Parkin is recruited selectively to impaired mitochondria and promotes their autophagy

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Introduction

Parkinson’s disease is the most common neurodegenerative movement disorder. Although most cases are sporadic, several genes have been recently linked to familial Parkinson’s disease, and loss-of-function mutations in Park2, the gene coding for the ubiquitin ligase Parkin, are a significant cause of early onset Parkinson’s disease. Although the role of Parkin in neuron maintenance is unknown, recent work has linked Parkin to the regulation of mitochondria. Its loss is associated with swollen mitochondria and muscle degeneration in Drosophila melanogaster, as well as mitochondrial dysfunction and increased susceptibility to mitochondrial toxins in other species. Here, we show that Parkin is selectively recruited to dysfunctional mitochondria with low membrane potential in mammalian cells. After recruitment, Parkin mediates the engulfment of mitochondria by autophagosomes and the selective elimination of impaired mitochondria. These results show that Parkin promotes autophagy of damaged mitochondria and implicate a failure to eliminate dysfunctional mitochondria in the pathogenesis of Parkinson’s disease.

Results and discussion

Previous studies yield conflicting conclusions on Parkin subcellular localization, finding the protein in the cytosol or associated with ER or mitochondria (Shimura et al., 1999; Darios et al., 2003; Kuroda et al., 2006). We examined the subcellular localization of endogenous Parkin in HEK293 cells, a cell line that expresses relatively high levels of Parkin, using the PRK8 monoclonal antibody (Pawlyk et al., 2003). Consistent with most studies, we found that endogenous Parkin was predominately located in the cytosol (Fig. 1, a and c). However, in some of the cells, colocalization was observed between Parkin and a subset of the mitochondria, which were small and fragmented (Fig. 1 a).

Mitochondrial fission has been recently linked to the function of Parkin (Deng et al., 2008; Poole et al., 2008; Yang et al., 2008) and to the autophagy of small defective mitochondria that lack membrane potential (Elmore et al., 2001; Tolkovsky et al., 2002; Twig et al., 2008). To test whether mitochondrial depolarization causes Parkin accumulation on mitochondria, we treated HEK293 cells with the mitochondrial uncoupler carbonyl cyanide m-chlorophenylhydrazone (CCCP). Within 1 h of adding CCCP, endogenous Parkin was recruited to mitochondria in the majority of cells (Fig. 1 b) and increased appearance in the heavy membrane pellet on Western blots (Fig. 1 c). Although rat cortical neuron cultures displayed more Parkin in the membrane pellet

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Abbreviations used in this paper: au, arbitrary units; CCCP, carbonyl cyanide m-chlorophenylhydrazone; Drp1, dynamin-related protein 1; FISH, fluorescence loss in photobleaching; Mfn, mitofusin; MEF, mouse embryonic fibroblast; ROI, region of interest; vMIA, viral mitochondrial-associated inhibitor of apoptosis; WT, wild type.

The online version of this article contains supplemental material.
decreases ATP consumption by mitochondrial uncouplers; 78.49 ± 2.61% [mean ± SD] with CCCP alone vs. 77.35 ± 7.64% with CCCP + oligomycin; Fig. 1, e and f). Western blots also show that YFP-Parkin redistributes from the cytosol to the heavy membrane pellet upon CCCP treatment (Fig. 1 g). Additionally, YFP-Parkin was recruited to depolarized mitochondria damaged by the pesticide paraquat, which is thought to increase complex I–dependent reactive oxygen species and has been linked to Parkinsonism (Figs. 1 h, S1, and S2, available at http://www.jcb.org/cgi/content/full/jcb.200809125/DC1; Brooks et al., 1999; Cocheme and Murphy, 2008). CCCP-induced recruitment was than did HEK293 cells, uncoupling of mitochondria with CCCP increased levels in the membrane pellet (Fig. 1 d). YFP-Parkin expressed in HeLa cells, which have little or no endogenous Parkin expression (Denison et al., 2003; Pawlyk et al., 2003), displayed a cytosolic distribution in >99% of cells. As with endogenous Parkin in HEK293 cells, CCCP exposure induced the redistribution of YFP-Parkin from the cytosol to the mitochondria (Fig. 1, e and f; and Video 1, available at http://www.jcb.org/cgi/content/full/jcb.200809125/DC1). This CCCP-induced accumulation of Parkin on mitochondria was not inhibited by the addition of the ATP synthase inhibitor oligomycin (which decreases ATP consumption by mitochondrial uncouplers; 78.49 ± 2.61% [mean ± SD] with CCCP alone vs. 77.35 ± 7.64% with CCCP + oligomycin; Fig. 1, e and f). Western blots also show that YFP-Parkin redistributes from the cytosol to the heavy membrane pellet upon CCCP treatment (Fig. 1 g). Additionally, YFP-Parkin was recruited to depolarized mitochondria damaged by the pesticide paraquat, which is thought to increase complex I–dependent reactive oxygen species and has been linked to Parkinsonism (Figs. 1 h, S1, and S2, available at http://www.jcb.org/cgi/content/full/jcb.200809125/DC1; Brooks et al., 1999; Cocheme and Murphy, 2008). CCCP-induced recruitment was
Figure 2. **FLIP analysis of Parkin diffusibility and selectivity of Parkin accumulation.** (a–c) FLIP analysis with quantification after treatment with DMSO (a, top, and b) or CCCP (a, bottom, and c; n ≥ 3 in each treatment). Rectangles in panel a indicate the bleach ROI. Outlines demarcate the edges of cells expressing YFP-Parkin. (d) YFP localization in WT and Mfn1−/−, Mfn2−/− double knockout MEF cells expressing YFP-Parkin. (e) YFP-Parkin scored for colocalization as in Fig. 1f. Error bars indicate standard deviation of at least three replicates. (f) Mfn1−/−, Mfn2−/− double knockout MEF cells transfected with YFP-Parkin (green) and pulsed with the potentiometric dye MitoTracker (blue in merge) 15 min before fixation. Cells were immunostained for cytochrome c (red). A line scan of fluorescence through two Parkin-positive mitochondria depicts colocalization between Parkin, MitoTracker, and cytochrome c. The right four panels show an enlarged view of the boxed area. Arrows indicate mitochondria (identified by anti-cytochrome c) that were depolarized (as assessed by their failure to take up the dye MitoTracker; arrowheads represent mitochondria (identified by anti-cytochrome c) that were electrochemically active (as assessed by their ability to take up the dye MitoTracker). YFP-Parkin colocalizes with depolarized mitochondria (arrows) but not with electrochemically active mitochondria. (g) The mitochondrial volume for each Mfn1−/−, Mfn2−/− MEF cell was segregated into Parkin-positive and Parkin-negative subsets. Mean MitoTracker fluorescence intensity was measured for each subset (n = 9). Bars: (a, d, and f, left) 5 μm; (f, right four panels) 1 μm.
not blocked by the antioxidant N-acetyl-cysteine, which suggests that reactive oxygen species production is not necessary for Parkin translocation (Fig. S1). The mitochondrial translocation of Parkin caused by mitochondrial depolarization was also assayed by fluorescence loss in photobleaching (FLIP). Mitochondrial-localized YFP-Parkin in CCCP-treated cells was depleted more slowly by photobleaching than the entire pool of YFP-Parkin in HeLa cells not exposed to CCCP, which suggests that YFP-Parkin’s affinity for mitochondria is increased upon depolarization (Fig. 2, a–c).

Chronic inhibition of mitochondrial fusion caused by double knockout of the genes expressing the partially redundant mitofusin (Mfn) proteins, Mfn1 and Mfn2, generates a heterogeneous population of fragmented mitochondria, some of which are relatively respiratory deficient and display a lower membrane potential (Chen et al., 2005). If Parkin recruitment occurs as a consequence of membrane depolarization, exogenous Parkin in Mfn1−/− Mfn2−/− double knockout mouse embryonic fibroblasts (MEFs) would be predicted to accumulate selectively on mitochondria with lower membrane potentials. YFP-Parkin

Figure 3. Mitochondrial fragmentation does not induce Parkin accumulation independently of mitochondrial membrane potential. (a–d) HeLa cells cotransfected with YFP-Parkin (green) and with empty vector (a), vMIA (b), or Drp1 K38A (c). Cells were treated with 10 μM CCCP (a, right, and c) or DMSO (a, left, and b) for 1 h. Mitochondria were immunostained for cytochrome c (red). The bottom two panels in each column show an enlarged view of the boxed regions. (d) YFP-Parkin colocalization with mitochondria were scored as in Fig. 1 f. Error bars indicate standard deviation of at least three replicates. Bars, 5 μm.
Figure 4. **Selective mitochondrial elimination by Parkin under depolarizing conditions.** (a and b) HeLa cells expressing YFP-Parkin (green) incubated for 12 h (a) or 48 h (b, left) with 10 μM CCCP. Cells were immunostained for Tom20 (red). Parkin-expressing HeLa cells display less mitochondrial mass compared with surrounding cells at 12 h and complete loss of mitochondria by 48 h. (b) Similar loss of mitochondria observed with anti-cytochrome c (red, middle) and anti-TRAP1 (red, right) antibodies. (c) No loss of peroxisomes immunostained for PMP70 (red) in YFP-Parkin–transfected cells relative to surrounding untransfected cells. Outlines demarcate the edges of cells expressing YFP-Parkin. Bars, 10 μm. (d–f) Electron microscopy of untransfected HeLa cells (d) or HeLa cells expressing YFP-Parkin (e) and treated with 10 μM CCCP for 48 h. Many mitochondria and few lysosomes were observed in control cells, and no mitochondria and many lysosomes were observed in YFP-Parkin–transfected cells. Bars, 500 nm. (f) The number of mitochondria and late lysosomes/μm² of cytoplasm in 22 randomly selected cells per condition. (g) The number of PMP70-stained peroxisomes per cell in YFP-Parkin–transfected and untransfected cells (n = 5). Error bars indicate standard deviation of at least three replicates. (h) Control HeLa cells or HeLa cells transfected with YFP-Parkin treated with 10 μM CCCP for 72 h (day 0) and cultured in glucose or galactose media for 1–4 d. Cells were fixed and stained for Tom20 and Hoechst33342 (nuclei). Cells with nonapoptotic nuclei in a representative area of the slide on days 0–4 were counted and represented in the graph as a percentage of nonapoptotic cells on day 0 (≥160 cells per condition on day 0 in at least two experiments).
Figure 5. Mitophagy induced by Parkin. (a) HeLa cells stably expressing GFP-LC3 (green) transfected with mCherry-Parkin (not depicted) and treated with 10 μM CCCP for 1 h. Parkin-negative cells (left) display less overlap between autophagosomes and mitochondria (red) than Parkin-positive cells (right), as assessed by (b) counting the number of mitochondria encapsulated by LC3-positive autophagosomes in >30 cells per condition in at least three independent experiments. (c) HeLa cells stably expressing GFP-LC3 (green) and transiently transfected with mCherry-Parkin (white) were immunostained for LC3, Parkin, and Cyt c. (d) WT MEFs and ATG5−/− MEFs treated with CCCP for 24 h. (e) WT and ATG5−/− MEFs with CCCP treatment for 24 h. (f) CCCP, CCCP+3MA, CCCP+Bafilomycin A1.
colocalized with mitochondria in 1.33 ± 1.15% of Mfn1−/− cells and 3.33 ± 1.15% of Mfn2−/− cells, in the range of the 1.99 ± 2% of cells displaying Parkin-positive mitochondria seen with wild-type (WT) MEFs. However, in Mfn1−/−,Mfn2−/− double knockout MEFs, YFP-Parkin colocalized with mitochondria in 86.20 ± 3.95% of cells (Fig. 2, d and e; and Fig. S2; P < 0.001 for Mfn1−/−,Mfn2−/− vs. WT [two-tailed t test]). Interestingly, in Mfn1−/−,Mfn2−/− cells, Parkin was recruited to a discreet subset of mitochondria within individual cells (Fig. 2, d and f). To test whether mitochondria labeled by Parkin display decreased membrane potential, we pulsed the cells with MitoTracker red, a potentiometric mitochondrial dye, before fixation. YFP-Parkin selectively accumulated on those mitochondria with lower MitoTracker staining (Fig. 2 f). To quantify this relationship, we digitally segregated the mitochondrial volume of these cells into Parkin-positive and Parkin-negative sets, and measured the mean MitoTracker intensity of these volumes for each cell. The mitochondrial volume labeled with YFP-Parkin displayed a 47% lower mean MitoTracker intensity relative to the mitochondrial volume with undetectable YFP-Parkin accumulation (Fig. 2 g; 487.00 ± 81.5 arbitrary units [au] vs. 258.3 ± 61.7 au; P < 0.001 [two-tailed, paired t test], n = 9 cells). These results show that Parkin can be recruited to individual mitochondria within cells and that compromised mitochondria display greater Parkin accumulation than electrochemically active mitochondria, which is consistent with the hypothesis that impaired mitochondria are selectively targeted by Parkin.

Depolarization of mitochondria is known to induce their fragmentation into multiple smaller organelles (Legros et al., 2002) by inhibiting organelle fusion (Meuesen et al., 2004). Recent genetic studies have linked Parkin activity to gene products controlling mitochondrial fission and fusion (Deng et al., 2008; Poole et al., 2008; Yang et al., 2008), which suggests that Parkin recruitment to mitochondria may be a consequence of depolarization-induced fragmentation. To test this hypothesis, fragmentation of mitochondria induced by CCCP (Fig. 3 a) was inhibited by overexpressing Drp1K38A, a dominant-negative mutant of the mitochondrial fission protein dynamin-related protein 1 (Drp1; Fig. 3 c; Smirnova et al., 2001). Although mitochondria in CCCP-treated cells expressing Drp1K38A fail to fragment, they still display Parkin accumulation along the elongated mitochondria (Fig. 3, c and d), which indicates that mitochondrial fragmentation is not necessary for Parkin translocation. Expression of viral mitochondrial-associated inhibitor of apoptosis (vMIA) in HeLa cells, which causes fragmentation of mitochondria with minimal perturbation of membrane potential (McCormick et al., 2003), did not cause accumulation of Parkin on mitochondria (Fig. 3, b and d), also indicating that excessive fragmentation of mitochondria by itself is insufficient to cause Parkin recruitment.

To further assess the effect of Parkin on depolarized mitochondria, we followed changes in mitochondrial morphology and mass over time. In HeLa cells lacking Parkin, the mitochondria appeared fragmented within 60 min after adding CCCP but underwent little other morphological change over the following 48 h (Fig. 4, a and b). In Parkin-expressing cells, in contrast, the mitochondrial mass appeared to be grossly reduced by 12 h (Fig. 4 a). Interestingly, by 48 h, no mitochondria remained detectable in Parkin-expressing cells assessed by immunocytochemistry using three independent mitochondria markers: Tom20, cytochrome c, and TRAP1 (Fig. 4 b). In contrast to the mitochondrial elimination, no significant decrease in the number of peroxisomes was observed (Fig. 4, c and g), which suggests that Parkin selectively induces mitophagy that is consistent with the mitochondria-specific localization upon CCCP treatment.

We also examined HeLa cell mitochondria by transmission electron microscopy after 48 h of CCCP treatment in the presence and absence of Parkin expression. Mitochondria were abundant in the control HeLa cells after CCCP treatment, although they appeared fragmented and had sparse cristae (Fig. 4 d). However, 90% of HeLa cells expressing YFP-Parkin had either few or no detectable mitochondrial structures (Fig. 4, e and f; 0.074 ± 0.21 mitochondria/μm² of cytoplasm with Parkin vs. 0.62 ± 0.06 mitochondria/μm² of cytoplasm without Parkin; P < 0.001, n = 22 cells per condition). Furthermore, Parkin-expressing HeLa cells lacking mitochondria displayed a large increase in electron dense lysosomal structures (Fig. 4, e and f; 0.38 ± 0.23 lysosomes/μm² cell area with Parkin vs. 0.06 ± 0.08 lysosomes/μm² of cytoplasm without Parkin; P < 0.001, n = 22 cells per condition).

To further confirm that cells had lost their mitochondria, we examined their growth in glucose media or galactose media, which lacked glucose. 72.8% of cells without detectable mitochondria were able to survive for 4 d in glucose media, whereas 0% were able to survive 4 d when cultured in galactose media (Fig. 4 h). In contrast, the majority of control cells, which had been treated with CCCP but lacked Parkin, retained their mitochondria and could survive in both glucose and galactose media for at least 4 d (Fig. 4 h). These results provide biochemical evidence that cells expressing Parkin lack mitochondrial function after depolarization, which is consistent with their having been eliminated.

Previous studies in mammalian cells (Elmore et al., 2001; Schweers et al., 2007; Sandoval et al., 2008; Twig et al., 2008) have concluded that depolarized mitochondria are degraded by autophagy. To test whether Parkin may be regulating this process, we assessed colocalization between a marker of autophagosomes, LC3, and mitochondria after mitochondrial depolarization using HeLa cells stably transfected with GFP-LC3 (Bampton et al., 2005). We also examined HeLa cell mitochondria by transmission electron microscopy after 48 h of CCCP treatment in the presence and absence of Parkin expression. Mitochondria were abundant in the control HeLa cells after CCCP treatment, although they appeared fragmented and had sparse cristae (Fig. 4 d). However, 90% of HeLa cells expressing YFP-Parkin had either few or no detectable mitochondrial structures (Fig. 4, e and f; 0.074 ± 0.21 mitochondria/μm² of cytoplasm with Parkin vs. 0.62 ± 0.06 mitochondria/μm² of cytoplasm without Parkin; P < 0.001, n = 22 cells per condition). Furthermore, Parkin-expressing HeLa cells lacking mitochondria displayed a large increase in electron dense lysosomal structures (Fig. 4, e and f; 0.38 ± 0.23 lysosomes/μm² cell area with Parkin vs. 0.06 ± 0.08 lysosomes/μm² of cytoplasm without Parkin; P < 0.001, n = 22 cells per condition).

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vs. 0.09 ± 0.36 LC3 encompassed mitochondria per cell; two-sided \( t \) test, \( P < 0.001 \); Fig 5 b). Consistent with the conclusion that Parkin accumulates on mitochondria destined for autophagy, Parkin colocalizes with LC3 after CCCP treatment (Fig. 5 c) but not before (not depicted).

To experimentally test if Parkin mediates mitochondrial elimination by autophagy, we examined Parkin activity in ATG5\(/-\) MEFs that lack a key component of the autophagy pathway (Hara et al., 2006). Supporting the hypothesis that Parkin promotes autophagic degradation of impaired mitochondria, cells lacking ATG5 retain Parkin-targeted mitochondria after CCCP treatment (Figs. 5, d and e). Likewise, bafilomycin, a lysosomal inhibitor, and 3-methyl adenine, an inhibitor of autophagy, blocked Parkin-induced mitophagy in HeLa cells (Figs. 5 f and S3, available at http://www.jcb.org/cgi/content/full/jcb.200809125/DC1).

We have shown that Parkin is recruited to depolarized mitochondria and that Parkin promotes their autophagic degradation. Spontaneous mitochondrial depolarization and depolarization after phototoxicity have been associated with mitophagy in mammalian cells (Kim et al., 2007; Twig et al., 2008). Although little is known about the proteins regulating this process in mammalian cells, recently, BNIP3L/NIX was found to promote degradation of mitochondria in reticulocytes by triggering the loss of mitochondrial membrane potential (Schweers et al., 2007; Sandalov et al., 2008). Our findings provide a new molecular link between mitochondrial membrane depolarization and autophagy by identifying Parkin as a mediator of mitophagy downstream of mitochondrial depolarization.

We do not know the extent to which Parkin mediates mitochondrial fidelity in vivo. Long-lived cells may require greater mitochondrial quality control than dividing cell populations that can discard damaged mitochondria wholesale by eliminating defective cells. Thus, certain cell types, such as neurons and myocytes, may require more robust intracellular mitochondrial surveillance than proliferating cell populations. Furthermore, it remains unknown to what extent alternative factors may promote mitophagy downstream of mitochondrial depolarization in different cell types or concurrently in the same cell.

In D. melanogaster, knockout of mitochondrial fusion genes can partially compensate for loss of Parkin phenotypes, which suggests that Parkin may normally facilitate mitochondrial fission (Deng et al., 2008; Poole et al., 2008; Yang et al., 2008). Our data support the view that Parkin has a less direct mode of compensating for defects in mitochondrial fusion and fission. Mitochondrial fragmentation does not itself signal Parkin recruitment, but a severe defect in mitochondrial fission does trigger recruitment of Parkin to mitochondria if they lose membrane potential. Additionally, mitochondrial fission appears to be a prerequisite for mitophagy (Twig et al., 2008). Thus, excess fission may compensate for Parkin loss in the fly by promoting mitophagy (Deng et al., 2008; Poole et al., 2008).

Parkin overexpression also has been shown to compensate for loss of Pink1 in D. melanogaster (Clark et al., 2006; Park et al., 2006). Our results suggest that Parkin may compensate by targeting impaired Pink1-deficient mitochondria for degradation. Knockdown of Pink1 leads to reduced HeLa cell mitochondrial membrane potential (Exner et al., 2007), which suggests that Parkin could maintain fidelity of mitochondria by activating the autophagy of dysfunctional mitochondria resulting from Pink1 loss.

Most importantly, our results suggest that loss of Parkin activity may allow the accumulation of dysfunctional mitochondria, leading to neuron loss in Parkinson’s disease, and that Parkin normally functions to survey mitochondrial activity and maintain mitochondrial fidelity by activating the autophagy of damaged organelles.

Materials and methods

Cell culture

Hela cells stably expressing YFP-Parkin using the flip-In system (Invitrogen) were creating according to the manufacturer’s instructions and maintained in 300 μg/ml hygromycin (Sigma-Aldrich). Rat cortical neurons were isolated on embryonic day 18 and grown in neurobasal media supplemented with B-27, l-glutamine, and penicillin/streptomycin. All cell culture materials were obtained from Invitrogen and all chemicals were obtained from Sigma-Aldrich. Chemicals were prepared from DMSO stock solutions, except paraquat, N-acetyl-cysteine, and 3-methyladenine, which were added fresh to media. Mn1\(-/-\), Mn2\(-/-\), and Mn1\(-/-\), Mn2\(-/-\), double knockout MEFs were generously donated by D.C. Chan (California Institute of Technology, Pasadena, CA), ATG5\(-/-\) MEFs were donated by N. Mizushima (Tokyo Medical and Dental University, Tokyo, Japan), Flip-In Hela cells were donated by V.V. Lobanenko (National Institutes of Health, Rockville, MD), and Hela cells stably expressing GFP-LC3 were donated by A. Tolkovsky (Cambridge University, Cambridge, UK).

Transfection/imunocytochemistry

Cultured cells seeded in borosilicate chamber slides (Thermo Fisher Scientific) were transfected or cotransfected with YFP-Parkin, ECFP-Parkin, mCherry-Parkin, DsRed-Mito (Clontech Laboratories, Inc.), pcDNA3.1 [Invitrogen], vMIA, and/or Drp1K38A constructs using Fugene 6 (Roche). Parkin-myc was a gift from M. Cookson [National Institutes of Health, Bethesda, MD]. Cells were fixed 12–24 h after transfection with 4% paraformaldehyde in PBS. Cells were stained with following primary antibodies: mouse monocular cytochrome c (BD), rabbit polyclonal Tom20 [Santa Cruz Biotechnol, Inc.], mouse monoclonal Parkin PKR8 [Santa Cruz Biotechnology, Inc.], rabbit polyclonal PN170 [Invitrogen], and/or mouse monoclonal TRAP1 (Abcam); and with the following secondary antibodies: mouse and/or rabbit Alexa 488, 594, and 633 [Invitrogen]. For assessment of mitochondrial membrane potential, cells were pulsed with 50 nM MitoTracker red [Invitrogen] for 15 min, washed, and incubated for an additional 10 min before fixation or imaging. For assessment of cell metabolic potential, cell nuclei were stained with Hoechst 33342 [Invitrogen].

Confocal microscopy

Fixed cells and live cells in the FLP assay were imaged using an inverted microscope (LSM510 Meta; Carl Zeiss, Inc.) with a 63×/1.4 oil DIC Plan APO objective at 25°C and 37°C, respectively. For the FLP assay, a bleach of region of interest (ROI) occupying approximately one eighth of the cell was positioned over a relatively mitochondria-free portion of the cytosol. Cells were alternately bleached (488 nm using a 30-mW argon laser at 75% power and 100% transmission for 150 iterations) and imaged (488 nm at 75% power and 2% transmission) for 10 min (~60 cycles over the length of the experiment). Two-channel prebleach and postbleach images were obtained with 488 and 594 lasers to assess the position of mitochondria before and after bleaching. Circular ROIs with diameters of ~1 and 5 μm, respectively, were placed over the mitochondria and cytosol of the target cell, and an ROI of 10 μm was placed over the control cell. Imaging of YFP-Parkin translocation in live HeLa cells was performed on a live cell imager system (UltraView LCI; PerkinElmer) at 35°C with a 100×/1.45 α-Plan-Fluar objective.

Image analysis

Image contrast and brightness were adjusted in Photoshop (Adobe). Colocalization was assessed with line scans using MetaMorph (MDS Analytical Technologies). For analysis of mitochondrial membrane potential in cells, mitochondrial voxels in each image (the cytochrome c channel threshold was ≥400 au) were segregated into Parkin-positive [the YFP-Parkin channel threshold was ≥1; 100 au] or Parkin-negative subsets, and MitoTracker intensity for each voxel was measured using Velocity software (Improvision). For each cell, the mean MitoTracker intensity per voxel was calculated for the
Parkin-positive and Parkin-negative subsets. The difference in mean Mitotracker intensity between the Parkin-positive and Parkin-negative subsets was calculated using a paired t test.

Western blotting
Hela cells stably expressing YFP-Parkin, HEK293 cells, and rat cortical neurons 2 d in vitro were harvested and fractionated as described previously (Karbowiak et al., 2007). Samples were run on SDS-PAGE and immunoblotted with the following antibodies: polyclonal rabbit anti-GFP (Invitrogen), mouse monoclonal anti-Parkin (PRK8), and mouse monoclonal anti-Parkin 31H1 (EMD).

Electron microscopy
Hela cells transfected with YFP-Parkin for 18 h were sorted for YFP using FACs. After sorting, 99.7% of cells contained a detectable YFP signal. After overnight culture, cells were treated with 10 μM CCCP for 48 h, fixed with 4% glutaraldehyde in 0.1 N sodium-cacodylate at room temperature for 1 h, and processed for electron microscopy using a standard protocol. 22 cells expressing Parkin and 22 untransfected cells were randomly selected and imaged at 8,000x magnification by transmission electron microscopy (200CX, JOEL Ltd.) and a digital camera system (KR-100; Advanced Microscopy Techniques, Corp.). The area of cytoplasm in each cell was calculated using National Institutes of Health Image.

Online supplemental material
Fig. S1 shows YFP-Parkin recruitment to mitochondria after paraquat and CCCP + N-acetyl-cysteine. Fig. S2 shows ECFP-Parkin recruitment to Mfn1+/- and Mfn2+/- cells and selective recruitment of YFP-Parkin to depolarized mitochondrial in Hela cells after paraquat. Fig. S3 shows a block of mitophagy by 3-methyladenine and bafilomycin. Video 1 depicts YFP-Parkin recruitment to mitochondria after depolarization with CCCP in Hela cells. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.200809125/DC1.

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