Review

Progress in the pathogenesis and genetics of Parkinson’s disease


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Recent progresses in the pathogenesis of sporadic Parkinson’s disease (PD) and genetics of familial PD are reviewed. There are common molecular events between sporadic and familial PD, particularly between sporadic PD and PARK1-linked PD due to α-synuclein (SNCA) mutations. In sporadic form, interaction of genetic predisposition and environmental factors is probably a primary event inducing mitochondrial dysfunction and oxidative damage resulting in oligomer and aggregate formations of α-synuclein. In PARK1-linked PD, mutant α-synuclein proteins initiate the disease process as they have increased tendency for self-aggregation. As highly phosphorylated aggregated proteins are deposited in nigral neurons in PD, dysfunctions of proteolytic systems, i.e. the ubiquitin–proteasome system and autophagy–lysosomal pathway, seem to be contributing to the final neurodegenerative process. Studies on the molecular mechanisms of nigral neuronal death in familial forms of PD will contribute further on the understanding of the pathogenesis of sporadic PD.

Keywords: Parkinson’s disease; familial Parkinson’s disease; pathogenesis; genetics

1. INTRODUCTION

Clinical features of Parkinson’s disease (PD) were first described by Parkinson (1817). He reported six patients in his monograph published in 1817 and described most of the typical clinical features such as bradykinesia, rest tremor, postural instability, stooped posture and micrographia. He did not describe rigidity, which was described by Charcot (1888); he proposed to call this disease as PD. In this review, we will focus on the recent progress in the pathogenesis of neuronal death in sporadic as well as familial PD.

2. CLINICAL FEATURES OF PD

Clinical features of PD include bradykinesia, rest tremor, rigidity and postural instability. In addition to these four cardinal symptoms, loss of automatic movements such as loss of arm swing, loss of blinking, reptile stare, masked face and difficulty in two simultaneous motor acts comprise motor features of PD. Furthermore, many non-motor symptoms frequently appear in PD, such as cognitive impairment, hallucination, delusion, behavioural abnormalities, depression, disturbances of sleep and wakefulness, loss of smell, pain, and autonomic dysfunctions such as constipation, hypotension, urinary frequency, impotence and sweating. Definition of PD has been proposed in various ways. For the research purpose, British Brain Bank criteria (Hughes et al. 1992) are frequently used, which define PD as those patients who have bradykinesia and at least one of the remaining four cardinal symptoms. Also, other causes of Parkinsonism have to be excluded by appropriate tests and/or clinical observation.

3. NEUROPATHOLOGY OF PD

The most characteristic features of neuropathology are loss of pigmented neurons in the substantia nigra (SN; Tretiakoff 1919) and the presence of eosinophilic cytoplasmic inclusion bodies (Lewy bodies); Lewy (1912) discovered these inclusions in the substantia innominata. Lewy bodies are usually absent in autosomal recessive young onset Parkinsonism due to parkin mutations (Takahashi et al. 1994; Mori et al. 1998). Also, in PARK8-linked PD, Lewy bodies may or may not be present (Wszolek et al. 2004).

Neuronal loss and Lewy body formation are seen not only in SN but also in locus coeruleus, pedunculopontine nucleus, raphe nucleus, dorsal motor nucleus of the vagal nerve, olfactory bulb, parasympathetic as well as sympathetic post-ganglionic neurons, Meynert nucleus, amygdaloid nucleus and cerebral cortices. These lesions are responsible for non-motor symptoms of PD. Braak et al. (2003) proposed a hypothesis that in PD and PD with dementia (PDD), Lewy bodies were first formed in the dorsal motor nucleus and the olfactory bulb and slowly involved higher structures along the brain stem, diencephalon and the cerebral cortex.
4. NEUROTOXIN-BASED MODELS OF PD

The following substances have been used in producing animal models of PD, i.e. 6-hydroxydopamine (6-OHDA), 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP), mitochondrial complex I-inhibitors such as rotenone, and α-synuclein overexpression. Systemic administration of MPTP produces selective degeneration of the dopaminergic neurons in SN in both humans and animals (Davis et al. 1979; Burns et al. 1983; Langston et al. 1983). We were interested in how MPTP killed nigral neurons. MPTP is oxidized by glial monoamine oxidase B to 1-methyl-4-phenylpyridinium (MPP⁺), which kills nigral neurons (Chiba et al. 1985; Javitch et al. 1987). We noted structural similarity between MPP⁺ and NAD⁺, which is an important cofactor of respiratory enzymes. We thought that MPP⁺ might inhibit the activities of mitochondrial NAD⁺-linked respiratory enzymes. Two groups reported inhibition of complex I by MPP⁺ (Nicklas et al. 1985; Ramsay et al. 1986). We independently made the same observation (Mizuno et al. 1987a). Furthermore, we found inhibition of the α-ketoglutarate dehydrogenase complex of the mitochondrial tricarboxylic acid cycle by MPP⁺ (Mizuno et al. 1987b). This enzyme synthesizes succinate from α-ketoglutarate; succinate is an electron donor for complex II of the electron transport chain. Thus dual inhibition of the activities of complexes I and II would impair deleteriously the electron transport and ATP synthesis. Inhibition of the electron transport induces oxidative damage by increasing the formation of reactive oxygen species.

5. AETIOLOGY AND PATHOGENESIS OF PD

We thought that mitochondrial function might be impaired in PD. Schapira et al. (1989) reported decreased activity of complex I in SN of PD. We found a decrease in complex I proteins by immunoblotting (Mizuno et al. 1989) and by immunohistochemistry (Hattori et al. 1991). We also found a decrease in the amount of α-ketoglutarate dehydrogenase complex in SN of PD by immunohistochemistry (Mizuno et al. 1994). Thus biochemical changes in PD were essentially similar to those of the MPTP-induced Parkinsonism.

Oxidative damage is also an important factor for nigral neuronal death; increase in iron (Youdim et al. 1989), increase in lipid peroxides (Dexter et al. 1989), decrease in glutathione (Sofic et al. 1992), increase in hydroxynonenal-modified proteins (Yoritaka et al. 1996) and increase in 8-hydroxy-deoxy guanine (Shimura-Miura et al. 1999) were reported in SN of PD. Reactive oxygen species impair mitochondrial proteins, further aggravating mitochondrial function. Ultimate outcomes are the dissipation of mitochondrial membrane potential and the release of cytochrome c into cytoplasm activating the apoptotic cascade. Apoptotic nigral neuronal death has been postulated in PD (Mochizuki et al. 1996; Anglade et al. 1997). The interaction of genetic predisposition and environmental factors is believed to trigger mitochondrial dysfunction and oxidative damage in sporadic PD. Additional aetiological as well as pathogenetic factors are summarized in figure 1.

6. DYSFUNCTION OF PROTEIN DEGRADATION IN PD

In recent years, dysfunction of protein degradation has emerged as an important contributor to nigral neuronal death in PD. Impaired protein degradation is likely to follow mitochondrial dysfunction and oxidative damage. In the presence of oxidative stress or mutated proteins, the folding process of proteins may be impaired resulting in an increase in misfolded proteins. Misfolded proteins are generally cytotoxic and have to be removed by protein degrading systems. In eukaryotic cells, the ubiquitin–proteasome system and the autophagy–lysosomal pathway are two major protein degradation systems. The ubiquitin system consists of three enzymes, i.e. the ubiquitin-activating enzyme (E1), the ubiquitin-conjugating enzyme (E2) and the ubiquitin-protein ligase; these enzymes work...
together to transfer ubiquitin molecules to target proteins that have to be metabolized by the 26S proteasome, which is an ATP-dependent proteolytic enzyme (Tanaka et al. 2004). Proteins with four or more than four ubiquitin molecules attached to lysine 48 residue of ubiquitin are recognized by the 26S proteasome. The 26S proteasome predominantly degrades short-lived nuclear and cytosolic proteins and misfolded proteins in the endoplasmic reticulum (Rubinsztein 2006).

The autophagy–lysosome pathway is able to degrade oligomers and aggregates of proteins as well as intracellular organelles (Yorimitsu & Klionsky 2005). In this pathway, double membrane-bound autophagosomes are generated by the elongation of small membranous structures, which encircle proteins to be digested. Then the autophagosome fuses with the lysosome to form the autophagosomes–lysosome. Then acidic hydrolases within the lysosome digest proteins that were incorporated into autophagosomes (Rubinsztein 2006).

What evidence do we have to suggest the dysfunction of protein degradation in PD? First of all, presence of Lewy bodies is strong evidence of impaired protein degradation. Lewy bodies consist of aggregated proteins and α-synuclein is the major component (Spillantini et al. 1997). Further interestingly, missense mutations of the α-synuclein gene (SNCA) cause autosomal dominant familial PD (Polymeropoulos et al. 1987; Krueger et al. 1998; Zarranz et al. 2004). α-Synuclein is a neuron-specific protein expressed predominantly in presynaptic membranes and the nucleus (Maroteaux et al. 1988). It is natively unfolded without a significant amount of secondary structure consisting of 140 amino acids (Weinreb et al. 1996).

Thus the aggregation of α-synuclein emerged as one of the most important processes in nigral degeneration in PD. The mutant α-synuclein has increased tendency for self-aggregation (El Agnaf et al. 1998). α-Synuclein is mainly located in the lipid raft in membranes (Fortin et al. 2004; Kubo et al. 2005) and this localization appears to be important in the trafficking of α-synuclein and its final localization in presynaptic and synaptic vesicular membranes.

α-Synuclein is degraded by both autophagy and the proteasome; however, mutant forms of α-synuclein and oligomers are dependent on the autophagy–lysosome pathway for their clearance (Webb et al. 2003). Wild-type α-synuclein is translocated into lysosomes for degradation by the chaperone-mediated autophagy pathway; however, mutant A53T and A30P proteins can bind to the chaperon-mediated autophagy-pathway receptor on the lysosomal membrane, but act as uptake blockers inhibiting their own degradation and that of other proteins (Cuervo et al. 2004). In sporadic PD, dysfunctions of both ubiquitin–proteasome and autophagy–lysosome systems appear to be present. As 26S proteasome is an ATP-dependent enzyme, dysfunction of mitochondria will compromise its function. Furthermore, oxidative stress enhances oligomer formation of α-synuclein. Thus formed oligomers impair membrane structures (Volles & Lansbury 2002) such as synaptic vesicles and mitochondria, and further increase oxidative stress and mitochondrial dysfunction. In this way, vicious cycles will be formed within nigral neurons leading to neuronal death (figure 2). Decrease in the 26S proteasomal activity was reported in PD (McNaught et al. 2003).

We have only indirect evidence of lysosomal dysfunction in PD. Activation of lysosomal functions...
were reported by treating cell lines with Parkinsonism-
inducing neurotoxins, such as overexpression of mutant α-synuclein (Stefanis et al. 2001), or protease-
ominal inhibitors (Ding et al. 2003; Rideout et al. 2004).
Other indirect evidence came from studies on the
association of Gaucher disease and PD. Gaucher
disease is an autosomal recessive lysosomal lipid
storage disease caused by mutations of a lysosomal
enzyme, glucocerebrosidase β-glucosidase. Gaucher
disease and its carrier state appear to be risk factors
for PD (Tayebi et al. 2003; Ahron-Peretz et al. 2004;
Goker-Alpan et al. 2004, 2006; Lwin et al. 2004; Sato
et al. 2005; Kono 2007). Furthermore, the recently
identified ATP13A2, the disease gene for PARK9-
linked PD (Kufor-Rakeb syndrome), encodes a lysoso-
mal membrane protein (Ramirez et al. 2006). These two
observations indicate the importance of lysosomal
function for the maintenance of nigral neurons.

7. PROGRESS IN FAMILIAR PD
Thirteen chromosome loci have been identified to be
linked to familial forms of PD (table 1). As PARK1 and
PARK4 represent the same locus, the number of the
familial forms is 12.

(a) PARK1- and PARK4-linked PD
PARK1- and PARK4-linked PD is an autosomal dominant
one caused by mutations of the α-synuclein gene (SNCA); PARK1 is caused by missense mutations
and PARK4 by multiplications of SNCA. Three
missense mutations, i.e. A53T (Polymeropoulos et al. 1997), A30P (Krüger et al. 1998) and E46K
(Zarranz et al. 2004), duplications (Chartier-Harlin et al.
2004; Ibanez et al. 2004; NishioKA et al. 2006; Fuchs et al.
2007) and triplications (Singleton et al. 2003; Farrer
et al. 2004) of SNCA are known. Missense mutations are
very rare; A53T is limited to families with Greece origin;
only one German family with A30P mutation and one
Spanish family with E46K mutation are known. Mul-
tiplications of SNCA appear to be more common.
Singleton et al. (2003) reported triplication of SNCA
in a large kindred (Iowanian family). The triplication
involved the 1.5 Mb region; exons of the adjacent genes
on both side of SNCA were also triplicated. The
amount of protein expressed would be doubled. Dupli-
cations of SNCA (Chartier-Harlin et al. 2004; Ibanez et al.
2004; NishioKA et al. 2006) were also reported. In the recently reported Swedish–American
family (Fuchs et al. 2007), patients in the Swedish
branch had duplication and those in the American
branch (Farrer et al. 2004) had triplication. They
suggested unequal recombination and unequal crossing
over as the potential mechanisms for duplication and
triplication, respectively (Fuchs et al. 2007).

There is a clinicogenic correlation. E46K
mutation and triplications are associated with Parkin-
sinsonism and dementia, and the age of onset is younger
than the other mutations; neuropathological changes
are those of diffuse Lewy body disease. A30P mutation
is usually not associated with dementia. Duplication
usually does not cause dementia but it can happen
(NishioKA et al. 2006; Fuchs et al. 2007). A53T
mutation may cause dementia and cortical Lewy bodies
are reported (Golbe et al. 1990).

Regarding the pathogenesis of PARK1-linked PD,
increased tendency for oligomer and aggregate for-
mations of mutant α-synuclein is likely to be the cause
(El Agnaf et al. 1998; Fredenburg et al. 2007). In
duplication and triplication, increased amount of normal
α-synuclein is probably predisposing nigral
neurons for oligomer and aggregate formations.
Recently, two groups independently reported that
SNCA polymorphic mutations are significant risk
factors for sporadic PD (Mueller et al. 2005; Mizuta
et al. 2006); some of those polymorphic mutations were
associated with increased α-synuclein expression. Thus
the molecular mechanism of nigral degeneration is
similar between SNCA-mutated and sporadic PDs.

Regarding the toxicity of oligomers, Volles &
Lansbury (2002) reported that protobrillar Ala30Pro
and Ala53Thr had greater permeabilizing activities per
mole than the wild-type protein. The leakage of
vesicular contents induced by protofibrillar
α-synuclein (Stefanis et al. 2004) and E46K
mutation may cause dementia and cortical Lewy bodies
are reported (Golbe et al. 1990).

(b) PARK2-linked PD
PARK2-linked PD is an autosomal recessive young onset
PD. Clinical features were first described by Yamamura
et al. in 1973. The usual age of onset is between 20
and 40, but it can be before 10 years and above 60 years.
When the age of onset is young, dystonic features and
sleep benefits are characteristic symptoms; sleep benefit
represents temporal improvement in Parkinsonism after
a sleep or nap. They respond well to L-dopa; however,
they will soon develop motor fluctuations. Patho-
logically, SN undergoes severe neuronal loss and gliosis;
the locus coeruleus is much less severely involved.
Usually no Lewy bodies are seen (Takahashi et al.
1994; Mori et al. 1998), although rare Lewy body
positive cases were reported (Farrer et al. 2001).
We identified the disease gene as follows. While we
were doing an association study between the genetic
polymorphism of the manganese superoxide dismutase

Table 1. Familial forms of PD. (AD, autosomal dominant;
AR, autosomal recessive; LB, Lewy bodies; SP, sporadic.)

<table>
<thead>
<tr>
<th>type</th>
<th>loci</th>
<th>genes</th>
<th>Inh</th>
<th>LB</th>
</tr>
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<tbody>
<tr>
<td>PARK1</td>
<td>4q21–23</td>
<td>α-synuclein (SNCA)</td>
<td>AD</td>
<td>+</td>
</tr>
<tr>
<td>PARK2</td>
<td>6q25.20–27</td>
<td>parkin (PRKN)</td>
<td>AR</td>
<td>±</td>
</tr>
<tr>
<td>PARK3</td>
<td>2p13</td>
<td>unknown</td>
<td>AD</td>
<td>+</td>
</tr>
<tr>
<td>PARK4</td>
<td>4q21–23</td>
<td>α-synuclein (SNCA)</td>
<td>AD</td>
<td>+</td>
</tr>
<tr>
<td>PARK5</td>
<td>4p14</td>
<td>UCH-L1</td>
<td>AD</td>
<td></td>
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<tr>
<td>PARK6</td>
<td>1p35–36</td>
<td>PINK1</td>
<td>AR</td>
<td>+</td>
</tr>
<tr>
<td>PARK7</td>
<td>1p36</td>
<td>DJ-1</td>
<td>AR</td>
<td></td>
</tr>
<tr>
<td>PARK8</td>
<td>12p11.2–q13.1</td>
<td>LRRK2</td>
<td>AD</td>
<td>±</td>
</tr>
<tr>
<td>PARK9</td>
<td>1p36</td>
<td>ATP13A2</td>
<td>AR</td>
<td></td>
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<tr>
<td>PARK10</td>
<td>1p32</td>
<td>unknown</td>
<td>SP</td>
<td></td>
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<tr>
<td>PARK11</td>
<td>2q36–37</td>
<td>unknown</td>
<td>AD</td>
<td></td>
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<tr>
<td>PARK12</td>
<td>Xq21–25</td>
<td>unknown</td>
<td>SP</td>
<td></td>
</tr>
<tr>
<td>PARK13</td>
<td>2p13</td>
<td>Omi/HtrA2</td>
<td>AD?</td>
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</tr>
</tbody>
</table>
gene (sod2) and sporadic PD (Shimoda-Matsubayashi et al. 1996), we found a family that appeared to be linked to the sod2 locus, which had been mapped to the telomeric region of the long arm of chromosome 6. We did linkage analysis on 13 similar families and mapped the disease locus to the long arm of chromosome 6 near the sod2 locus (6q25.2–27; Matsumine et al. 1997).

While we were doing linkage analysis on additional families, we found a patient who showed deletion of one of the microsatellite markers (D6S305) that we were using in the linkage analysis (Matsumine et al. 1998). We thought that this microsatellite marker might be located within the disease gene. By screening the Keio BAC library (Asakawa et al. 1997) using D6S305, we cloned a cDNA consisting of 2960 base pairs, of which 1.4 Mb was 1.4 Mb, the second largest gene after dystrophin. The number of exons was 12. The gene product consisted of 462 amino acids. There were unique structures in parkin protein (figure 3). There was 30% homology to ubiquitin in the amino terminal domain and there were two RING-finger-like motifs in the carboxyl half of the protein. RING stands for rare interesting gene and RING-like structures have been found in proteins with ubiquitin-ligase activity (Lorick et al. 1999). By northern blot, parkin messengers were ubiquitously expressed including the systemic organs (Kitada et al. 1998).

Reported mutations in parkin now exceed 100 (Hattori et al. 1998; Abbas et al. 1999; Klein et al. 2000; Kann et al. 2002; Khan et al. 2003; Hedrich et al. 2004). Not only exonic deletions but also missense and nonsense mutations and multiplications of exons were reported.

We thought that parkin might be related to the ubiquitin–proteasome system (UPS); in fact the parkin protein had ubiquitin–protein ligase activity (Shimura et al. 2000). Since then many parkin-interacting proteins have been reported; the following are substrate candidates: CDCrel-1 (Zhang et al. 2000), which is believed to be negatively regulating transmitter release; glycosylated α-synuclein (Shimura et al. 2001); synphilin-1 (Chung et al. 2001), which is an α-synuclein–interacting protein; PAEL-receptor (Imai et al. 2001), which is an endoplasmic reticulum protein; p38 (Corti et al. 2003); polyglutamine (Tsai et al. 2003); α- and β-tubulins (Ren et al. 2003); cycline-E (Staropoli et al. 2003); SEPT5_v2 (Choi et al. 2003), which is also known as cell division-control protein-2; DJ-1 (Moore et al. 2005); RanBP2 (Um et al. 2006), which is a protein localized in the cytosolic filament of the nuclear core complex; and protein-1 (Ko et al. 2006). Also, parkin-regulatory proteins have been reported, i.e. CHIP (Imai et al. 2002), which is a chaperone; HSP-70 (Imai et al. 2002); Rpn10 subunit (Sakata et al. 2003); BAG5 (Kalia et al. 2004); Nrdp1/FLRF (Zhong et al. 2005); LRRK2 (Smith et al. 2005); and 14–3–3ζ (Sato et al. 2006a,b). In addition, non-lysine 48-related ubiquitylation substrates were reported. Lysine-63 polyubiquitylation is believed to be related to endocytosis, DNA repair, translation, iCB activation, DNA silencing, virus budding, protein sorting and protein trafficking (Tanaka et al. 2004). Recently, Lim et al. (2005) reported that synphilin-1 was polyubiquitylated at lysine 63 residue of ubiquitin. Other lysine sites are mono–ubiquitylated. Despite vast number of parkin-interacting proteins, there is no immunohistochemical proof of accumulation of above parkin-interacting proteins in autopsied patients.

Parkin-knockout (KO) mice do not show nigral neuronal loss or striatal dopamine deficiency (Goldberger et al. 2003; von Coelln et al. 2004; Perez & Palmiter 2005; Ko et al. 2005; Sato et al. 2006). What were reported are only subtle changes in dopaminergic functions. von Coelln et al. (2004) found some loss of neurons in the locus coeruleus and reduced startle response. Ko et al. (2005) found an increase in the amount of the aminoacyl-tRNA synthase cofactor p38 in the midbrain/hindbrain region of both young and old parkin-null mice. They postulated that p38 is a substrate of parkin as E3 ligase. They further showed that overexpression of p38 in the SN in mice lead to loss of dopaminergic neurons. They analysed the level of p38 in the cortical regions of the patients with parkin mutations by Western blotting; they found an increase in p38. We studied striatal dopamine receptors by ex

Figure 3. A schematic of the parkin gene. The coding region consists of 12 exons. In the amino terminal region, ubiquitin-like domain is indicated as ‘Ubl’, and in the carboxyl terminal side, two RING finger motives are indicated as ‘RING1’ and ‘RING2’. RING, rare interesting gene; IBR, in between RINGs.

Phil. Tran. R. Soc. B (2008)
which showed apoptotic cell death. Furthermore, they
a parkin-knockdown cell line using SH-SY5Y cells,
neuronal degeneration. That parkin was functioning in the downstream of
KO-induced damage. Furthermore, they showed
but PINK1 overexpression could not rescue parkin-
et al (2006) made
similar findings. Then Clark
neurons in these flies. Pesah
mitochondria to complex I inhibitors such as rotenone,
reduced lifespan, locomotor defects and male sterility.
Locomotor defects were due to muscle degeneration
with mitochondrial damage consisting of disruption
phila produced by Creene et al (2003) exhibited
reduced lifespan, locomotor defects and male sterility.
Locomotor defects were due to muscle degeneration
with mitochondrial damage consisting of disruption
and disintegration of the cristae. There was no
neuronal loss in the brain including dopaminergic
neurons in these flies. Pesah et al (2004) also reported
similar findings. Then Clark et al (2006a,b) and Park
Both groups reported that overexpression of parkin rescued PINK1-KO-induced muscle damage;
but PINK1 overexpression could not rescue parkin-
KO-induced damage. Furthermore, they showed
interaction of parkin and PINK1. They concluded that parkin was functioning in the downstream of
PINK1 in a common pathway to keep mitochondrial
integrity. Their flies also showed dopaminergic
neuronal degeneration.

At a cellular level, Machida et al (2005) constructed a parkin-knockdown cell line using SH-SY5Y cells,
which showed apoptotic cell death. Furthermore, they
found increase in the auto-oxidized forms of L-dopa
and dopamine (Dopa chrome+dopamine chrome),
suggesting the presence of anti-oxidative property in
parkin. We reported a profound accumulation of iron in
the SN of a -mutated patient (Takanashi et al 2001). Taken together, oxidative stress appears to be a
pathogenetic pathway common to PARK2-linked and
sporadic PDs.

(c) PARK6-linked PD
PARK6-linked PD is another form of young onset
autosomal recessive PD. The age of onset is slightly
older than that of PARK2, i.e. from 32 to 48 years
(Valente et al 2001). Therefore, dystonic features and
sleep benefit are uncommon. Affected patients show
L-dopa-responsive Parkinsonism. The disease gene
was identified as PINK1 (PTEN-induced kinase 1;
Valente et al 2004a,b). PTEN stands for phosphatase
with tensin homology. PINK1 has eight exons and cDNA
spans 1.8 kb. It encodes a protein with 581 amino
acids. The protein is ubiquitously expressed including
brain and systemic organs. Interestingly, it is a
mitochondrial protein located in the matrix and the
intermembrane space. It has a serine/threonine protein
kinase domain. However, its function is not known
(Valente et al 2004).

Many missense and nonsense mutations have been
reported (Hatano et al 2004; Healy et al 2004; Rohe
et al 2004; Valente et al 2004; Li et al 2005). In
contrast to parkin, most of the PINK1 mutations
reported are either missense or nonsense mutations,
although one family with a large deletion mutation is
known (Li et al 2005); this deletion involved exons 6–8
homozgyously.

Regarding the molecular mechanisms of nigral
neuronal death, as PINK1 has a protein kinase domain as
LRRK2 has, dysfunction in some phosphorylation
reactions may be important in the pathogenesis. PINK1
is inducible by PTEN and PTEN is an oncogene mutated
in many neoplastic cells (Li et al 1997). As oncogenesis
and degeneration are the opposite sides of eukaryotic cell
fate, elucidation of the function of PINK1 in relation to
PTEN is an interesting topic.

(d) Do heterozygotes for parkin or PINK1
mutations develop PD?
In autosomal recessive diseases, usually both alleles
should have a mutation to show the disease. But in cases of PINK1 (Valente et al 2004; Bonifati et al
2005; Fung et al 2006; Criscuolo et al 2006; Toft et al
2007) as well as parkin mutations (Hedrich et al 2002;
Khan et al 2002; West et al 2002; Oliviera et al 2003;
Clark et al 2006a,b; Schlieter et al 2006), at times only
one mutation can be found (heterozygote). The question is, how do they get the disease? There are
several possibilities. First of all, the second mutation
may be localized in a place that is difficult to find by
the currently available methods. The second possibility is the
haploinsufficiency (West et al 2002); here the
amount of normal gene product is not sufficient to keep
nigral neurons alive. But usually in autosomal recessive
diseases, only one normal gene is sufficient to prevent
the disease; parents (usually carriers) of a patient are
normal in most of the cases. The third possibility is the
interaction at the protein level; the mutated protein
might interfere with the functions of normal protein
(dominant-negative effect); but this possibility has not
been proved. Finally, single heterozygous state might
be acting as a risk factor for sporadic PD (Schlieter et al
2006). Another interesting observation in parkin
heterozygotes was made by Oliviera et al (2003) who
reported that mutations in the first RING finger
domain tended to be heterozygotic and associated
with later age of onset.

(e) PARK7-linked PD
PARK7-linked PD is another young onset PD. Clinical features are very similar to those of PARK2-linked PD
(Duijin et al 2001); the age of onset is usually 20–40
years. Some atypical features such as psychiatric
symptoms (anxiety attacks; Dekker et al 2003), and
short stature and brachydactyly (Dekker et al 2004)
have been reported. The disease gene was identified as
DJ-1 (Bonifati et al 2003), which had been cloned by
Nagakubo et al (1997). The size of DJ-1 is 24 kb with
eight exons encoding a protein consisting of 189 amino
acids. PARK7-linked PD is very rare (Bonifati et al

The function of DJ-1 protein is not well known. The
active form of DJ-1 is a dimer of monomeric DJ-1. DJ-1
is a cytoplasmic protein; however, it can translocate
into the mitochondria. It has a strong anti-oxidative
property (Nagakubo et al 1997; Abou-Sleiman et al.

Phil. Trans. R. Soc. B (2008)
2003; Canet-Aviles et al. 2004; Moore et al. 2005) that depends on its cysteine residue at 106, which undergoes oxidation to form a disulphide bond (Canet-Aviles et al. 2004). Downregulation of endogenous DJ-1 protein of the neuronal cell line by siRNA was reported to enhance the cell death induced by oxidative stress, ER stress and proteasome inhibition, but not by pro-apoptotic stimulus (Yokota et al. 2003). The Leu166-Pro mutant DJ-1 protein has a reduced anti-oxidative activity (Takahashi-Niki et al. 2004). DJ-1 protein expression is increased upon oxidative stress induced by paraquat (Mitsumoto et al. 2001). As nigral neurons are exposed to high oxidative stress owing to the presence of dopamine, DJ-1 may be acting as a strong anti-oxidative protein. As mutant DJ-1 was reported to depend on its cysteine residue at 106, which under-}

**Phil. Trans. R. Soc. B**

(2008)

**Review. Pathogenesis and genetics of PD**

Y. Mizuno et al.

2221

(2007); some of the mutant LRRK2 have increased kinase activity (Gloeckner et al. 2006). Other functional domains are believed to be important in protein–protein interactions (Zimprich et al. 2004). LRRK2 also interacts with other familial PD proteins; Smith et al. (2005) reported interaction of LRRK2 with parkin through the ROC domain; however, the interaction with parkin did not enhance polyubiquity-

**Recently, Hatano et al. (2007) made a detailed observation on the intracellular distribution of LRRK2. It was found to be present in Golgi apparatus, plasma membrane, synaptic vesicles and particularly in the lipid rafts; presence in the lipid rafts suggests that LRRK2 is probably involved in signal transduction, membrane trafficking and cytoskeletal organization (Brawn & London 1998). Biskup et al. (2006) also reported the presence of LRRK2 in membrane structures, such as lysosomes, endosomes, transport vesicles and mitochondria. In this regard it is interesting to note that α-synuclein is also expressed in the presynaptic membranes and lipid rafts (Fortin et al. 2004; Kubo et al. 2005).**

**FAPK5-linked PD**

PARK8-linked PD is an autosomal recessive PD linked to the centromeric region of chromosome 12 (Funayama et al. 2002). Clinical features were described back in 1978 on a large Japanese family (Nukada et al. 1978); clinical features are essentially similar to those of sporadic PD, except for slightly earlier onset of age. Dementia is not a common feature but it is known to occur (Wszolek et al. 1997).

The disease gene was identified as lrrk2 (Paisan-Ruiz et al. 2004; Zimprich et al. 2004); lrrk2 is a huge gene encompassing 144 kb, consisting of 7449 bp and encoding a protein consisting of 2517 amino acids, and has 51 exons. The carboxyl half of the LRRK2 contains several functional domains such as ANK (ankyrin-repeat domain), LRR (leucine-repeat-rich), ROC (Ras of complex proteins), COR (carboxy terminal of ROC), MAPKKK (mitogen activated protein kinase kinase kinase) and WD domain that is rich in tryptophan and aspartate repeats. Pathogenetic mutations are concentrated in these functional domains.

**PARK5-linked PD** is now believed to be the most common form of autosomal dominant familial PD and 20 missense or nonsense mutations have been reported (Paisan-Ruiz et al. 2004; Zimprich et al. 2004; Aasy et al. 2005; Di Fonzo et al. 2005; Funayama et al. 2005; Hernandez et al. 2005; Kachergus et al. 2005; Nichols et al. 2005; Paisan-Ruiz et al. 2005; Mata et al. 2006). lrrk2 Mutations were also found in some of the apparently sporadic PD patients (Gilks et al. 2005). One of the polymorphic mutations, G2385R, is a genetic risk factor for sporadic PD in Asian populations (Di Fonzo et al. 2006; Funayama et al. 2007; Tan et al. 2007).

Four different neuropathologies were reported within the same family (Wszolek et al. 2004); one of their patients showed brain stem-type Lewy body disease, the second showed diffuse-type Lewy body disease, the third accumulation of tau in the remaining nigral neurons and the last simple nigral atrophy. This observation tells us the difficulty of defining a disease by neuronal inclusions.

Function of LRRK2 is not well known. The ROC domain is able to bind GTP but it does not have GTPase activity, but GTP binding is essential for the MAPKKK domain to exert kinase activity (Ito et al. 2007); some of the mutant LRRK2 have increased kinase activity (Gloeckner et al. 2006). Other functional domains are believed to be important in protein–protein interactions (Zimprich et al. 2004). LRRK2 also interacts with other familial PD proteins; Smith et al. (2005) reported interaction of LRRK2 with parkin through the ROC domain; however, the interaction with parkin did not enhance polyubiquity-
was found in the affected members. Deletion of exons 7 and 8 in mouse UCH-L1 causes gracile axonal dystrophy (gad mouse); this is an autosomal recessive condition characterized by axonal degeneration and formation of spheroid bodies in motor and sensory nerve terminals (Saigho et al. 1999).

UCH-L1 is an enzyme that cleaves carboxy-terminal peptide bond of polyubiquitine chains. Thus UCH-L1 is an ubiquitin-recycling enzyme. UCH-L1 is a neuron-specific enzyme. Catalytic activity of Ile93Met-mutated UCH-L1 was reported to be half of the wild enzyme (Leroy et al. 1998). Thus the supply of ubiquitin for 26S proteasome may be reduced with this mutation.

PARK10 was found by genome-wide scanning. Hicks et al. (2002) studied 51 Icelandic families with more than one PD patient; they analysed 117 patients and 168 of their unaffected relatives using 781 microsatellite markers. Allele-sharing, model-independent analysis of their results showed linkage to a region on chromosome 1p32 with a LOD score of 4.9. They designate this region PARK10. The disease gene has not been identified yet. Clinical features are essentially similar to those of sporadic PD and the mean age of onset was 65.8 years.

PARK11 was also found by genome-wide scanning; Pankratz et al. (2003a,b) screened 85 families with a very strong family history of PD and found an evidence of linkage to the long arm of chromosome 2 (LOD = 4.9). Clinical features are essentially similar to those of sporadic PD with the mean age of onset at 58 years.

PARK12 was also found by genome-wide scanning on sporadic PD; Pankratz et al. (2003a,b) screened 277 families without a strong family history of PD and detected linkage to the long arm of chromosome X (LOD = 3.2).

PARK13-linked PD was reported to have a mutation (G399S) in Omi/HtrA2 (Strauss et al. 2005); they found G399S mutation in four German sporadic PD patients. They also identified a novel A141S polymorphism that was associated with PD (p < 0.05). Both mutations resulted in defective activation of the protease activity of Omi/HtrA2. Further studies are necessary before concluding that this is a new familial PD-inducing protein. A cDNA of Htra2 was first isolated by Faccio et al. (2000); it encoded a protein (Omi) consisting of 458 amino acids and had homology to bacterial HtrA endoprotease and had a PDZ domain. Omi mRNA was expressed ubiquitously, and the gene was localized on human chromosome 2p12 near the PARK3 locus; however, PARK3-linked PD patients did not have this mutation. Omi/HtrA2 is a nucleary encoded mitochondrial protein localized in the intermembrane space. Further interestingly, it has a serine protease domain and it binds to apoptosis-inhibiting protein upon release into the cytoplasm (Suzuki et al. 2001). G399S mutant Omi/HtrA2 induces mitochondrial dysfunction associated with altered mitochondrial morphology and cells over-expressing G399S mutant Omi/HtrA2 are more susceptible to stress-induced cell death than wild-type (Strauss et al. 2005).

Finally, there are many families in which linkage analysis failed to show linkage to any one of the known loci that are associated with familial PD. By elucidating the functions of familial PD proteins, pathogenesis of sporadic PD will be better understood.

This study was in part supported by the grant for research on diseases of the brain from Ministry of Education, Science and Sports in Japan.

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