Defective Fas expression exacerbates neurotoxicity in a model of Parkinson’s disease

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In PD patients, membrane-bound Fas and Fas ligand (FasL) expression are reduced in the SN (7). Concomitantly, soluble Fas, which acts as a decoy receptor and blocks the binding of FasL to Fas, is elevated in PD (8, 9). Thus, Fas signaling in PD patients may be diminished by reduced cell surface Fas expression and by the presence of soluble Fas. Apoptosis is believed to be a factor in the neurodegeneration of PD (10), but in vitro models indicate that caspase-8, the upstream caspase activated during Fas-mediated apoptosis, is not involved, suggesting that Fas may not be the principal death effector in PD neurodegeneration (11).
We used mice bearing mutations in the Fas/FasL system to determine directly the role of Fas signaling in the MPTP model of PD. We demonstrate here that reduced Fas expression dramatically increases neuronal susceptibility to MPTP toxicity in vivo, strongly supporting a neuroprotective role for Fas.

RESULTS AND DISCUSSION
Fas deficiency results in markedly increased susceptibility to MPTP–induced dopaminergic neuron degeneration
We compared the MPTP susceptibility of WT C57BL/6 (B6), Fas–deficient lymphoproliferative (lpr), and FasL–mutated generalized lymphoproliferative (gld) mice that share the B6 genetic background. Lpr mice express low to absent cell surface Fas because of the insertion of a transposable element within a Fas intron (12). Gld mice have a point mutation in the extracellular domain of FasL that decreases the affinity of the Fas/FasL interaction, resulting in reduced signaling through Fas (13, 14). We treated mice with a subacute toxicity regimen of MPTP consisting of an injection of 25 mg/kg/d for 5 consecutive d and quantified tyrosine hydroxylase positive (TH⁺) neurons as a marker for dopaminergic neurons in the midbrain (SN and ventral tegmental area, VTA) 4 d after the final injection of MPTP. Consistent with previous findings (15), WT mice treated with this subacute regimen of MPTP exhibited only a marginal, nonsignificant loss of midbrain dopaminergic neurons at this time point (Fig. 1, A–C). In contrast, we observed a dramatic loss of dopaminergic neurons in Fas–deficient mice. We found that the SN and VTA of MPTP-treated lpr mice showed a 58% (P < 0.001) and 40% (P < 0.05) loss of dopaminergic neurons, respectively, compared with saline-treated lpr mice. MPTP-treated gld mice lost 26% (P < 0.05) of the dopaminergic neurons in the SN compared with saline-treated gld mice (Fig. 1, A–C). The pretreatment number of TH⁺ neurons was not significantly different in lpr, gld, and WT midbrains (Fig. 1, B–C). The depletion of neuron cell bodies in the SN of MPTP–treated lpr mice was confirmed in cresyl violet–stained sections (unpublished data). We also observed a striking decrease in dopaminergic innervation to the striatum in MPTP–treated lpr mice and to a lesser extent in gld mice (Fig. 1 D). In fact, the loss of terminals in the caudate putamen of the striatum and the sparing of the olfactory tubercle and nucleus accumbens in MPTP–treated lpr mice resembles the pattern of terminal loss seen in the striatum of PD patients. The increased susceptibility of lpr mice to MPTP occurs despite lower levels of MPP⁺ accumulation in the striatum than WT B6 mice, as determined by HPLC 4 h after the third dose of MPTP (B6: 3.29 ± 0.15 µg/g tissue; lpr: 2.29 ± 0.12 µg/g tissue; gld: 2.13 ± 0.37 µg/g tissue). Increased neurodegeneration in the presence of decreased levels of bioavailable MPP⁺ further emphasizes the enhanced sensitivity to neurodegeneration in the absence of Fas. Thus, Fas–deficient lpr mice treated with MPTP display a dramatic degeneration of the nigrostriatal system. Gld mice, which have a partial Fas–signaling deficit (14), demonstrate an intermediate degree of neuronal loss.

Fas deficiency results in tremor, hypokinesia, and decreased motor coordination after MPTP treatment
WT mice did not exhibit significant spontaneous behavioral changes during or after the MPTP treatment course. In sharp contrast, we found that Fas–deficient lpr mice displayed marked hypokinesia (Fig. 2 A) and developed a tremor after the second to third dose of MPTP (Videos 1–3, available at http://www.jem.org/cgi/content/full/jem.20050163/DC1). Over four independent experiments, 78% of the lpr mice (n = 32) became immobile during the first 4 d after the initiation of MPTP treatment, although they gradually recovered spontaneous mobility (Fig. 2 B). WT mice maintained normal activity levels throughout the treatment course (Fig. 2, A and B), and gld mice displayed a behavioral...
phenotype more closely resembling that of WT mice, correlating with their less severe neuronal loss (Fig. 2 A).

Over the 5 d of MPTP treatments, the lpr mice were too impaired for assessment of coordination. 3 d after the final MPTP injection, we found no impairment in WT mice, consistent with previous work (15). However, we observed that lpr mice had impaired coordination by Rotarod testing, achieving only 39% (P < 0.05) of the score of their WT counterparts (Fig. 2 C). Gld mice seemed to be slightly impaired, but this decrease did not reach statistical significance. Thus, Fas-deficient mice became severely hypokinetic, developed tremor, and displayed decreased coordination after exposure to MPTP at a dose that causes no spontaneous behavioral deficits in WT mice.

These results suggest that Fas provides a neuroprotective signal that is missing in lpr mice and is reduced in gld mice. This putative Fas-induced neuroprotective signal is probably ligan
dependent, because gld mice, like lpr mice, displayed increased susceptibility to neuronal loss after MPTP administration, although degeneration was less extensive in gld mice than in lpr mice. The residual signal transmitted through Fas in gld mice (14) might explain the less severe degenerative and behavioral phenotype seen in gld mice as compared with lpr mice.

**Fas engagement is protective against MPTP/MPP⁺ neurotoxicity in vitro, and this neuroprotection is independent of caspase-8 activation**

To determine whether Fas engagement is directly protective against MPTP toxicity in dopaminergic neurons, we treated cultured midbrain neurons with a FasL construct to induce Fas signaling, followed by exposure to MPTP. Treatment with FasL protected primary TH⁺ neurons from MPTP toxicity (Fig. 3 A). We repeated this experiment using the Fas-positive neuroblastoma cell line SH-SY5Y to determine whether Fas-induced neuroprotection operated independently of glia. We found that administration of FasL significantly reduced MPP⁺ toxicity (Fig. 3 B). Fas-mediated protection did not occur in a Fas-negative subline of SH-SY5Y cells (Fig. 3 B). To determine whether the neuroprotective effect of Fas required caspase-8 activation, we used a specific cell permeant caspase-8 inhibitor, IETD-fmk, which effectively protects Jurkat T cells from FasL-induced apoptosis (Fig. 3 C). Unlike Fas-mediated apoptosis, Fas-mediated neuroprotection was not blocked by IETD-fmk (Fig. 3 D). Thus, Fas engagement protected dopaminergic neurons from MPTP/MPP⁺ toxicity even in the absence of glia and independently of caspase-8 activation.

**Fas-mediated neuroprotection in vivo is independent of the Fas death domain**

Our in vitro data suggested that Fas-mediated neuroprotection may be independent of the Fas death domain (DD), because the DD serves to anchor and activate caspase-8 via the adaptor protein Fas-associated DD. We tested this hypothesis in two strains of mice bearing disruptions in their Fas DD. Mice bearing an engineered disruption of the Fas DD (16) commonly are referred to as “Fas null,” because Fas-induced death is abolished in these mice. However, the mice express a truncated Fas molecule lacking exon 9, which encodes most of the DD, but retain the remainder of the intracellular Fas domains as well as Fas expression at the cell surface, unlike lpr mice, which express no detectable Fas by flow cytometry (Fig. 4 A). These Fas exon 9 KO mice are resistant to MPTP (Fig. 4 A and reference 17), in contrast to the dramatic susceptibility of lpr mice, as shown by striatal dopamine and dopamine metabolite levels. These mice show no significant differences in MPP⁺ levels (Exon 9 KO: 3.48 ± 0.34 µg/g; B6: 3.29 ± 0.15 µg/g). We propose that this difference in susceptibility between lpr and exon 9 KO mice is based on Fas expression levels (Fig. 4 A), with Fas expression being neuroprotective.

An analogous, naturally occurring point mutation, lpr.cg, causes local unfolding of the DD and likewise abolishes Fas-induced apoptosis, although lpr.cg mice express normal levels of cell surface Fas and can mediate nonapop-
totic signaling (18). The \textit{lpr.cg} mutation is available only on the CBA background; therefore, \textit{lpr.cg} mice cannot be compared directly with \textit{lpr}, Fas exon 9 KO, and \textit{gld} mice, all of which are on the B6 background. Therefore, we compared MPTP susceptibility of \textit{lpr.cg} mice with that of their WT CBA counterparts. We found no significant difference in TH$^+$ neuron loss in the SN of \textit{lpr.cg} versus WT CBA mice (Fig. 4 B); in fact, we observed a statistically significant protection in the VTA of \textit{lpr.cg} compared with CBA mice (Fig. 4 B). Behaviorally, both Fas exon 9 KO and \textit{lpr.cg} mice were resistant to MPTP administration (reference 17 and Fig. 4 B, respectively). Together, these data indicate that a functional DD is not required for Fas-mediated neuroprotection. The observation that Fas exon 9 KO (17) and \textit{lpr.cg} mice are slightly more resistant to MPTP than are WT mice suggests that Fas neuroprotective signaling in the absence of Fas apoptotic signaling may confer
lead to genetically determined PD in humans (21). Thus, Fas expressed by stressed neurons may provide protective signals via protein kinase pathways that, when disrupted, lead to increased susceptibility to PD.

**PBLs from PD patients show decreased Fas up-regulation upon activation**

Because of the extreme susceptibility to toxin-induced PD demonstrated by mice with reduced Fas expression, we investigated Fas expression in patients diagnosed having idiopathic PD. We obtained blood samples from patients who had PD and from controls who did not have PD as a simple and minimally invasive means to measure Fas expression. We found that baseline Fas expression in PBLs from patients who had PD did not differ from that in control subjects who did not have PD. However, when we stimulated the peripheral blood T cells (PBTs) with mitogen to induce Fas up-regulation, we found a highly significant deficit (P < 0.001) in the ability of PBTs from PD patients to up-regulate Fas (Fig. 5). Thus, patients who have PD show an impairment of Fas up-regulation, at least in PBTs.

Although it is possible that the medication prescribed for PD may influence Fas regulation, two of the patients included in our study were not taking any medication, and both of these individuals displayed very low levels of Fas up-regulation, similar to levels in treated patients who had PD. Furthermore, there was no correlation between level of Fas up-regulation and disease duration in our patients. Thus, it is possible that decreased ability to up-regulate Fas was a pre-existing condition in these patients. If this impairment in Fas up-regulation in T cells correlates with defective up-regulation of Fas in other tissues upon cellular stress, this impairment may confer predisposition to PD. Although the clinical data are in accordance with the results from our mouse study, it will be important to validate the clinical findings in a larger patient population.

Our studies demonstrate for the first time that a reduction in Fas expression or signaling dramatically increases neuronal susceptibility to neurodegeneration in vivo, strongly supporting a neuroprotective role for Fas, at least in some contexts. We propose that the lack of Fas in lpr mice and the decreased Fas signaling in gld mice is responsible for the increased neuronal death caused by the lack of a Fas-dependent neuroprotective signal. The striking level of dopaminergic neuron degeneration in the midbrain of MPTP-treated lpr mice, together with their profound behavioral phenotype, may provide a new model for PD research in which potential therapeutics and neuroprotective strategies can be tested. Moreover, individuals with an impaired ability to up-regulate Fas expression may be at increased risk of developing PD after exposure to environmental neurotoxins.

**MATERIALS AND METHODS**

**Mice and MPTP treatment.** We used 8–10-wk-old female B6 (Charles River Laboratories), lpr, gld, Fas exon 9 KO (“Fas null”), CBA, and lpr.cg mice (Jackson ImmunoResearch Laboratories). We administered five sub-
cutaneous injections of 25 mg/kg MPTP (Sigma-Aldrich) or saline, once per day for 5 consecutive d. Mice were used according to the protocols approved by McGill University Animal Care Committee.

**Behavioral analysis.** We performed automated activity monitoring (AM1053 system, Cambridge Neurotechnology Ltd.) over 5-min periods. We assessed Rotarod (IITC Life Science) performance as the average of three trials of 1 min each at 20 revolutions/min. Statistical analysis was by analysis of variance and Tukey test.

**Brain preparation, immunohistochemistry, and stereology.** We perfused mice, cut 50-μm coronal brain sections through the stratum and midbrain using a freezing sledge microtome (Leica), and performed immunohistochemistry with anti-TH antibody (1:2,000, Pel-Freeze Biologicals) on every third serial section (22). A second series was processed using 0.1% nohistochemistry with anti-TH antibody (1:2,000, Pel-Freez Biologicals) as described previously (22).

**Primary cultures.** We prepared and treated P2–P5 midbrain cells from B6 mice with MPTP as described (23). FasL construct (400 ng/ml, Sigma-Aldrich) was administered where indicated 30 min before MPTP. After 7 d, TH+ cells were stained with IgG-PE Zenon kit (Molecular Probes) bound to monoclonal mouse anti-TH antibody (Sigma-Aldrich).

**Neuroprotection assay.** We plated 2 x 10^6 Fas-positive SH-SY5Y neuroblastoma cells per well in phenol-red-free DMEM in 96-well plates. We pretreated the cells with FasL construct (100 ng/ml), added MPP+ at the indicated concentrations 30 min later, then incubated the cells for 3 d at 37°C/5% CO2. We assayed cell viability using WST-1 reagent (Roche Diagnostics) according to the manufacturer’s instructions. As a control, the same procedure was performed on Fas-negative SH-SY5Y cells. IETD-fmk (BD Biosciences) was used where indicated and was tested by incubating 10^5 Jurkat cells/well at 37°C for 1 h with IETD-fmk to which FasL (100 ng/ml) was added for 2.5 h. WST-1 was used to assay viability.

**HPLC.** HPLC was performed as described (24) with modifications (see supplemental Materials and methods, available at http://www.jem.org/cgi/content/full/jem.20050163/DC1). Monoamines were detected with an ESA system with 5011 analytical cells, and a Higgins Analytical HAISIL 100 C18 column (5 μm, 150 x 4.6 mm). MPP+ levels were measured using a Beckman 32 Karat System with a diode array detector (295 nm) on a Gemini C18 RP 150 x 4.6 mm analytical column (Phenomenex, Inc.).

**Patients.** We recruited patients who had idiopathic PD from five consecutive weekly Montreal Neurological Institute Movement Disorders Clinics. Diagnosis of idiopathic PD was established according to the following criteria: tremor, bradykinnesia, and rigidity (two of three), asymmetric onset, and fasting plasma noradrenaline > 350 μg/l. All patients included in this study, because we were unable to recruit enough women for statistical significance. Age-matched men with no history of PD or inflammatory disease were recruited as controls (average ages: patients with PD, 65.78 ± 6.94 yr; control subjects, 68.43 ± 15.41 yr). We obtained informed consent from all participants, and all experiments involving humans were approved by the Institutional Review Board of McGill University.

**Flow cytometry.** We stimulated mouse lymph node cells overnight with 2.5μg/ml Concanavalin A (Sigma-Aldrich) in RPMI 1640/10% FCS and then labeled the cells with PE-conjugated anti-human CD3 and PE-conjugated anti-human CD95 or PE-conjugated isotype-matched control antibodies (BD Biosciences). Human PBLs were prepared by ficoll density centrifugation from 10 ml blood. PBLs were divided into unstimulated cells and stimulated cells using Concanavalin A as described earlier. Cells were labeled with FITC-conjugated anti-human CD3 and PE-conjugated anti-human CD95 or PE-conjugated isotype-matched control antibodies (BD Biosciences). Fas up-regulation was defined as the change in mean PE fluorescence between the unstimulated and stimulated populations gated on live CD3+ cells.

**Online supplemental material.** Videos 1–3 show mice 20 h after the first and second doses of MPTP. Mice and MPTP treatment were as described in Materials and methods. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20050163/DC1.

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