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Impaired Autophagy in the Lipid-Storage Disorder Niemann-Pick Type C1 Disease

Sovan Sarkar,1 Bernadette Carroll,2 Yosef Buganim,1 Dorothea Maetzel,1 Alex H.M. Ng,3 John P. Cassady,1 Malkiel A. Cohen,1 Souvik Chakraborty,4 Haoyi Wang,1 Eric Spooner,1 Hidde Ploegh,1 Joerg Gsponer,3 Viktor I. Korolchuk,2 and Rudolf Jaenisch1,*

1Whitehead Institute for Biomedical Research, Massachusetts Institute of Technology, 9 Cambridge Center, Cambridge, MA 02142, USA
2Institute for Ageing and Health, Newcastle University, Campus for Ageing and Vitality, Newcastle upon Tyne NE4 5PL, UK
3Department of Biochemistry and Molecular Biology, Centre for High-Throughput Biology, University of British Columbia, Vancouver, BC V6T 1Z4, Canada
4Department of Pediatrics, University of Pittsburgh School of Medicine, Children’s Hospital of Pittsburgh of UPMC, Pittsburgh, PA 15224, USA
*Correspondence: jaenisch@wi.mit.edu
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SUMMARY

Autophagy dysfunction has been implicated in misfolded protein accumulation and cellular toxicity in several diseases. Whether alterations in autophagy also contribute to the pathology of lipid-storage disorders is not clear. Here, we show defective autophagy in Niemann-Pick type C1 (NPC1) disease associated with cholesterol accumulation, where the maturation of autophagosomes is impaired because of defective amphisome formation caused by failure in SNARE machinery, whereas the lysosomal proteolytic function remains unaffected. Expression of functional NPC1 protein rescues this defect. Inhibition of autophagy also causes cholesterol accumulation. Compromised autophagy was seen in disease-affected organs of Npc1 mutant mice. Of potential therapeutic relevance is that HP-β-cyclodextrin, which is used for cholesterol-depletion treatment, impedes autophagy, whereas stimulating autophagy restores its function independent of amphisome formation. Our data suggest that a low dose of HP-β-cyclodextrin that does not perturb autophagy, coupled with an autophagy inducer, may provide a rational treatment strategy for NPC1 disease.

INTRODUCTION

Autophagy, an intracellular degradation pathway for aggregation-prone proteins and damaged organelles, is essential for cellular homeostasis. This dynamic process, defined as autophagic flux, encompasses the generation of autophagosomes and its fusion with late endosomes to form amphisomes, which subsequently fuse with lysosomes forming autolysosomes for degrading its cargo (Figure S1A). Starvation induces autophagy for maintaining energy homeostasis by recycling of cytosolic components (Ravikumar et al., 2010). Tissue-specific abrogation of constitutive autophagy, such as by deletion of essential autophagy genes Atg5 or Atg7, in the brain or liver of mice in the absence of any pathogenic protein results in degeneration in the affected organs, suggesting that impaired autophagy contributes to the disease-related phenotypes in neurodegenerative and liver diseases (Hara et al., 2006; Komatsu et al., 2006, 2007). Thus, compromised autophagy is attributable to the etiology of several neurodegenerative disorders and certain liver diseases where upregulation of autophagy is considered beneficial (Meijer and Codogno, 2006; Mizushima et al., 2008; Rubinsztein et al., 2012; Sarkar, 2013).

Autophagy also regulates the metabolism of lipids including cholesterol (Singh et al., 2009), which are essential structural components of membranes and govern intracellular trafficking (Ikonen, 2008). Niemann-Pick type C1 (NPC1) disease, associated with neurodegeneration and liver dysfunction, is characterized by cholesterol accumulation in the late endosomal/lysosomal (LE/L) compartments resulting from disease-causing mutations primarily in the NPC1 protein (Karten et al., 2009; Rosenbaum and Maxfield, 2011). The transmembrane NPC1 protein comprises five sterol-sensing domains, possibly mediating cholesterol efflux from late endosomes (Higgins et al., 1999; Kwon et al., 2009). How alterations in cholesterol homeostasis in lipid-storage disorders might perturb autophagy is not completely understood. Here, we show defective autophagic flux in NPC1 disease, in which stimulation of autophagy restores the function of the pathway.

RESULTS

Accumulation of Autophagosomes in NPC1 Mutant Cells Is due to a Block in Autophagic Flux

We initially confirmed accumulation of cholesterol and lipids by Filipin and BODIPY staining in NPC1 patient fibroblasts, in
Figure 1. Accumulation of Autophagosomes in NPC1 Mutant Cells Is due to a Block in Autophagic Flux

(A and B) Filipin and BODIPY fluorescence staining (A) and immunofluorescence staining with anti-LC3 antibody (B) in control (Con) and NPC1 patient fibroblasts, Npc1+/+ and Npc1–/– MEFs, and in Npc1wt and Npc1null CHO-K1 cells are shown. Details of control and NPC1 patient fibroblast lines are listed in Figure S1B. The scale bars represent 10 μm. See also Figure S1D.

(C) Electron microscopy (EM) images and quantification of autophagic vacuoles in control and NPC1 patient fibroblasts (fib), and in Npc1+/+ and Npc1–/– MEFs, are shown. The scale bars represent 500 nm. See also Figures S1E and S1F.

(D) Immunoblot analyses with anti-LC3 and anti-actin antibodies in control and NPC1 patient fibroblasts, Npc1+/+ and Npc1–/– MEFs, and in Npc1wt and Npc1null CHO-K1 cells treated with or without 400 nM bafA1 (Baf) for 4 hr are shown. High exposure (HE) and low exposure (LE) of the same immunoblot are shown.

(legend continued on next page)
Npc1−/− MEFs from npsc1(+/−) mutant mice exhibiting NPC1 clinical abnormalities (Loftus et al., 1997), and in Chinese hamster ovary-K1 (CHO-K1) cells containing a deletion in the Npc1 locus (Npc1(−/−)) (Millard et al., 2000) (Figures 1A and S1B). In these Npc1 mutant cells, the NPC1 protein was either low or not detected (Figure S1C). Perturbation in autophagy was measured by the steady-state number of autophagosomes, which correlates with the autophagosome-associated form of microtubule-associated protein 1 light-chain 3 (LC3−II) (Kabeya et al., 2000; Klionsky et al., 2012). We found accumulation of autophagosomes in the Npc1 mutant cells, as assessed by elevated LC3-II levels and LC3+ vesicles, including autophagic vacuoles analyzed by electron microscopy (Figures 1B, 1C, and S1C–S1F). Previous studies have attributed this increase in the steady-state number of autophagosomes in NPC1 disease to activation of autophagy (Ishibashi et al., 2009; Ordonez et al., 2012; Pacheco et al., 2007). Because both synthesis and degradation affect steady-state LC3-II levels, we determined autophagic flux using baflomycin A1 (baFA1), which prevents lysosomal acidification and accumulates LC3-II by inhibiting its degradation. In baFA1-treated conditions, an autophagy inducer increases LC3-II levels, whereas an autophagy blocker has no change compared to controls (Klionsky et al., 2012; Sarkar et al., 2009) (see Supplemental Experimental Procedures). Despite significant LC3-II accumulation in Npc1 mutant cells compared to controls, this difference was no longer detected following baFA1 treatment (Figure 1D). Thus, in contrast to previous studies by Ishibashi et al. (2009), Ordonez et al. (2012), and Pacheco et al. (2007), our data suggest that LC3-II accumulation is not due to increased autophagosome synthesis but rather is caused by impaired degradation of autophagosomes.

**Defective Amphisome Formation in NPC1 Mutant Cells due to Impaired Recruitment of Components of the SNARE Machinery to Late Endosomes**

To gain mechanistic insights, we performed mass spectrometry (MS) analyses in Npc1 MEFs. Gene Ontology (GO) annotations indicated changes in intracellular transport in Npc1−/− MEFs when compared to Npc1+/− MEFs (Figures S1G and S1H). We analyzed genes with a significant difference in expression levels and GO annotations linked to autophagy, endocytosis, or lysosomes (Figure 1E). For example, Rab7, a late endosome-resident GTPase regulating endosomal/autophagosomal maturation (Jäger et al., 2004; Stenmark, 2009), was enriched in Npc1−/− MEFs. We confirmed an elevation of Rab7, and other late endosome markers, such as cation-independent mannose-6-phosphate receptor (M6PR) and lysobisphosphatidic acid (LBPA) (Kobayashi et al., 1999), suggesting accumulation of late endosomes in NPC1 mutant cells (Figures 1E–1G, S1I, and S1J).

Because the loss of NPC1 protein from LE/L compartments in NPC1 mutant cells (Carstea et al., 1997; Higgins et al., 1999; Karten et al., 2009) leads to increase in autophagosomes (LC3+ and late endosomes (Rab7+)), we investigated the formation of amphisomes arising due to fusion of these vesicular compartments (Berg et al., 1998). Although starvation increases their number in control cells (Jäger et al., 2004), EGFP-LC3+/mRFP-Rab7+ amphisomes were significantly reduced in Npc1−/− MEFs both under basal (full medium [FM]) and starvation (HBSS) conditions (Figures 2A and S2A), suggesting impaired formation of amphisome in NPC1 mutant cells. Further analyzing this process with endogenous LC3+ and Rab7+ vesicles revealed a similar defect in starved Npc1−/− MEFs (Figure S2B). Additionally, using FITC-conjugated dextran that undergoes cellular uptake through the endocytic pathway, NPC1 mutant cells exhibited significantly less amphisomes as assessed by FITC-dextran+/mRFP-LC3+ colocalization (Figures 2B and S2C).

The defect in autophagosome-late endosome fusion could be due to perturbations in the formation of specific SNARE complexes, such as between autophagosomal syntaxin 17 (Stx17) and LE/L VAMP8 mediated by SNAP-29 (Itakura et al., 2012). Despite an increase in VAMP8 levels in Npc1−/− MEFs, as revealed by MS data (Figures 1E, 1F, and S1I), the fusion between Myc-Stx17+ autophagosomes and FLAG-VAMP8+ vesicles, as well as coimmunoprecipitation between these SNARE proteins, was significantly decreased both under basal and starvation conditions as compared to Npc1+/+ MEFs (Figures 2C and 2D). We found impaired localization of VAMP8 to mRFP-Rab7+ late endosomes in Npc1−/− MEFs, possibly contributing to this defect in forming SNARE complex (Figures 2E and S2D). Other SNARE proteins implicated in autophagosome maturation include VAMP3 (regulates amphisome formation) and VAMP7 (regulates fusion with lysosomes) (Fader et al., 2009), which were elevated in Npc1−/− MEFs (Figures 1F and S1I). Similar to VAMP8, localization of EGFP-VAMP3, but not of EGFP-VAMP7, to mRFP-Rab7+ late endosomes was reduced in Npc1−/− MEFs (Figures 2F and S2E). Consistently, the localization of autophagosomal Myc-Stx17+ to late endocytic Rab7+ vesicles, which is an indicator of amphisome formation during starvation as seen in Npc1+/+ MEFs, was significantly reduced in Npc1−/− MEFs (Figures 2G and S2F). Thus, the inability to recruit multiple components of the SNARE machinery to late endosomes in NPC1 mutant cells impairs amphisome formation.

**Impaired Autophagosome Maturation in NPC1 Mutant Cells Retards Autophagic Cargo Clearance**

Defective amphisome formation will affect the maturation of autophagosomes into autolysosomes. We analyzed this process using tandem fluorescent-tagged mRFP-GFP-LC3 reporter where autophagosomes emit both mRFP/GFP signals, but...
autolysosomes emit only an acid-stable mRFP signal because the pH-sensitive GFP signal is quenched in acidic lysosomes (Kumura et al., 2007). Unlike control cells displaying autolysosomes (mRFP-GFP-LC3), the majority of accumulated vesicles in NPC1 mutant cells were autophagosomes (mRFP-GFP-LC3) (Figures 3A and S3A), suggesting a defect in autophagosome maturation. Consequently, the clearance of p62, a specific autophagy substrate (Pankiv et al., 2007), was decreased in NPC1 mutant cells, leading to its accumulation and aggregation that contained with LC3+ vesicles (Figures 3B, 3C, S2B, and S3C). Using tandem fluorescent-tagged mCherry-GFP-p62 reporter (Pankiv et al., 2007), we found that the majority of p62 aggregates in Npc1+/− MEFs were autophagosomes associated (mCherry+GFP−p62), in contrast to those in controls that were mostly autolysosome associated (mCherry−GFP+p62 aggregates) (Figure 3D).

Although the levels of p62 in Npc1+/− MEFs were comparable to that in autophagy-deficient Atg5−/− MEFs (Figure S3D) that do not have autophagosomes/LC3-II (Kuma et al., 2004), BafA1 treatment further increased p62 levels in Npc1+/− MEFs (Figure S3E). Moreover, the kinetics of endogenous p62 degradation in the presence of cycloheximide (inhibitor of protein translation) was substantially slower in Npc1+/− MEFs compared to Npc1+/+ MEFs, whereas no clearance of p62 occurred in Atg5−/− MEFs (Figures 3E and S3F). These data suggest that the impairment in autophagic flux in NPC1 mutant cells is not absolute.

Consistent with effects that are associated with autophagy impairment, aggregation of mutant huntingtin (EFGP-HDQ74), an autophagy substrate (Ravikumar et al., 2004), and ubiquitylated proteins (Korolchuk et al., 2009) were increased in NPC1 mutant cells (Figures S3G and S3H). Autophagy also removes damaged mitochondria (mitophagy) (Yole and Narendra, 2011). Defective autophagy in Npc1+/− MEFs increased mitochondrial load, as assessed by elevated levels of Tom20, a translocase of outer mitochondrial membrane (Figure 3F). Furthermore, the MS data revealing decreased DJ-1 levels for 24 hr in FM and then starved in HBSS for the last 1 hr, are shown. The scale bars represent 10 μm. See also Figure S2C.

Figure 2. Perturbation of SNARE Machinery on Late Endosomes Impairs Amphisome Formation in NPC1 Mutant Cells
(A) Fluorescence staining and quantification of colocalization (Coloc.) of mRFP-Rab7+ and EGFP-LC3+ vesicles (an indication of amphisome formation) in Npc1+/− and Npc1+/− MEFs, expressing mRFP-Rab7+ and EGFP-LC3 for 24 hr and cultured under basal (FM) and starvation (HBSS; last 1 hr) conditions, are shown. The scale bars represent 10 μm. See also Figure S2A.
(B) Fluorescence staining and quantification of colocalization of mRFP-LC3+ and FITC-dextran+ structures in Npc1+/− and Npc1−/− MEFs, expressing mRFP-LC3 for 24 hr and then incubated in HBSS with Alexa Fluor 488 (FITC)-conjugated dextran for 15 or 30 min, are shown. The scale bars represent 10 μm. See also Figure S2C.
(C) Coinmunoprecipitation (coIP) of FLAG-Vamp8 and Myc-Syntaxin17 (Stx17) in Npc1+/− and Npc1−/− MEFs, expressing Myc-Syntaxin17 and either empty vector or FLAG-VAMP8 for 24 hr, then lysed and immunoprecipitated (IP) with anti-FLAG beads, is shown. Immunoblotting analysis with anti-Myc and anti-FLAG was done on inputs (with equal loading) and immunoprecipitated fractions.
(D) Fluorescence staining and quantification of colocalization of FLAG-VAMP8+ and Myc-Syntaxin17+ (Stx17) structures in Npc1+/− and Npc1−/− MEFs, expressing FLAG-VAMP8 and Myc-Syntaxin17 for 24 hr under basal (FM) and starvation (HBSS; last 1 hr) conditions, are shown. The scale bars represent 10 μm. (E and F) Fluorescence staining and quantification of colocalization of FLAG-VAMP8+ (E) or EGFP-VAMP3+ (F) structures with mRFP-Rab7+ vesicles in Npc1+/− and Npc1−/− MEFs, expressing mRFP-Rab7 and either FLAG-VAMP8 (E) or EGFP-VAMP3 (F) for 24 hr in FM, are shown. The scale bars represent 10 μm.
(G) Immunofluorescence staining with anti-Rab7 antibody and quantification of colocalization of Rab7+ and Myc-Syntaxin17+ (Stx17) structures in Npc1+/− MEFs, expressing Myc-Syntaxin17 for 24 hr in FM and then starved in HBSS for the last 1 hr, are shown. The scale bars represent 10 μm. Graphical data denote mean ± SEM. ***p < 0.001, **p < 0.01, and *p < 0.05.

Our data link NPC1 deficiency to defective mitophagy, a phenomenon linked to increased susceptibility to proapoptotic insults (Ravikumar et al., 2008; Yole and Narendra, 2011). Consequently, treatment with carbonyl cyanide m-chlorophenyl-hydrazone (CCCP), an uncoupler of mitochondrial membrane potential, substantially increased cell death in Npc1+/− MEFs compared to Npc1+/+ MEFs (Figure 3G).

Upstream events regulating autophagosome biogenesis (Ravikumar et al., 2010), such as Atg5-Atg12 conjugation and phagophore formation (Atg16+ vesicles), including beclin 1 and mTOR activity remained constant (Figures S1A and S3K–S3M). Thus, contrary to previous reports suggesting autophagy activation in NPC1 disease (Ishibashi et al., 2009; Ordonez et al., 2012; Pacheco et al., 2007), our data are consistent with autophagosome accumulation being due to a block in autophagic flux late in the pathway.

NPC1 Mutant Cells Exhibit No Overt Defects in Endocytic Cargo Degradation and Lysosomal Proteolytic Function
Because NPC1 mutant cells exhibit accumulation of late endosomes, we examined any perturbations in endocytic traffic by the uptake of FITC-dextran and its colocalization with LysoTracker+ LE/L compartments. Although FITC-dextran and LysoTracker+ vesicles accumulated in Npc1+/− MEFs, the fraction localizing with LysoTracker+ vesicles was comparable with the control cells (Figure 3H). We also assessed clathrin-mediated endocytic degradation of epidermal growth factor receptor (EGFR). Despite elevated EGFR levels in NPC1 mutant cells, the rate of EGFR-induced EGFR degradation was comparable to that of control cells (Figure S3I), suggesting that endocytic trafficking and lysosomal proteolysis are not compromised. Consistent with data in Npc1+/− mouse brain (Seleat et al., 2012), we confirmed increased LAMP1, and mature cathepsin B and cathepsin D levels as revealed by MS data, suggesting an accumulation of lysosomes and lysosomal proteases (Figures 1E, 3I, and 3J). Furthermore, cathepsin B activity was increased in Npc1+/− MEFs, although no significant alterations were found in NPC1 patient fibroblasts, compared to the respective control cells (Figure 3K). In contrast to an earlier
Figure 3. Impaired Autophagosome Maturation Retards Autophagic Cargo Clearance in NPC1 Mutant Cells that Are Associated with Defective Mitophagy, whereas Lysosomal Proteolysis Is Not Perturbed

(A) Fluorescence staining and quantification of autophagosomes (mRFP+GFP−LC3) and autolysosomes (mRFP+GFP−LC3) in Npc1+/+ and Npc1+/− MEFs, expressing mRFP-GFP-LC3 reporter for 24 hr, are shown. The scale bar represents 10 μm.

(B) Immunofluorescence staining with anti-p62 antibody in control and NPC1 patient fibroblasts, and in Npc1+/+ and Npc1+/− MEFs, are shown. Quantification of the percentage of NPC1 mutant cells exhibiting increased p62+ aggregates is shown in the scale bar represents Figure S3B. The scale bar represents 10 μm.

(C) Immunoblot analysis with anti-p62 and anti-actin antibodies in control and NPC1 patient fibroblasts, and in Npc1+/+ and Npc1+/− MEFs, is shown.

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Functional NPC1 Protein Rescues the Autophagy Defects in NPC1 Mutant Cells, whereas Cholesterol-Depletion Treatment with HP-β-Cyclodextrin Blocks Autophagic Flux

Expression of functional NPC1 protein corrected the cholesterol phenotype in NPC1 mutant cells (Carstea et al., 1997). We found that overexpression of NPC1-EGFP in Npc1<sup>−/−</sup> MEFs also rescued the autophagy defects, as assessed by a reduction in p62 and LC3-II levels, and clearance of p62<sup>+</sup> aggregates, LC3<sup>+</sup> and LysoTracker<sup>+</sup> vesicles when compared to EGFP-transfected mutant cells (Figures 4A–4C and S4A). Consistent with NPC1 protein mediating vesicular traffic, transient expression of NPC1-EGFP that partially colocalized with mRFP-LC3<sup>+</sup> vesicles subtly increased autophagosome synthesis, as measured by increased LC3-II levels with or without bafA<sub>i</sub> (Figures S4B and S4C). This is likely due to a compensatory signal sensed by NPC1 protein-mediated increased autophagic flux causing rapid clearance of autophagosomes.

Cholesterol-depletion treatment with HP-β-cyclodextrin is a potential therapeutic strategy for NPC1 disease (Rosenbaum and Maxfield, 2011). We assessed whether this could also rescue the autophagy defects. Despite HP-β-cyclodextrin causing a dose-dependent reduction in cholesterol accumulation (Filipin staining) in Npc1<sup>−/−</sup> MEFs, it impaired autophagy, leading to dose- and time-dependent elevation in autophagosome/LC3-II and p62 levels (Figures 4D–4F and S4D–S4G). Similar results were obtained with 1% and 4% HP-β-cyclodextrin in rat primary cortical neurons (Figures 4G and S4H). Impairment of autophagy by HP-β-cyclodextrin is caused by inhibition of autophagosome maturation, causing a block in autophagic flux, as analyzed with the mRFP-GFP-LC3 reporter and bafA<sub>i</sub> assay (Figures 4H, 4I, and S4I). Low doses of HP-β-cyclodextrin, sufficient to deplete cholesterol, had a lesser impact on autophagy (Figures 4D–4F and S4E–S4G). HP-β-cyclodextrin-mediated accumulation of p62 was autophagy dependent because it had no effects in autophagy-deficient Atg5<sup>−/−</sup> MEFs (Figure 4J). However, endocytosis-mediated EGFR degradation remained unaffected, indicating that endosomal maturation and lysosomal proteolysis are not perturbed (Figure S4J). Thus, apart from NPC1 mutations causing cholesterol accumulation, substantial depletion of cholesterol also impairs autophagy possibly due to changes in membrane lipid composition retarding the vesicle fusion events (Koga et al., 2010; Zhang et al., 2009).

Thus, we infer a role for the NPC1 protein in mediating autophagic traffic independently of its effect on cholesterol handling.

Stimulation of Autophagy in NPC1 Mutant Cells Facilitates Autophagosome Maturation and Autophagic Cargo Clearance Independent of Amphisome Formation

Upregulation of autophagy is beneficial in several neurodegenerative diseases (Ravikumar et al., 2004; Rubinsztein et al., 2012; Sarkar, 2013; Sarkar et al., 2007). Using mTOR-dependent (starvation, rapamycin) and mTOR-independent (lithium) autophagy enhancers (Ravikumar et al., 2004; Sarkar et al., 2005; Blommaart et al., 1995), we assessed whether this approach will be rational in an NPC1 disease context and if autophagic flux can be restored in NPC1 mutant cells by measuring p62 clearance. Stimulating autophagy significantly reduced p62 and LC3-II/autophagosome levels in NPC1 mutant cells as a result of an increased autophagic flux (Figures 5A, 5B, and S5A–S5C). Restoration of functional autophagy under starvation in Npc1<sup>−/−</sup> MEFs is due to increased autophagosome maturation, as assessed with mRFP-GFP-LC3 reporter (Figure 5C). However, this process was independent of amphisome formation as indicated by reduced colocalization of LC3<sup>+</sup> and Rab7<sup>+</sup> vesicles, in contrast to starved Npc1<sup>−/−</sup> MEFs (Figures 2A, S2A, S2B, and S5D). Likewise, starvation or rapamycin reduced p62 levels in Npc1<sup>−/−</sup> MEFs with siRNA knockdown of VAMP8 (Figure S5E), which mediates amphisome formation (Itakura et al., 2012). Instead, autophagosomes possibly fused directly with the lysosomes during starvation-induced autophagy in Npc1<sup>−/−</sup> MEFs, as evident from increased colocalization between mRFP-LC3<sup>+</sup> and LAMP1-EGFP<sup>+</sup> vesicles (Figure 5D). Thus, stimulating autophagy could bypass the amphisome-forming vesicle fusion step to enable cargo clearance.

Starvation-induced autophagy also lowered p62 accumulation in Npc1<sup>−/−</sup> MEFs treated with a high dose (4%) of HP-β-cyclodextrin (Figures S5F and S5G) (depleted cholesterol by 85%–90% but further blocked autophagy; Figures 4D–4G and S4D–S4I), suggesting that combining a lower dose with autophagy enhancers may be rational to rescue both the cholesterol and autophagy defects. Indeed, Npc1<sup>−/−</sup> MEFs treated with 0.2% HP-β-cyclodextrin (depleted cholesterol by 40%–50% but not affecting autophagy; Figures 4D–4F and S4E–S4G) and
Figure 4. Rescue of Autophagy Defects in NPC1 Mutant Cells by Expressing Functional NPC1 Protein, whereas Cholesterol-Depletion Treatment Blocks Autophagic Flux

(A) Immunoblot analyses with anti-p62, anti-LC3, anti-NPC1, anti-EGFP, and anti-actin antibodies in Npc1+/+ and Npc1−/− MEFs, expressing either EGFP or NPC1-EGFP for 48 hr, are shown.

(B and C) Immunofluorescence staining with anti-p62 (B) and anti-LC3 (C) antibodies, and quantification of cells exhibiting accumulated p62+ aggregates (B) and LC3+ vesicles (C) in Npc1+/+ and Npc1−/− MEFs, expressing either EGFP or NPC1-EGFP for 48 hr, are presented. Arrows (white) show transfected cells, whereas arrowhead (orange) denotes a nontransfected cell. The scale bars represent 10 μm.

(D and E) Filipin staining (D) and quantification of Filipin intensity (E) in Npc1−/− MEFs, either left untreated or treated with 0.1%–4% HP-β-cyclodextrin for 24 hr, are shown. The scale bar represents 10 μm.

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rapamycin or lithium significantly reduced p62 levels in the presence of HP-β-cyclodextrin (Figure 5E).

**Inhibition of Autophagy Causes Cholesterol Accumulation, whereas Inducing Autophagy Increases Cell Viability in NPC1 Mutant Cells without Affecting Cholesterol Levels**

Autophagy regulates lipid metabolism because abrogation of autophagy increases intracellular lipids in autophagy-deficient (Atg5+/−) cells (Singh et al., 2009). We found that accumulation of cholesterol (filipin staining) also occurred in Atg5−/− MEFs as well as in bafA1-treated Npc1+/− MEFs, similar to the effects arising due to the loss of NPC1 protein in Npc1−/− MEFs (Figures 5F and 5G). Although 0.2% HP-β-cyclodextrin reduced cholesterol accumulation in Npc1−/− MEFs, stimulation of autophagy with rapamycin or lithium had no significant effect. Combining 0.2% HP-β-cyclodextrin with these autophagy inducers reduced cholesterol to what could be achieved with HP-β-cyclodextrin alone (Figures 5F and 5G). These data suggest that whereas inhibition of autophagy exhibits an NPC1-like cholesterol phenotype, activating autophagy in the context of NPC1 disease was unable to lower cholesterol levels.

We further examined the effects of HP-β-cyclodextrin and rapamycin on cellular viability in CCCP-treated Npc1−/− MEFs, which were more susceptible to apoptotic insults compared to Npc1+/− MEFs (Figures 3G and 5H). Although rapamycin, either alone or in combination with 0.2% HP-β-cyclodextrin, significantly rescued from cell death, 0.2% HP-β-cyclodextrin had no significant protective effects in Npc1−/− MEFs (Figure 5H). Thus, our data raise the possibility of activation of autophagy as a therapeutic strategy.

**Defective Autophagic Flux In Vivo in Cerebellum and Liver of Npc1−/− Mice**

Finally, we characterized defective autophagy in the organs primarily affected in NPC1 disease using cerebellum and liver from Npc1−/− mice (Loftus et al., 1997), where LC3-II and p62 levels were significantly elevated, thus confirming a block in autophagic flux in vivo (Figures 6A and 6B). Notably, similar to the clinical features of NPC1 disease, autophagy deficiency in the brain or liver of normal mice develops degeneration in Purkinje neurons or hepatocyte dysfunction, respectively (Hara et al., 2006; Komatsu et al., 2006, 2007). In addition, accumulation of p62 in autophagy-deficient mouse liver causes liver defects (Komatsu et al., 2010). Therefore, brain- and liver-specific interference with autophagy in mice associated with neurodegenerative diseases of impaired autophagy in NPC1 disease.

**Induction of Autophagy Is Protective in a Neuronal Model of NPC1 Disease**

To assess the efficacy of compounds in neurons, we used Npc1 knockdown cells to establish mouse neuronal cultures (Figure S6A). Because it is difficult to inhibit gene expression by shRNA in neurons, we initially infected mouse neural stem cells (mNSCs) (Nestin+/Sox1+; Figure S6B) with five independent lentiviral Npc1 shRNAs, with Npc1_2 shRNA being the most effective construct in reducing NPC1 protein levels (Figure 6C). Neural stem cells stably expressing Npc1_2 shRNA were then differentiated with retinoic acid into neurons (Robertson et al., 2008), which express the neuronal markers Tuj1 and MAP2 (Figures 6D and 6E). Consistent with our data, neurons expressing Npc1_2 shRNA had increased LC3+ vesicles as well as LC3-II and p62 levels compared to control shRNA (Figures 6D and 6E), effects that were attributable to impaired autophagic flux as evident from the bafA1 assay (Figure 6F). Likewise, NPC1 knockdown in neurons derived from human embryonic stem cells expressing NPC1 shRNA also displayed an increase in LC3-II levels (Ordonez et al., 2012).

Treatment of Npc1 knockdown mouse neurons (Npc1_2 shRNA) with rapamycin, either alone or in combination with 0.2% HP-β-cyclodextrin, significantly reduced p62 levels (Figure 6G). However, 0.2% HP-β-cyclodextrin had no effects on p62 clearance (Figure 6G), suggesting that its low dose does not perturb autphagic flux in neuronal culture. We further show that Npc1 knockdown neurons (Npc1_2 shRNA) were associated with increased cell death (Figures 6H and 6I). Notably, this deleterious effect was significantly rescued by rapamycin or 0.2% HP-β-cyclodextrin, whereas the combination treatment, although exhibiting the greatest protection, was not significantly better than rapamycin alone (Figure 6I). Thus, our data suggest that stimulation of autophagy may be beneficial for NPC1 disease and raise the possibility for a combination treatment approach with agents inducing autophagy and depleting cholesterol.

**DISCUSSION**

In summary, our data imply that the NPC1 protein functions at the crossroads of autophagy and endocytosis to regulate amphiphilic molecule formation, and its loss of function predominantly impairs autophagy-specific traffic (Figures 7 and S7). This is attributable to a defective SNARE complex machinery, and it is likely that the...
Figure 5. Simulating Autophagy Rescues Autophagy Defects in NPC1 Mutant Cells by Facilitating Autophagosome Maturation Independent of Amphisome Formation, whereas Abrogation of Autophagy Leads to Accumulation of Intracellular Cholesterol
(A) Immunoblot analysis with anti-p62 and anti-actin antibodies in Npc1+/+ and Npc1–/– MEFs, cultured in FM with or without 400 nM rapamycin (Rap) or 10 mM lithium (LiCl) for 48 hr, or under starvation condition (HBSS; last 4 h), is presented. High exposure and low exposure of the same immunoblot are shown.
(B) Immunoblot analysis with anti-p62 and anti-actin antibodies in control and NPC1 patient fibroblasts, cultured either in basal (FM) or starvation (HBSS; 6 hr) condition, is shown.
(C) Fluorescence staining and quantification of autophagosomes (mRFP+-GFP+-LC3) and autolysosomes (mRFP+-GFP–LC3) in Npc1–/– MEFs, expressing mRFP-EGFP-LC3 reporter for 24 hr and cultured under basal (FM) or starvation (HBSS; last 1 hr) conditions, are shown. Cells were subjected to starvation for 1 hr to visualize LC3+ vesicles, instead of 4 hr where there was a substantial clearance of these vesicles (Figures S5B and S5C). The scale bar represents 10 μm.
(D) Filipin staining of Atg5+/+ and Atg5–/– fibroblasts, and Npc1+/+ and Npc1–/– fibroblasts, cultured under different conditions, is shown.
(E) Apoptotic cell quantification in Atg5+/+ and Atg5–/– fibroblasts, and Npc1+/+ and Npc1–/– fibroblasts, cultured under different conditions, is shown.

(legend continued on next page)
LE/L-resident NPC1 protein plays a role in mediating membrane-tethering events between autophagosomes and late endosomes. Furthermore, abrogation of autophagy also causes cholesterol accumulation that mimics the mutant NPC1-like phenotype. Therefore, the underlying defect in autophagy in NPC1 disease may be deleterious and can act as a positive mediator for accumulating cholesterol. Additionally, brain- and liver-specific abrogation of basal autophagy in mice is associated with degeneration in the affected organs, which may imply similar pathogenic effects of defective autophagy in patients with NPC1 mutations.

Although autophagy upregulation is a potential treatment strategy for neurodegenerative disorders (Rubinsztein et al., 2012; Sarkar, 2013), the utility of such an approach for lipid-/lysosomal-storage diseases is not clear (Lieberman et al., 2012). Our study reveals that stimulating autophagy in the context of NPC1 disease can restore the clearance of autophagic cargo by mediating autophagosome-lysosome fusion independent of amphiphase formation (Figure 7), which also suggests that the lysosomal proteolysis is functional. Our findings argue against inhibition of autophagy as a therapeutic strategy as reported recently by Ordonez et al. (2012) because such treatment may perturb its vital housekeeping functions (Hara et al., 2006; Komatsu et al., 2006, 2007, 2010; Ravikumar et al., 2010; Singh et al., 2009).

Our data suggest that stimulating autophagy does not rescue the cholesterol phenotype in NPC1 mutant cells, possibly because cholesterol is trapped in late endosomal compartments, whereas facilitating direct autophagosome-lysosome fusion restores functional autophagy. On the other hand, HP-β-cyclodextrin serves as cholesterol-depletion agent for NPC1 disease (Rosenbaum and Maxfield, 2011). Because HP-β-cyclodextrin also blocks autophagic flux, and with high doses being neurotoxic (Peake and Vance, 2012), our data emphasize the need for careful dosing of this drug. Thus, a low dose of HP-β-cyclodextrin that partially depletes cholesterol without perturbing autophagy, coupled with an autophagy inducer that restores autophagic flux by overcoming its block, may provide a rational combination treatment strategy for NPC1 disease. We have validated some of these clinically relevant observations in human hepatocytes derived from NPC1 patient-specific-induced pluripotent stem cells, where impaired autophagy is rescued by small molecules enhancing autophagy (D.M., S.S., H.W., and R.J., unpublished data). Our study points to upregulating autophagy as a possible therapeutic strategy for the treatment of lipid-/lysosomal-storage disorders.

**EXPERIMENTAL PROCEDURES**

Details of Experimental Procedures can be found in Supplemental Experimental Procedures.

**Culture of Mammalian Cells, Neural Stem Cells, and Primary Cortical Neurons**

Culture of Npc1+/+ and Npc1-/- MEFs (Loftus et al., 1997) (gift from Peter Lobel), Atg5+/+ and Atg5-/- MEFs (Kuma et al., 2004) (gift from Noboru Mizushima), Human embryonic kidney 293T cells, rat primary cortical neurons, mNSCs, and neuronal culture derived from mNSCs are described in the Supplemental Experimental Procedures.

**Immunoblot Analysis**

Cell lysates were subjected to western blot, as previously described (Sarkar et al., 2009). See the Supplemental Experimental Procedures for details and a list of primary antibodies.

**Immunofluorescence and Image Analysis**

Cells were fixed with 4% paraformaldehyde, permeabilized, and incubated with primary antibodies, as detailed in the Supplemental Experimental Procedures. Image analysis was performed using ImageJ software (NIH), as described in the Supplemental Experimental Procedures.

**Filipin and BODIPY Staining for Detecting Cholesterol and Lipid Accumulation**

Cholesterol accumulation in cells was visualized with Filipin staining (Filipin complex from Streptomyces pilninensis; F9765, Sigma-Aldrich). After paraformaldehyde fixation, cells were incubated with 1:5 mg/ml glycine for 10 min and incubated in 50 µg/ml Filipin for 2–3 hr at room temperature. Accumulation of neutral lipids in cells was visualized with BODIPY 493/503 staining (Singh et al., 2009) (4,4-Difluoro-1,3,5,7,8-Pentamethyl-4-bora-3a,4a-Diaza-s-Indacene; D-3922, Life Technologies). Cells were incubated with 1 µM BODIPY 493/503 in FM for 1 hr prior to paraformaldehyde fixation.

**MS Analysis**

Whole-cell lysates of Npc1+/+ and Npc1-/- MEFs from triplicate experiments were subjected to MS analysis. Sample preparation, chromatographic separations, MS, and data analysis are detailed in the Supplemental Experimental Procedures.

**Autophagy Analyses**

**Analysis of Autophagosome Synthesis with bafA1,**

Autophagosome synthesis was analyzed by measuring LC3-II levels (immunoblotting with anti-LC3 antibody) in the presence of 400 nM bafA1, as previously described (Sarkar et al., 2009). See the Supplemental Experimental Procedures for details.

**Analysis of Autophagic Flux with mRFP-GFP-LC3 Reporter**

Autophagosomes (mRFP+GFP+LC3) and autolysosomes (mRFP+GFP-LC3) were quantified by ImageJ software using parameters as previously described by Kimura et al. (2007). See the Supplemental Experimental Procedures for details.
Figure 6. Impaired Autophagic Flux In Vivo in Organs from Npc1−/− Mice and Rescue of Cell Death in Neurons with NPC1 Knockdown

(A and B) Immunoblot analyses with anti-NPC1, anti-p62, anti-LC3, and anti-actin antibodies in cerebellum (A) and liver (B) tissues from Npc1+/+ and Npc1−/− mice are shown.

(C) Immunoblot analyses with anti-NPC1, and anti-actin antibodies in primary mNSCs transduced with five different lentiviral Npc1 shRNAs or control shRNA are presented. High and low exposures of the same immunoblot are shown. Densitometric analysis was done on low exposures of immunoblots. Schematic representation of generating NPC1 knockdown neuronal cells is shown in Figure S6A.

(D) Immunofluorescence staining with anti-LC3 and anti-Tuj1 antibodies in neurons differentiated from mNSCs expressing control or Npc1−/− shRNA is shown. The scale bar represents 10 μm.

(E) Immunoblot analyses with anti-NPC1, anti-p62, anti-LC3, and anti-actin in neurons differentiated from mNSCs expressing control or Npc1−/− shRNA are shown.

(F) Immunoblot analysis with anti-LC3 and anti-actin antibodies in neurons differentiated from mNSCs expressing control or Npc1−/− shRNA, treated with or without 400 nM bafA1, for 4 hr, is shown.

(G) Immunoblot analysis with anti-p62 and anti-actin antibodies in neurons differentiated from mNSCs expressing Npc1−/− shRNA, treated with or without 200 nM rapamycin, 0.2% HP-β-cyclodextrin, or both for 72 hr, is shown.

(H) Immunofluorescence staining with anti-Tuj1 antibody in neurons differentiated from mNSCs expressing control or Npc1−/− shRNA is presented. Nuclei were stained with DAPI, and arrows show an apoptotic nucleus. The scale bar represents 10 μm.

(I) Analysis of cell death in Tuj1+ neurons differentiated from mNSCs expressing control or Npc1−/− shRNA, where neurons with NPC1 knockdown were treated with or without 200 nM rapamycin, 0.2% HP-β-cyclodextrin, or both for 72 hr, is presented. Graphical data denote mean ± SEM. ***p < 0.001, **p < 0.01, and *p < 0.05. ns, nonsignificant.
rescues the autophagy defects by facilitating autophagosome maturation through their fusion with the lysosomes independent of amphisome formation, thereby mediating the clearance of autophagic cargo. Overview of perturbations in the autophagy pathway in NPC1 disease is listed in Figure S7.

Analysis of Autophagic Cargo Flux with mCherry-GFP-p62 Reporter
p62 aggregates associated with autophagosomes (mRFP+ G-FP+ p62) and autolysosomes (mRFP+ G-FP+ p62) were quantified by ImageJ software using parameters as previously described by Pankiv et al. (2007). See the Supplemental Experimental Procedures for details.

Statistical Analyses
Densitometry analyses on the immunoblots from multiple experiments were performed by ImageJ software, as previously described (Sarkar et al., 2007). The control condition was set to 100%, and the data represented mean ± SEM. The p values for various analyses were determined by Student’s t test (unpaired) using Prism 6 software (GraphPad): ***p < 0.001, **p < 0.01, *p < 0.05 ("ns" indicates nonsignificant).

SUPPLEMENTAL INFORMATION
Supplemental Information includes Supplemental Experimental Procedures and seven figures and can be found with this article online at http://dx.doi.org/10.1016/j.celrep.2013.10.042.

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