVA levels. In the majority of the patients with mutations in the SPR gene described in the literature (Bonafe et al., 2001; Neville et al., 2005, Abeling et al., 2006, Friedman et al., 2006), the L-Dopa-responsive movement disorder was associated with other symptoms, such as ataxia, oculogyric crises, dystautonomia symptoms as hypersalivation, microcephaly or growth retardation. Two of our patients had oculogyric crises. In addition, mental retardation was observed in patient ITD498, and patient ITD613 had behavioural features, including sleep disorders or hyperphagia, that might be related to deficits in other neurotransmitters such as serotonin. Analysis of the TH and SPR genes in DRD patients is not yet part of routine screening. Our results suggest that it should be performed in selected patients with dystonia associated with others symptoms, such as infantile parkinsonism, mental retardation or oculogyric crises but also in negative GCH1 patients with typical DRD. Indeed, mutations in TH or SPR genes can both result in a clinical presentation of typical DRD (Ludecke et al., 1995; Furukawa et al., 2001; Steinberger et al., 2004) even if this form is less frequently observed than a complex one.

To investigate all of the enzymes of the BH4 biosynthesis pathway, we sequenced the PTS, PCBD, QDPR and PARK2 genes in the 12 remaining DRD patients without mutations in GCH1, SPR or TH genes. Despite an observation of dystonia in one patient with a mutation in the PTS gene (Hanihara et al., 1997) we found no mutations in this gene in our DRD patients. This is not surprising, since deficits in these enzymes usually result in

![Figure 3](https://academic.oup.com/brain/article-abstract/132/7/1753/325176/10)
hyperphenylalaninemia, which is detected in newborn children and treated by early administration of L-Dopa and BH4 which prevents the development of dystonia. The identification of a PARK2 homozygous mutation in one patient of our cohort confirm that defects in this gene can cause DRD similar to DRD secondary to GCH1 mutations. In Parkinson’s disease (either genetic or not), the DRD phenotype seems to be related with a juvenile onset (Lucking et al., 2000). In such patients, only studies using 123I-FP-CIT SPECT or [18F]dopa PET scans would allow to rule out dopaminergic cell loss and point to a BH4 or dopamine biosynthesis defect.

Of the 11 patients without mutations, 10 had pure DRD with a mean age at onset of 9.1 years ± 9.3 (range 3 months to 27 years), slightly higher than that of patients with GCH1 mutations (7.5 years ± 4.8, range 4 months to 27 years). The inability to detect GCH1 mutations in apparently typical phenotypes was also reported in the papers of Hagenah et al. (2005) and Zirn et al. (2008) and is still unexplained. Several hypotheses could account for this observation, such as undetected mutations in GCH1 promotor or regulatory regions leading to a decreased expression of the gene. For these patients the hypothesis of juvenile Parkinson’s disease not caused by PARK2 may also be considered.

The value of measuring pterins and neurotransmitters levels in the CSF was not systematically assessed in this study focused on genetic aspects of DRD. However, these dosages help to guide molecular analyses of TH and SPR genes in DRD-plus syndromes. Finally, CSF study could be crucial for DRD patients without mutations to formally discriminate between those with neurotransmitters or pterins deficiencies.

In conclusion, patients with isolated DRD and with a good and sustained response to low doses of L-Dopa should be tested, firstly for point mutations, then for large deletions in GCH1 or in SPR in those with DRD-plus syndromes, particularly when onset occurs during the first year of life and before the age of 10. Ideally, the genetic testing should be guided by biochemical analysis of the CSF. Our study also suggests that molecular analyses of other genes involved in hyperphenylalaninemia are likely to be negative. DRD presentation of juvenile parkinsonism should be carefully ruled out by testing patients for PARK2 mutations and by performing 123I-FP-CIT SPECT or [18F]dopa PET scans. Interestingly, the yield of genetic analyses exceeds 4/5 in patients with pure DRD or DRD-plus syndromes, but the genes involved are clearly different in the two groups: GCH1 in pure DRD and TH or SPR in DRD-plus syndromes.

Acknowledgements

We are grateful for the contribution of the patients and their relatives. We wish to thank the clinicians who referred patients to us (Drs Yves Agid, Richard Baronnet, Patrick Berquin, Eric Bieth, Thierry Billette de Villemeur, Emmanuel Broussole, Pierre Burbaud, Patrick Calvas, Jean-Paul Carrière, Christian Confavreux, Pierre Crost, Karin Dahan, Valérie Drouin Garraud, Franck Durif, Bernard Echenne, Laurence Faivre, Annaik Feve, Pierre Genton, Philippe Goas, Lucie Guyant-Marechal, Didier Hannequin, Bertrand Isidor, Pierre Jedynak, Philippe Jonveaux, Alain Laguery, Caroline Moreau, Jacques Motte, Sylvie Odent, Frédéric Sedel, Marion Simonetta-Moreau, Clémence Simonin, Mohnsh Suri, Van Gaever, François Viallet, Jean-Sébastien Vital, Catherine Vincent-Delorme, Isabelle Vuillaume and Sandra Vukusic). We thank Dr Merle Ruberg for her helpful suggestions on the article (INSERM U679), Ms Lydia Guennec, Isabelle Lagroua and Christelle Dussert (DNA and cell bank of IFR70) for their technical assistance.

Funding

INSERM, Réseau National des Dystonies and GIS-Maladies Rares.

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