A new glucocerebrosidase-deficient neuronal cell model provides a tool to probe pathophysiology and therapeutics for Gaucher disease

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ABSTRACT

Glucocerebrosidase is a lysosomal hydrolase involved in the breakdown of glucocerebrosides. Gaucher disease, a recessive lysosomal storage disorder, is caused by mutations in the gene GBA1. Dysfunctional glucocerebrosidase leads to accumulation of glucosylceramide and glucosylsphingosine in various cell types and organs. Mutations in GBA1 are also a common genetic risk factor for Parkinson disease and related synucleinopathies. In recent years, research on the pathophysiology of Gaucher disease, the molecular link between Gaucher and Parkinson disease, and novel therapeutics, have accelerated the need for relevant cell models with GBA1 mutations. Although induced pluripotent stem cells, primary rodent neurons, and transfected neuroblastoma cell lines have been used to study the effect of glucocerebrosidase deficiency on neuronal function, these models have limitations because of challenges in culturing and propagating the cells, low yield, and the introduction of exogenous mutant GBA1. To address some of these difficulties, we established a high yield, easy-to-culture mouse neuronal cell model with nearly complete glucocerebrosidase deficiency representative of Gaucher disease. We successfully immortalized cortical neurons from embryonic null allele gba−/− mice and the control littermate (gba+/+) by infecting differentiated primary cortical neurons in culture with an EF1α-SV40T lentivirus. Immortalized gba−/− neurons lack glucocerebrosidase protein and enzyme activity, and exhibit a dramatic increase in glucosylceramide and glucosylsphingosine accumulation, enlarged lysosomes, and an impaired ATP-dependent calcium-influx response; these phenotypical characteristics were absent in gba+/− neurons. This null allele gba−/− mouse neuronal model provides a much-needed tool to study the pathophysiology of Gaucher disease and to evaluate new therapies.

KEY WORDS: Gaucher disease, Glucocerebrosidase, Neuron, Glucosylceramide, Glucosylsphingosine

INTRODUCTION

The enzyme glucocerebrosidase (GCase), a lysosomal-resident hydrolase encoded by the gene glucocerebrosidase (GBA1), is involved in the breakdown of two substrates, glucosylceramide (GlcCer) and glucosylsphingosine (GlcSph). Gaucher disease (GD, MIM #606463), an autosomal recessive lysosomal storage disorder, is caused by mutations in GBA1. Deficient GCase leads to lysosomal substrate accumulation in cells of the macrophage lineage and clinical manifestations including organomegaly, anemia, thrombocytopenia, osteopenia and inflammation (Beutler and Grabowski, 2001; Sidransky, 2004). GD is classified into three types: a non-neuronopathic type 1, an acute neuronopathic type 2, and a chronic neuronopathic type 3, with a broad continuum of clinical manifestations in between (Sidransky, 2004). Mutations in GBA1 have now been established as an important risk factor for the development of synucleinopathies including Parkinson disease (PD) (Sidransky et al., 2009), dementia with Lewy bodies (DLB) (Nalls et al., 2013), and multiple system atrophy (MSA) (Mitsui et al., 2015). Furthermore, GCase enzyme activity and protein expression levels are reduced in select brain regions of individuals with PD without GBA1 mutations (Murphy et al., 2014; Gegg et al., 2012). Until recently, uncovering GD-associated cellular impairments was challenging because of the lack of relevant cell models. Primary dermal fibroblast cultures established from skin biopsies taken from individuals with GD were the only available cell model to study the biological implications of GCase deficiency, but these cells do not store lysosomal substrate. In recent years, intense research on the link between GBA1 mutations and synucleinopathies, as well as the development of novel therapeutics, has prompted the development of novel cell models. The majority of neuronal cell models commonly used for such studies include wild-type neuroblastoma cell lines or primary rodent neurons where GCase enzyme activity or GBA1 expression levels are exogenously modulated by treatment with the GCase suicide inhibitor conduritol B epoxide (CBE) (Manning-Bog et al., 2009; Cleeter et al., 2013; Dermentzaki et al., 2013), transfection with GBA1-specific siRNAs (Mazzulli et al.,...
Establishment of CD24-positive immortalized neurons

As previously mentioned, cultures established from mouse cortex contain a mixed cell population consisting of neurons and glial cells. We performed immuno-cytochemistry on the established SV40-T immortalized gba\(^{-/-}\) and gba\(^{+/+}\) cultures with the neuronal marker microtubule-associated protein-2 (MAP-2) and the astroglial marker glial fibrillary acidic protein (GFAP). The immortalized cultures of each genotype were positive for both MAP-2 and GFAP (Fig. 2A,B,E,F). Interestingly, GFAP-positive cells were only sporadically detected in gba\(^{-/-}\) cultures (Fig. 2F). We next selected cells that were negative for the neural stem and precursor cell marker CD29 and positive for the differentiated neuron marker CD24 (Pruszak et al., 2007). Immortalized cortical cell cultures of both genotypes were subjected to positive CD24 selection and negative CD29 selection using fluorescence-activated cell sorting (FACS) (Fig. 2C,G). After FACS, the vast majority of cells stained positive for MAP-2, whereas GFAP-positive cells were absent (Fig. 2D,H). Multiple studies have shown that SV40-T immortalization of cells induces aberrant karyotypes (Bloomfield and Duesberg, 2015; Stoner et al., 1991; Touli et al., 2002), a phenomenon also frequently observed in widely used cell lines such as HeLa and HEK293 (Landry et al., 2013; Stepunenko and Dmitrenko, 2015). Chromosome analysis on the gba\(^{-/-}\) and gba\(^{+/+}\) CD24-positive immortalized cortical neurons revealed aberrant heterogeneous

2011), or over-expression of plasmids containing mutant GBA1 (Cullen et al., 2011). Although these models have proven useful, exogenous manipulation of GCase or GBA1 expression often creates unwanted off-target effects. Primary neuronal cultures from one mouse model were used to probe mitochondrial function in GD (Osellame and Duchen, 2013; Osellame et al., 2013). Recently, the development of induced pluripotent stem cell (iPSC) lines from GD patients and carriers has gained popularity, providing the opportunity to develop cell cultures of previously inaccessible diseased human neurons (Tiscornia et al., 2013; Woodard et al., 2014; Sun et al., 2015; Schondorf et al., 2014; Awad et al., 2015).

The main disadvantages of both primary rodent neuronal cultures and iPSC-generated neurons are low cell culture yield and the labor-intensiveness of establishment and maintenance. We hypothesized that immortalized GD neurons derived from a GD mouse model could provide a high-yield, easy-to-maintain alternative for investigations of the cellular mechanisms involved in GD. Such immortalized neurons could also have utility for the evaluation of novel therapeutics and the validation of different reagents and antibodies.

Immortalization of primary cells is accomplished by exogenous introduction of immortalizing genes such as the SV40 large T antigen (SV40-T), which increases lifespan and induces unlimited proliferation by inactivation of the cell-cycle suppressors pRB, SEN6 and p53 (Ozer et al., 1996; Tevet ethia et al., 1998; Manfredi and Prives, 1994; Ozer, 2000; Jha et al., 1998). Neurons are terminally differentiated post-mitotic cells, which makes gene delivery via traditional transfection methods difficult. Lentiviral expression vectors have the ability to transduce proliferating and non-proliferating cells, and have been used for infection of primary rodent neuronal cultures (Lewis et al., 1992; Weinberg et al., 1991; Zhang et al., 2006; Ding and Kilpatrick, 2013; Eleftheriadou et al., 2014; Li et al., 2012). In this study, we report the successful SV40-T-mediated immortalization of mouse cortical neurons derived from a previously established mouse model deficient in murine glucocerebrosidase (Tybulewicz et al., 1992).

RESULTS

The EF1\(\alpha\) promoter drives expression in cultured mouse cortical cells

Several independent studies established that promoter determination for optimal gene expression in a specific cell type is beneficial (Day et al., 2009; Tsuchiya et al., 2002). Therefore, we tested a panel of eight different promoters fused to enhanced green fluorescent protein (eGFP) for their expression capacity in C57BL/6 primary mouse neuronal cultures (Table 1). Brains from 17E C57BL/6 embryos were harvested and neuronal cultures were established. Six-day-old primary embryonic cortical neuronal cultures were transduced with lentivirus containing recombinant genes encoding mPoI2, Grp78, FerH, CAG, CMV13, PGK, EF1\(\alpha\) or TRE-Tight fused to eGFP. We identified the EF1\(\alpha\) promoter as an optimal promoter for primary mouse cortical cells with robust eGFP expression five days after infection at multiplicity of infection (MOI) 40 (Fig. 1A). At this point, the infected primary mouse cortical cell cultures consist of a mixed population of neurons and glial cells. Our findings were in agreement with previous studies where EF1\(\alpha\) was identified as a suitable promoter for expression in rat cortical cell cultures and mouse neuronal precursor cells (Tsuchiya et al., 2002; Zeng et al., 2003).

**Table 1. Promoter panel**

<table>
<thead>
<tr>
<th>Promoter</th>
<th>Promoter description</th>
<th>Reporter</th>
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<tbody>
<tr>
<td>CMV</td>
<td>Human cytomegalovirus immediate early promoter/Enhancer</td>
<td>eGFP</td>
</tr>
<tr>
<td>FerH</td>
<td>Human ferritin heavy chain promoter, SV40 enhancer</td>
<td>eGFP</td>
</tr>
<tr>
<td>mPoI2</td>
<td>Murine RNA polymerase II promoter</td>
<td>eGFP</td>
</tr>
<tr>
<td>Grp78</td>
<td>Hamster glucose-response protein 78 promoter, CMV enhancer</td>
<td>eGFP</td>
</tr>
<tr>
<td>CAG</td>
<td>Chicken (\beta)-actin promoter, CMV enhancer</td>
<td>eGFP</td>
</tr>
<tr>
<td>PGK</td>
<td>Human phosphoglycerate kinase promoter</td>
<td>eGFP</td>
</tr>
<tr>
<td>EF1(\alpha)</td>
<td>Human elongation factor (1\alpha) promoter</td>
<td>eGFP</td>
</tr>
<tr>
<td>TRE-Tight</td>
<td>Modified CMV promoter inducible with doxycycline</td>
<td>eGFP</td>
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karyotypes, which was expected as the cultures are heterogeneous and not clonal. Chromosomal abnormalities include numerical abnormalities (+Y, +5, +14, +16) and morphological abnormalities like translocation 5;19 (Fig. 3A,B).

gba−/− immortalized neurons have deficient GCase enzymatic activity and show substrate storage

The previously described neonatal-lethal mouse model of type 2 GD is characterized by severe GCase enzyme deficiency and accumulation of GlcCer in the brain (Tylbulewicz et al., 1992). We analyzed the CD24-positive immortalized mouse neurons and found that these characteristics were preserved. gba−/− immortalized neurons showed a severe deficiency in enzyme activity (3.40±0.36% relative GCase activity, mean±s.e.m.) compared with gba+/+ immortalized neurons (93.44±12.26% relative GCase activity), which was highly significant (P=0.0017) (Fig. 3C). GCase protein could not be detected in gba−/− lysates with the previously described GCase-specific inhibody MDW933.
Subsequently, we performed LC-MS-MS analysis of glycosphingolipids, which revealed significant GlcCer storage ($P=0.0005$) in $gba^{-/-}$ immortalized neurons (1500±118.9 GlcCer/mg protein) compared with $gba^{+/+}$ immortalized neurons (165.1±6.14 GlcCer/mg protein) (Fig. 3E). Significant GlcSph storage ($P<0.0001$) was observed in $gba^{-/-}$ immortalized neurons (485.7±21.24 GlcSph/mg protein) compared with $gba^{+/+}$ immortalized neurons (0.071±0.02 GlcSph/mg protein) (Fig. 3F). Next, we analyzed expression of alpha-synuclein ($\alpha$-syn), which is a small protein (14 kDa) with abundant expression in neurons. Aggregation of $\alpha$-syn results in the formation of insoluble oligomeric and fibrillar inclusions, a prominent pathological feature in the brain of individuals with synucleinopathies (Fearnley and Lees, 1991; Puschmann et al., 2012; Puschmann, 2013). High $\alpha$-syn protein expression has been reported in cultured primary mouse neurons, including $gba$-deficient mouse neurons (Osellame et al., 2013). Western blot analysis with two different antibodies against $\alpha$-syn did not show any monoclonal $\alpha$-syn protein expression in $gba^{-/-}$ and $gba^{-/-}$ immortalized mouse neurons (data not shown).

$gba^{-/-}$ immortalized neurons have enlarged lysosomes

Gaucher cells, engorged macrophages with lysosomal GlcCer accumulation, are primarily found in the spleen, liver and bone marrow of individuals with GD (Sidransky, 2012). These typical enlarged, lipid-laden lysosomes were previously identified in the liver and bone marrow of $gba^{-/-}$ mice (Tybulewicz et al., 1992). We investigated whether the CD24-positive $gba^{-/-}$ neurons, which show GlcCer and GlcSph substrate storage (Fig. 3E,F), have enlarged lysosomes by estimating the lysosomal volume per cell in $gba^{-/-}$ and $gba^{-/-}$ neurons using LysoTracker®, which specifically stains acidic endosomal compartments. Using an established FACS analysis method to calculate the fold-change in LysoTracker® (Fig. 3D, lane 2).
ratio of the geometric means of LysoTracker® in stained and unstained samples (Rodriguez-Gil et al., 2013), we detected a significant increase ($P=0.0003$) in intensity of LysoTracker® staining of gba$^{+/−}$ neurons (fold-change $17.7±0.83$) compared with gba$^{−/−}$ (fold-change $7.13±0.23$) (Fig. 4A). This was confirmed with a 96-well high-throughput imaging assay (Acosta et al., 2015) where enlarged lysosomes had increased LysoTracker® signal intensity, reflecting the size and number of acidic endosomes. After segmentation, the number of LysoTracker® objects or region of interest (ROI) and total pixels per image were quantified and divided by the number of cells in the image. Lysosomal volume in gba$^{+/−}$ cells (80.22±1.79), measured as total LysoTracker® pixels per cell, was almost four times greater than gba$^{−/−}$ cells (22.12±1.85) (Fig. 4B). The number of ROIs acquired per cell was also significantly higher in gba$^{−/−}$ (6.79±0.11) compared with gba$^{+/−}$ (2.36±0.13) (Fig. 4C).

gba$^{−/−}$ neurons show an impaired ATP-dependent Ca$^{2+}$ response

Previous studies have shown that rodent neuronal cell models and brain samples from individuals with GD showed increased Ca$^{2+}$ release from intracellular Ca$^{2+}$ stores such as the endoplasmic reticulum (ER) into the cytosol (Korkotian et al., 1999; Pelled et al., 2000, 2005; Lloyd-Evans et al., 2003a,b). Cytosolic Ca$^{2+}$ can also be modulated by influx of Ca$^{2+}$ from the extracellular environment into the cytosol via ATP-selective purinergic receptors (P2X receptors), which are expressed on the plasma membrane of glial cells and neurons (Saez-Orellana et al., 2015). We measured ATP-dependent Ca$^{2+}$ influx with the intracellular Ca$^{2+}$ marker Fluo-4 AM (Fig. 4D). Immediately after treatment with 3 µM, 1 µM, 0.3 µM or 0.1 µM of ATP, we observed a significant dose-dependent elevation of Ca$^{2+}$ influx in gba$^{+/+}$ (black dots) compared with gba$^{−/−}$ neurons (white dots) ($P=0.0036$), which suggest that treatment with ATP failed to induce Ca$^{2+}$ influx in gba$^{−/−}$ neurons (Fig. 4D). The Ca$^{2+}$ influx data was normalized to the number of cells seeded in each well of the 96-well plate with the CellTag 700 assay.

DISCUSSION

The establishment of high-yield and easy-to-manipulate immortalized gba$^{−/−}$ neuronal cells from a previously described gba-deficient mouse model can serve as a valuable tool to test newly discovered cellular mechanisms or therapeutics. This is particularly useful before moving to primary neurons or iPSC-derived neurons, which have a low cell culture yield, are costly, and are labor-intensive to establish and maintain. Most other available neuronal cell models rely on the GCase suicide inhibitor CBE, gba1 gene silencing, or exogenous introduction of GBA1 mutants to modulate GCase (Manning-Bog et al., 2009; Cleeter et al., 2013; Dermentzaki et al., 2013; Mazzulli et al., 2011; Cullen et al., 2011).

Primary neurons are post-mitotic cells that are terminally differentiated. However, upon introduction of SV40-T, primary cells are forced into proliferation resulting in increases in life-span (Ozer et al., 1996; Tevethia et al., 1998; Manfredi and Prives, 1994; Ozer, 2000; Jha et al., 1998). After SV40-T-mediated immortalization, we obtained actively dividing cortical cells that retained the neuronal marker MAP-2 and glial marker GFAP. FACS on cortical cell cultures allowed us to isolate CD24-positive neurons, which were exclusively positive for MAP-2 and negative GFAP. Cellular defects observed in the mouse model such as the absence of GCase protein expression and enzyme activity as well as elevated levels of GlcCer and GlcSph substrate (Tybulewicz et al.,...
levels contribute to neuronal cell death via increased ryanodine GlcSph storage. Current literature proposes that elevated GlcCer (Volonte et al., 2003). ATP-dependent P2X receptor-mediated Ca2+ influx in gba−/− neurons and the associated implications on neurological function.

Multiple studies have shown that SV40-T-mediated immortalization of primary cells induces aberrant karyotypes (Bloomfield and Duesberg, 2015; Stoner et al., 1991; Toouli et al., 2002), which is also frequently observed in widely used cell lines such as HeLa and HEK293 (Landry et al., 2013; Stepanenko and Dmitrenko, 2015). Chromosomal analysis of the immortalized gba−/− and gba+/− CD24-positive neuronal cultures revealed heterogeneous aberrant karyotypes, which was expected as the cultures are not clonal. We are confident that the observed phenotypes are related to absence of gba1 and not random integration location. Recently, Gramlich and co-workers used this immortalized gba−/− cell model as an in vitro model for the evaluation of neuronal uptake and substrate turnover of newly developed recombinant GCase proteins. Uptake of GCase proteins into gba−/− neurons showed a significant reduction of GlcSph storage (Gramlich et al., 2016). We were aware that phenotype drifting might happen; however, confirmation of experimental reproducibility on different cell passage numbers revealed little variation.

In summary, we describe the first successful SV40-T-mediated immortalization of mouse cortical neurons derived from a previously established gba-deficient mouse model (Tybulewicz et al., 1992). The immortalized gba−/− neurons express neuronal markers and exhibit a gba-deficient phenotype characterized by GCase enzyme deficiency, absent GCase protein expression, and significant accumulation of GlcCer and GlcSph. This original neuronal cell line constitutes a relevant, high-yield, and easy-to-manipulate in vitro tool for not only assessing the molecular and cellular defects associated with GD, but also for developing and evaluating novel therapeutic strategies (Gramlich et al., 2016).

MATERIALS AND METHODS
Culturing of primary mouse neurons
Animal studies were in accordance with protocol G-05-4, which was approved by NHGRI Animal Care and Use Committee (National Institutes of Health, Bethesda, MD, USA). Brains from gba-deficient or C57BL/6 mouse embryos at day 17 (17E) were harvested and placed in cold dissecting media [10 mL L15 media, 0.15 mL HEPES buffer, and 0.15 mL pen/strep (Life Technologies, Grand Island, NY, USA)]. The meninges was removed, cortices were isolated, minced and incubated for 45 min at 37°C in papain solution with DNasel (Worthington Biochemical Corporation, Lakewood, NJ, USA). Minced cortices were gently triturated (10-15 times) followed by centrifugation at 164 g for 5 min at room temperature (RT). The supernatant was removed and cell pellet was resuspended in 500 μl papain inhibitor (Worthington Biochemical Corporation) with DNasel. After 10 min, stop solution was aspirated and 10 ml of a 10/10 solution HBSS (Life Technologies, Grand Island, NY, USA) was added to the settled cells. The cells were spun down at 105 g for 10 min. After removing the supernatant, cell pellets were resuspended in 2 ml neurobasal growth media [500 μl neurobasal media, 1.50 (v/v) B27, 1.200 (v/v) glutamine, and 25 mM HEPES (Life Technologies)], 500 μl of cell suspension with 2.5 ml of neurobasal growth media was added to each well of a 6-well plate precoated with poly-L-lysine (Sigma Aldrich). 50% of the neurobasal growth media was changed every 3 days.

Chemicals and antibodies
Coniduritol B epoxide (CBE) (Sigma Aldrich), an irreversible inhibitor of glucocerebrosidase, was dissolved in DMSO to a stock solution of 100 μM. Valproic acid (Sigma Aldrich), a histone deacetylase inhibitor, was dissolved in ethanol to a stock solution of 200 mM. The following...
antibodies were used for western blotting: anti-SV40T mouse monoclonal (Santa Cruz Biotechnology Inc., CA, USA, sc-148, 1:2000), anti-α synuclein rabbit polyclonal (Santa Cruz Biotechnology Inc., sc-7011-R, 1:1000), anti-α synuclein polyclonal (EMD Millipore, Billerica, MA, USA, AB5038, 1:1000), anti-beta Actin conjugated to HRP (Abcam, Cambridge, MA, USA, ab20272, 1:5000), and MAP-2 rabbit polyclonal (Cell Signaling, Danvers, MA, USA, 8705S, 1:1000). The following antibodies were used for immunocytochemistry: anti-SV40T mouse monoclonal (Santa Cruz Biotechnology Inc., sc-148, 1:100), anti-GFAP rabbit polyclonal (Abcam, ab16997, 1:100), anti-MAP2 chicken polyclonal (Abcam, ab92434, 1:100).

Lentiviral vector production and transfection
Lentiviral plasmid DNA was co-transfected with ViraPower Lentiviral packaging plasmids (Life Technologies) into HEK293T cells to generate VSV-g pseudotyped lentivirus particles. The cells received fresh DMEM media (Life Technologies) 24 h post-transfection and the culture supernatant was harvested 48 h post-transfection. The crude lentivirus stock was filtered, centrifuged and concentrated using Amicon Ultra-15 columns (EMD Millipore). Virus titer was determined with the Global Ultra Rapid Lentiviral Titer kit (System Biosciences, Mountain View, CA, USA) according to the manufacturer’s guidelines. Lentiviral particles were infected at multiplicity of infection (MOI) 40 with the TransDux reagent according to the manufacturer’s guidelines (System Biosciences).

Promoter testing and immortalization of primary mouse neurons
Packed lentiviral particles, containing enhanced green fluorescent protein (eGFP) driven by distinct promoters (mPol2, Gp78, FehH, CAG, CMV13, PGK, EF1α, TRE-Tight), were ordered from Leidos Biomedical Research Inc. (Frederick, MD, USA). 6-day-old primary cortical neuron cultures from C57BL/6 mice were infected at MOI 10, 20 and 40 with the TransDux reagent. eGFP expression was evaluated after 5 days of infection with a fluorescence microscope (Zeiss, San Diego, CA, USA). Packed lentiviral particles containing EF1α-SV40T were ordered from Leidos Biomedical Research Inc and 6-day-old primary cortical neuron cultures from gba−/− and gba+/− mice were infected at MOI 40 with TransDux reagent (System Biosciences). After 4 days of infection, the cultures were treated with 1 µg/ml of puromycin (Sigma Aldrich) for 4 weeks; the media was changed every 3 days.

In vivo tumor formation
Animal studies were in accordance with a protocol approved by the Local Ethics Committee of Ghent University Hospital (Ghent, Belgium). At the age of 5 weeks, female Swiss nu/nu mice (five mice per genotype; Charles River Laboratories, Brussels, Belgium) were injected intraperitoneally with 10⁶ cells resuspended in 100 µl matrigel. Tumor growth was assessed after 4 weeks of injection.

Spectral karyotyping
Metaphase slides were prepared after mitotic arrest with 2-4 h Colcemid (0.015 µg/ml; Thermo Fisher Scientific), 20 min hypotonic treatment (0.075 mol/l KCl, 37°C), and fixation with methanol–acetic acid (3:1). For spectral karyotyping we used commercial SKY probe (Applied Spectral Imaging Inc., Carlsbad, CA, USA) allowing the visualization of the individually colored chromosomes. This technique is used to identify structural and numerical chromosome aberrations in mouse cell lines (Schrock et al., 1996).

Immunocytochemistry and laser scanning confocal microscopy
Cells were grown for 48 h on Lab-Tek chamber slides (Thermo Scientific, Waltham, MA, USA). Cells were fixed in 4% paraformaldehyde (Electron Microscopy Sciences, Hatfield, PA, USA), blocked in 1× PBS (Life Technologies) containing 0.1% saponin (Sigma Aldrich), 100 µM glycine (Sigma Aldrich), and 2% donkey serum (Jackson Immunoresearch Laboratories Inc, West Grove, PA, USA) followed by a 4°C overnight incubation with primary antibodies. Cells were washed with 1× PBS and incubated with the following secondary antibodies (all from Life Technologies): anti-mouse Alexa Fluor 488 (A-11001; 1:300), anti-chicken Alexa Fluor 488 (A-11039; 1:300), anti-rabbit Alexa Fluor 555 (A-21428; 1:300), for 1 h at RT, washed again, and mounted with Prolong Gold antifade reagent with or without DAPI (Life Technologies). Cells were imaged with a Zeiss 510 META confocal laser-scanning microscope (Carl Zeiss Microscopy, Munich, Germany) using a 488 argon, a 543 HeNe, and a diode laser. Images were acquired using a Plan Neofluor 40×/1.4 oil DIC objective or a Plan Apochromat 63×/1.4 oil DIC objective. Bright-field images were obtained for visualization of neuron morphology.

Fluorescence-activated cell sorting (FACS)
Neurons and glial cells of immortalized gba−/− and gba+/− neuronal cultures were separated by FACS. Cells of each genotype were labeled with FITC hamster anti-rat CD29 and PE rat anti-mouse CD24 (BD Biosciences, San Jose, CA, USA). Single-stained and unstained cells were used as a control. Cells were sorted using a BD FACSAriaIIi cytometer (BD Biosciences). Results were analyzed with FACSDiva software version 6.1.3 (BD Biosciences).

Western blotting
The amount of protein for each sample was determined by DC™ protein assay (Bio-Rad Laboratories, Hercules, CA, USA). An equal amount of protein for each sample was loaded onto a 4-20% Mini-PROTEN® TGXTM gel (Bio-Rad Laboratories). After blotting with the Trans-Blot Turbo transfer system (Bio-Rad Laboratories), PVDF membranes (Bio-Rad Laboratories) were blocked for 1 h at RT in blocking solution [1× PBS, 0.5% (v/w) milk, 0.1% Tween (Sigma Aldrich)]. PVDF membranes were probed overnight with primary antibodies in blocking solution at 4°C. PVDF membranes were washed 3× 5 min at RT with blocking solution. This was followed by incubation with HRP-coupled secondary anti-mouse or anti-rabbit antibodies (Amersham Biosciences, Piscataway, NJ, USA, NA931 and NA934, respectively, 1:4000). PVDF membranes were washed 3× 5 min with blocking solution followed by 3× 5 min with 1× PBS plus 0.1% Tween. The antigen-antibody complexes were detected with an Enhanced Chemiluminescence (ECL) kit (Amersham Biosciences).

Quantification of GCase protein levels
Fluorescent activity-based probes specific for GCase (MDW933) were synthesized at the Imaging Probe Development Center (National Heart Lung and Blood Institute, Bethesda, MD, USA) as previously described (Witte et al., 2010). Total protein concentration of each sample was measured using a Bradford assay according to the manufacturer’s guidelines (Bio-Rad Laboratories). Cell homogenate was incubated with 1 µM of green fluorescent MDW933 probe in citrate phosphate buffer (pH 5.4) for 90 min. Samples were analyzed on a 4-20% Mini-PROTEN® TGXTM gel (Bio-Rad Laboratories) using 1.2 µM imiglucerase (Genzyme, Cambridge, MA, USA) with 1 µM MDW933 probe as a control. A Typhoon Variable Mode Imager (Amersham Biosciences, Piscataway, NJ, USA), set to excitation wavelength (λex)=488 nm and emission wavelength (λem)=520 nm, was used to measure the fluorescent signal in the gel.

GCase enzyme activity assay
Cell lysates were prepared in citrate-phosphate extraction buffer [150 mM citrate-phosphate buffer pH 5.4, 0.25% Triton X-100, protease inhibitor mix (Roche Diagnostics, Indianapolis, IN, USA)] and sonicated for 20 s at 50% amplitude using a mechanical tissue homogenizer (Omni International, Kennesaw, GA, USA). Cell homogenates were then centrifuged at 10,000 g for 15 min at 4°C. GCase enzyme activity was measured in an assay buffer composed of citrate-phosphate buffer (pH 5.4) with 10 mM 4-methylumbelliferyl-[β-D-glucopyranoside (Sigma Aldrich). Cell homogenate (5 µl) was added to each individual well of a black 384-well plate (VWR International, Bridgeport, NJ, USA) and each sample was read in triplicate. To correct for cytosolic gba2 activity, 5 µl of a 100 µM CBE solution (Sigma Aldrich) was added in triplicate and assay buffer was pipetted to each well to bring the total assay volume to 30 µl. The plate was briefly centrifuged and then incubated at 37°C for 1 h at 600 rpm. The reaction mixtures were quenched by the addition of 30 µl of stop solution (1 M glycine, pH 12.5) and fluorescence was measured using a FlexStation
3 Multi-Mode Microplate Reader (Molecular Devices, Sunnyvale, CA, USA), at λex=520 nm and λem=440 nm. Enzyme activity was normalized based on total protein amount. Data were analyzed by a Student’s two-tailed t-test and are represented as mean±s.e.m.

**FACS analysis for lysosomal size**

gba+/− and gba−/− neurons were plated in 60 mm tissue culture dishes (VWR International) and grown to 80% confluency. The cells were given fresh neurobasal growth media 24 h before analysis. On the day of analysis, cells were incubated with neurobasal media supplemented with 1 μM Lysotracker Red DND-99 (Thermo Fisher Scientific) for 1 h at 37°C. FACS analysis was performed on a FACSCalibur (BD Biosciences, Franklin Lakes, NJ, USA) according to a previously described protocol (Rodriguez-Gil et al., 2013). Biological duplicates were analyzed in three independent experiments (n=3). Fold-change was calculated as the ratio of the geometric means of Lysotracker Red stained and unstained samples. Data were analyzed by a Student’s two-tailed t-test and represented as mean±s.e.m.

**High-throughput imaging for lysosomal size**

A recently described protocol was optimized for high-throughput imaging on SV40 immortalized gba+/− and gba−/− neurons (Acosta et al., 2015). The cell lines were plated in a black clear bottom 96-well plate in neurobasal media. Sixteen wells per cell line were plated. After 72 h, cells were treated with 1 μM Lysotracker Red (Life Technologies) for 20 min and washed with 1× PBS. Cells were fixed with 4% paraformaldehyde for 5 min followed by 3× washes with PBS. Cells were counterstained with 300 nM DAPI (Life Technologies). The BD Pathway® 855 High Content Bioimager (BD Biosciences, Franklin Lakes, NJ) was used to acquire images in each well under identical settings for exposure, dynamic range, and laser autofocus. Images for each well were taken using a 2×2 montage with the 20× objective yielding an average of 400 cells per image (~6400 cells per treatment). For each well, fluorescent signal (excitation/emission) was acquired at λex=560 nm and λem=465 nm for the red signal and λex=380 nm and λem=440 nm for the blue signal. Image segmentation was performed using Attovision® software (BD Biosciences). Cell count was obtained using polygon segmentation for the nucleus DAPI signal. LysoTracker® regions of interest (ROI) were obtained by polygon segmentation of one of each compartment detected in the red signal. Segmentation data was analyzed by BD Data Explorer® software (BD Biosciences). An average of LysoTracker® pixels per cell was calculated for each image. Averages of the sixteen images (n=16) were used to estimate the value of each treatment. Data were analyzed by a Student’s two-tailed t-test and represented as mean±s.e.m.

**Lipidomics**

Glycosphingolipids (glucosyl- and galactosyl-sphingosines, glucosyl- and galactosyl-ceramides) were extracted with methanol from mouse homogenized immortalized neurons containing N,N-dimethylglycero-phosphoinosine and galactosylceramide (d18:1 8:0) as internal standards. Glycosphingolipid analysis was initially carried out for quantification of glycosphingolipins and glucosylceramides using a Varian reverse phase C-18 metasil column that was connected to an API 4000 LC-MS-MS system (Applied Biosystems). Later isomer separation of glycosphingolipids was performed using a Supelco HILIC column for determination of the isomer composition. Positive ion electrospray method using MRm was used for both analyses. Data were normalized to protein content in the samples. Data was analyzed by a Student’s two-tailed t-test and represented as mean±s.e.m.

**Calcium assay**

On day one, SV40-T immortalized neurons were seeded at 70% confluency in a black flat clear bottom 96-well plate (Corning Inc., Kennebunk, ME). On day 3, neurobasal media was removed from the cells and assay buffer, which consists of physiological salt solution (PSS) buffer (126 mM NaCl, 5 mM KCl, 1.2 mM MgCl2, 10 mM HEPES, 10 mM glucose, 1 mM CaCl2 +0.2 mM sulpfinpyrazone +0.1 mM CaCl2 +12 μl pluronic F-127 (Life Technologies)+60 μg fluo-4 AM (Life Technologies), was added and incubated for 1 h at 37°C and 10% CO2. Assay buffer was removed and cells were washed once with 1× PBS followed by incubation with PSS buffer+0.2 mM sulpfinpyrazone+0.1 mM CaCl2 for 10 min at 37°C and 10% CO2. The 96-well plate was inserted into the Flexstation 3 plate reader (Molecular Devices, Sunnyvale, CA) and the cells were treated with 10 μM, 3 μM, 1 μM, 0.3 μM and 0.1 μM of ATP dissolved in PSS buffer. PSS buffer without ATP was included as a negative control. The Flex mode setting was used with λex=494 nm and λem=516 nm. ATP-dependent Ca2+ response was followed for 120 s over 10 s intervals with six readings per well. The experiment included quadruplicate samples per plate and was repeated two independent times. Dose-dependent curves were fitted and EC50 was calculated.

**CellTag 700 assay**

After data acquisition on the Flexstation-3 plate reader, the cells in the black 96-well plate were fixed in 4% paraformaldehyde for 1 h at RT. This was followed by permeablilization with 0.1% Triton-X (Sigma Aldrich) for 10 min at RT. The cells were washed with 1× PBS followed by incubation with CellTag 700 (LI-COR Biosciences, Lincoln, NE, USA) (1:3000) for 1 h at RT. After washing twice with 1× PBS, the plate was dried and imaged on the LI-COR imaging station (LI-COR Biosciences).

**Statistical analysis**

Data obtained from GCase enzyme activity, substrate storage, and lysosomes were analyzed by a Student’s two-tailed t-test with GraphPad Prism® software version 6.0 (GraphPad, San Diego, CA, USA) and data are represented as mean±s.e.m. For ATP-dependent Ca2+ response, dose curves were fitted and EC50 was calculated with the GraphPad Prism® (version 6.0).

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**Competing interests**

The authors declare no competing or financial interests.

**Author contributions**


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**References**


