Identification of a feedback loop involving β-glucosidase 2 and its product sphingosine sheds light on the molecular mechanisms in Gaucher disease

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Gaucher disease is one of the most common lysosomal storage disorders in humans. It results from a deficiency in the activity of the lysosomal enzyme, acid β-glucosidase GBA1 (also termed GCase) (1). So far, more than 200 different mutations in the GBA1 gene have been identified in Gaucher patients (2), all leading to the loss of enzyme activity, resulting in GlcCer accumulation in the lysosome. This is predominantly evident in tissue macrophages, which turn into massively enlarged “Gaucho” cells, causing an up to 25-fold increase in organ size (organomegaly) of liver and spleen (3, 4). Gaucher disease has been classified into three major subtypes, namely types I, II, and III (4). Type I is the most common, with patients displaying organomegaly of liver and spleen and defects in lung and bone marrow. Type II patients have the acute infantile neuropsychological form, characterized by severe neurological defects and an early onset of disease. These patients usually die within the first 2–3 years of life, whereas type III patients develop a slowly progressive neuropsychological phenotype. It has been assumed that residual GBA1 activity might help to predict the severity of Gaucher disease, but the severity of the disease even differs between patients carrying the same mutation (5). Thus, little genotype-phenotype correlation has been established so far.

How the accumulation of GlcCer in the lysosomes causes the complex Gaucher pathology is not well understood. Moreover, deficiency of GBA1 also causes accumulation of glycosylsphingosine (GlcSph) (6–8), which may also contribute to the neurological manifestation (9, 10). It has been proposed that in Gaucher cells, both, GlcCer and GlcSph, leave the lysosome, becoming substrates for the non-lysosomal β-glucosidase GBA2 (11, 12), which resides at the cytoplasmic surface of the ER and cis-Golgi (13). In turn, GBA2 might hydrolyze GlcCer to glucose and ceramide and GlcSph to glucose and sphingosine (11, 12). Ceramide can be further broken down to sphingosine and a fatty acid by neutral ceramidases. Hence, on the back-
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ground of reduced GBA1 activity in lysosomes and leakage of its substrates outside the lysosomes, GBA2 activity might lead to an increased generation of sphingosine at the ER and cis-Golgi. It has been proposed that sphingosine is the cytotoxic metabolite that causes some of the defects associated with Gaucher disease, at least upon its chronic accumulation (12). In fact, deletion of GBA2 rescued some of the pathologies by reducing the accumulation of sphingosine (12). This is in line with our previous findings, indicating that GBA2 activity is altered when GBA1 activity is lost (13).

Here, we set out to investigate the role of GBA2 in Gaucher disease. We demonstrate that GBA2 activity depends on GBA1 activity, but not vice versa. GBA2 activity is inhibited by the cytotoxic metabolite sphingosine, which directly binds to GBA2. Our results suggest a negative feedback loop in Gaucher cells, in which sphingosine prevents its excessive accumulation by inhibiting the activity of GBA2 through direct binding.

Results

GBA2 activity is down-regulated in the absence of GBA1 activity

Based on our previous results (13), we analyzed GBA2 activity in fibroblasts from different types of Gaucher patients and in control fibroblasts using a fluorescence-based activity assay (13) that contains the artificial and water-soluble substrate 4-methylumbelliferyl-β-D-glucopyranoside (4-MUG) and determines GBA1 activity at pH 4 and GBA2 activity at pH 6. For each pH, we included the GBA1-specific inhibitor conduritol B epoxide (CBE) and the GBA2-inhibitor N-butyldeoxynojirimycin (NB-DNJ) at concentrations that only inhibit the respective enzyme (13). As expected, GBA1 activity was almost absent in hypotonic lysates from Gaucher fibroblasts, with residual activities of 8, 2.6, and 5.6% for types I, II, and III, respectively (Fig. 1A). In line with our earlier findings (13), GBA2 activity in all types of Gaucher fibroblasts was decreased to around 60% of the activity in control cells (Fig. 1B). There was no difference in GBA2 activity between fibroblasts derived from patients with different genotypes and phenotypes, indicating that GBA2 activity is reduced independent of the Gaucher genotype and phenotype. To confirm this result, we measured GBA2 activity in two independent GBA1-deficient human fibroblast-like cell lines (HAP1) generated via CRISPR/Cas9 (Fig. 1, C and D). The first GBA1-deficient HAP1 cell line (HZGH002786c001, abbreviated #001) contains a 479-bp insertion in exon 6 of the GBA1 gene and the second GBA1-deficient HAP1 cell line (HZGH002786c010, abbreviated #010) contains a 1-bp insertion in exon 6, both resulting in a frameshift and, therefore, in gene silencing. In both cell lines, GBA1 activity was absent and GBA2 activity was reduced by ~40% (Fig. 1, C and D). As a control, we determined the GBA1 activity in two independent GBA2-deficient human fibroblast-like cell lines generated via CRISPR/Cas9 (Fig. 1, E and F). However, in the absence of GBA2 activity, GBA1 activity remained largely unchanged (Fig. 1, E and F). In summary, GBA2 activity is down-regulated in the absence of GBA1 activity, but not vice versa.

To study whether the decrease in GBA2 activity is due to a change in GBA2 expression, we analyzed GBA2 mRNA and protein expression. The mRNA expression in dermal fibroblasts from different types of Gaucher and control patients was determined using quantitative real-time PCR (Fig. 1, G and H). For both, GBA1 and GBA2, there was no significant difference in relative mRNA expression between control fibroblasts and Gaucher fibroblasts from the different genetic backgrounds (Fig. 1, G and H). Protein expression in dermal fibroblasts from Gaucher and control patients was analyzed by Western blotting (Fig. 1I). The GBA1 protein level in fibroblasts from Gaucher patients was significantly reduced compared with control cells with GBA1 expression being lowest in fibroblasts from type II patients (Fig. 1, J and K). However, GBA2 protein expression remained largely unchanged in control and Gaucher fibroblasts (Fig. 1, J and K). Thus, down-regulation of GBA2 activity in the absence of GBA1 activity is not due to a decrease in GBA2 mRNA or protein expression.

GBA2 activity depends on GBA1 activity in vitro and in vivo

To gain mechanistic insight how GBA1 controls GBA2 activity, we analyzed whether blocking GBA1 activity is sufficient to reduce GBA2 activity. Here, we applied a pharmacologic approach. Control human fibroblasts were treated with 25 μM CBE for 48 h to block GBA1 activity (Fig. 2, A and B). Of note, this CBE concentration does not block GBA2 activity (13). GBA1 activity was dramatically reduced in CBE-treated cell lysates compared with the non-treated controls (Fig. 2A). In line with our findings from Gaucher and GBA1-deficient fibroblasts, GBA2 activity in CBE-treated cells was reduced to ~39% of the activity in non-treated control cells (Fig. 2B). These results demonstrate that blocking GBA1 activity is sufficient to reduce GBA2 activity. We also tested this experimental paradigm in HEK293 cells transiently overexpressing mGBA2 and endogenously expressing GBA1 (Fig. 2, C and D). Again, full block of GBA1 activity (Fig. 2C) reduced GBA2 activity to ~46% of the activity in non-treated control cells (Fig. 2D). As a control, we incubated embryonic fibroblasts from GBA1-deficient mice with 25 μM CBE for 48 h (Fig. 2, E and F), which allows to measure CBE-dependent effects on GBA2 activity independent of a change in GBA1 activity. GBA1-deficient embryonic fibroblasts lack GBA1 activity (Fig. 2E), and the activity of GBA2 remained unchanged in these cells (Fig. 2F). In addition, we analyzed GBA2 protein expression in CBE-treated HEK293 cells overexpressing mGBA2, but there was no difference between treated and non-treated cells (Fig. 2, G and H). We also performed the experiments vice versa in HEK293 cells overexpressing mGBA2 by blocking GBA2 activity with 2 μM NB-DNJ for 48 h (Fig. 2, I and J). Whereas GBA2 activity was completely abolished in NB-DNJ-treated cells (Fig. 2I), GBA1 activity remained unchanged (Fig. 2J). Thus, our results suggest that GBA1 activity regulates GBA2 activity, but not vice versa, and that the regulation occurs independently of changes in protein expression.

Next, we analyzed the time course of the GBA1-dependent regulation of GBA2 activity. GBA1 activity was blocked with 25 μM CBE for 10 min up to 48 h (Fig. 2K). GBA1 activity was significantly reduced after 3 h of CBE treatment and was max-
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GBA2 activity is down-regulated in the absence of GBA1. A, GBA1 activity in fibroblasts from control and Gaucher patients. GBA1 activity was measured in hypotonic lysates from control (ctrl) and Gaucher fibroblasts (types I, II, and III) using 1.67 mM 4-MUG as a substrate. Data were normalized to the control. 100% GBA1 activity: 32.3 pmol/μg of protein/h. B, see A for GBA2 activity. 100% GBA2 activity: 0.9 pmol/μg of protein/h. C, GBA1 activity in wild-type (WT) and GBA1-deficient (KO) HAP1 fibroblasts. GBA1 activity was measured in hypotonic lysates using 1.67 mM 4-MUG; two independent GBA1-deficient cell lines (#001 and #010) were analyzed. Data were normalized to wild-type cells. 100% GBA1 activity: 8.9 pmol/μg of protein/h. D, see C for GBA2 activity. 100% GBA2 activity: 2.2 pmol/μg of protein/h. E, see C for wild-type (WT) and GBA2-deficient (KO) HAP1 fibroblasts. GBA1 activity: 7.4 pmol/μg of protein/h. F, see E for GBA2 activity. 100% GBA2 activity: 2.2 pmol/μg of protein/h. G, GBA1 mRNA expression in control and Gaucher patients (types I, II, and III) analyzed by quantitative PCR. Data were normalized to the control. H, see G for GBA2. I, GBA1 and GBA2 protein in control and Gaucher patients (types I and II). Hypotonic lysates were subjected to Western blotting analysis using GBA1- and GBA2-specific antibodies. Calnexin was used as a loading control. J, quantification of GBA1 protein expression levels, normalized to the loading control and then to control samples. For quantification, all GBA1 bands were taken into account. K, see J for GBA2. All data are represented as mean ± S.D.; n are indicated in parentheses.

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GBA2 activity was only reduced when GBA1 activity was almost absent (Fig. 2K). This result suggests that GBA2 activity responds to GBA1-dependent changes in the cell that take some time to develop, e.g., the accumulation of the substrates, GlcCer, and GlcSph, in the lysosomes or the changes of downstream metabolites in the cytoplasm.

To investigate whether the GBA1-dependent regulation of GBA2 activity occurs not only in cell culture, but also in mice in vivo, we used the following approach. A Gaucher phenotype can be obtained by intraperitoneal (i.p.) injection of low doses of CBE (14, 15). Eight-day-old 6OlaHsd mice were injected with 25–100 mg of CBE/kg/day for 10 days. After treatment, mice were sacrificed and the brain was dissected. GBA1 and GBA2 activities were assayed in hypotonic brain lysates from CBE-treated and control mice. All tested CBE concentrations blocked GBA1 activity by >85% (Fig. 3A) (15). In line with our earlier findings, GBA2 activity was also reduced at all CBE concentrations tested (Fig. 3B). Of note, at high concentrations, CBE also inhibits the activity of GBA2 (13, 16). The final con-
centration of CBE in the brain is difficult to estimate. However, the reduction in GBA2 activity was similar, independent of the applied CBE dose (Fig. 3B), indicating that the reduction of GBA2 activity is GBA1-dependent and not due to a direct inhibition by CBE. As a control, we also analyzed GBA2 protein expression in CBE-treated mouse brains compared with controls (Fig. 3, C and D). However, GBA2 protein expression was not affected by CBE treatment. Thus, the GBA1-dependent regulation of GBA2 activity occurs not only in vitro in isolated cells in culture, but also seems to be present in vivo, independent of changes in protein expression levels.

**Investigating the underlying mechanism**

Previous studies have reported an increase of GBA2 activity in cells from Gaucher patients (17, 18). This is in contrast to our findings, which is why we first performed additional experi-
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Figure 3. GBA2 activity is also reduced in vivo in a pharmacological Gaucher mouse model. A, GBA1 activity in brain from CBE-injected mice. GBA1 activity was measured in hypotonic brain lysates from control (PBS) and CBE-injected mice using 1.67 mM 4-MUG as a substrate. Data were normalized to the control. 100% GBA1 activity: 6.2 pmol/µg of protein/h. B, see A for GBA2 activity. 100% GBA2 activity: 84.6 pmol/µg of protein/h. C, GBA1 and GBA2 protein expression in brain from control (PBS) and CBE-injected mice. Hypotonic lysates were subjected to Western blotting analysis using GBA1- and GBA2-specific antibodies. Calnexin was used as a loading control. A representative blot for one CBE concentration and three different animals is shown. CHO cells stably expressing GBA1 and GBA2 were used as positive control.

Figure 2. GBA2 activity depends on GBA1 activity. A, GBA1 activity in CBE-treated human fibroblasts. GBA1 activity was measured in hypotonic lysates from control (ctrl) and fibroblasts treated with 25 µM CBE for 48 h using 1.67 mM 4-MUG as a substrate. Data were normalized to the control. 100% GBA1 activity: 261.7 pmol/µg of protein/h. B, GBA2 activity. 100% GBA2 activity: 6.0 pmol/µg of protein/h. C, GBA1 activity in CBE-treated HEK293 cells stably over-expressing GBA2. GBA1 activity was measured in hypotonic lysates from control and cells treated with 25 µM CBE for 48 h using 1.67 mM 4-MUG as a substrate. Data were normalized to the control. 100% GBA1 activity: 27.0 pmol/µg of protein/h. D, see C for GBA2 activity. 100% GBA2 activity: 206.0 pmol/µg of protein/h. E, GBA1 activity in CBE-treated GBA1-deficient mouse embryonal fibroblasts. GBA1 activity was measured in hypotonic lysates from wild-type (+), GBA1-deficient (−), CBE-treated GBA1-deficient (± 25 µM CBE, 48 h) mouse embryonal fibroblasts using 1.67 mM 4-MUG as a substrate. Data were normalized to the non-treated wild-type cells. 100% GBA1 activity: 125.9 pmol/µg of protein/h. F, see E for GBA2 activity. 100% GBA2 activity: 5.5 pmol/µg of protein/h. G, GBA1 and GBA2 protein expression in control (DMSO-treated) and CBE-treated (CBE, 25 µM, 48 h) HEK293 cells transiently over-expression GBA2. Hypotonic lysates were subjected to Western blotting analysis using GBA1- and GBA2-specific (anti-HA) antibodies. Tubulin was used as a loading control for HEK293 cells. CHO cells stably expressing GBA1 and GBA2 were used as positive control. H, quantification of GBA1 and GBA2 protein expression levels in CBE-treated cells (data from H), normalized to control samples. I, GBA1 activity in NB-DNJ-treated HEK293 cells transiently over-expressing GBA2. GBA1 activity was measured in hypotonic lysates from control and HEK293 cells treated with 2 µM NB-DNJ for 48 h using 1.67 mM 4-MUG as a substrate. Data were normalized to the control. 100% GBA1 activity: 26.3 pmol/µg of protein/h. J, see I for GBA2 activity. 100% GBA2 activity: 195.8 pmol/µg of protein/h. K, time course of the GBA1-dependent regulation of GBA2 activity in CHO cells stably over-expressing mGBA2. Cells were incubated with 25 µM CBE for 10 min up to 48 h. β-Glucosidase activity was analyzed in hypotonic cell lysates in the presence of 1.67 mM 4-MUG. 100% GBA1 activity: 7.4 pmol/µg of protein/h; 100% GBA2 activity: 405.0 pmol/µg of protein/h. All data are represented as mean ± S.D.; n are indicated in parentheses.

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GBA2 activity depends on GBA1 activity. A, GBA1 activity in CBE-treated human fibroblasts. GBA1 activity was measured in hypotonic lysates from control (ctrl) and fibroblasts treated with 25 µM CBE for 48 h using 1.67 mM 4-MUG as a substrate. Data were normalized to the control. 100% GBA1 activity: 261.7 pmol/µg of protein/h. B, GBA2 activity. 100% GBA2 activity: 6.0 pmol/µg of protein/h. C, GBA1 activity in CBE-treated HEK293 cells stably over-expressing GBA2. GBA1 activity was measured in hypotonic lysates from control and cells treated with 25 µM CBE for 48 h using 1.67 mM 4-MUG as a substrate. Data were normalized to the control. 100% GBA1 activity: 27.0 pmol/µg of protein/h. D, see C for GBA2 activity. 100% GBA2 activity: 206.0 pmol/µg of protein/h. E, GBA1 activity in CBE-treated GBA1-deficient mouse embryonal fibroblasts. GBA1 activity was measured in hypotonic lysates from wild-type (+), GBA1-deficient (−), CBE-treated GBA1-deficient (± 25 µM CBE, 48 h) mouse embryonal fibroblasts using 1.67 mM 4-MUG as a substrate. Data were normalized to the non-treated wild-type cells. 100% GBA1 activity: 125.9 pmol/µg of protein/h. F, see E for GBA2 activity. 100% GBA2 activity: 5.5 pmol/µg of protein/h. G, GBA1 and GBA2 protein expression in control (DMSO-treated) and CBE-treated (CBE, 25 µM, 48 h) HEK293 cells transiently over-expression GBA2. Hypotonic lysates were subjected to Western blotting analysis using GBA1- and GBA2-specific (anti-HA) antibodies. Tubulin was used as a loading control for HEK293 cells. CHO cells stably expressing GBA1 and GBA2 were used as positive control. H, quantification of GBA1 and GBA2 protein expression levels in CBE-treated cells (data from H), normalized to control samples. I, GBA1 activity in NB-DNJ-treated HEK293 cells transiently over-expressing GBA2. GBA1 activity was measured in hypotonic lysates from control and HEK293 cells treated with 2 µM NB-DNJ for 48 h using 1.67 mM 4-MUG as a substrate. Data were normalized to the control. 100% GBA1 activity: 26.3 pmol/µg of protein/h. J, see I for GBA2 activity. 100% GBA2 activity: 195.8 pmol/µg of protein/h. K, time course of the GBA1-dependent regulation of GBA2 activity in CHO cells stably over-expressing mGBA2. Cells were incubated with 25 µM CBE for 10 min up to 48 h. β-Glucosidase activity was analyzed in hypotonic cell lysates in the presence of 1.67 mM 4-MUG. 100% GBA1 activity: 7.4 pmol/µg of protein/h; 100% GBA2 activity: 405.0 pmol/µg of protein/h. All data are represented as mean ± S.D.; n are indicated in parentheses.
the membrane and cytosolic fraction (Fig. 4, A and B). Both sphigosine and GlcSph levels displayed an elevating trend in membrane fractions of Gaucher disease or GBA1-deficient fibroblasts, respectively (Fig. 4, A and B).

We therefore hypothesized that cells accumulating GlcCer and GlcSph, due to a loss of GBA1 activity, might have developed a mechanism, whereby GBA2 activity is diminished to avoid a cytotoxic accumulation of sphingosine or GlcSph. The simplest scenario that could be envisioned in this regard is a direct regulation of GBA2 activity by these metabolites. To test this hypothesis, we first analyzed whether the GBA2 activity is sensitive to sphingosine. CHO cells stably overexpressing mGBA2 were incubated with 20 μM sphingosine complexed to BSA, and GBA1 and GBA2 activity was measured (Fig. 4, C and D).
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Figure 5. GBA2 expression and activity in E. coli. A, GBA2 expression was induced by 1 mM IPTG and expression was verified by Western blotting analysis using an anti-His antibody. β-Glucosidase activity in bacterial lysates before (−) and after induction with 1 mM IPTG (+) was measured at pH 4 and 6. There was no difference in β-glucosidase activity in the presence or absence of 25 μM CBE at pH 4, demonstrating that there is no endogenous GBA1 activity. The IPTG-induced β-glucosidase activity at pH 6 is blocked by 8.3 μM NB-DNJ, demonstrating that the activity is conveyed by GBA2. Data represent n = 1, 8. Dose-response relationship of GBA2 activity to NB-DNJ at pH 6. Maximal activity (2.2 pmol/μg of protein/h) has been set to 100%. Gray line represents the exponential fit. C, see B for sphingosine. D, see B for glucosylsphingosine. E, see B for sphingosine 1-phosphate. F, see B for FTY720 (Fingolimod). G, see B for sphinganine. H, see B for C18 ceramide. I, see B for C6 ceramide. J, see B for C8 ceramide.

Figure 4. Sphingosine blocks GBA2 activity. A, quantitative lipid analysis by mass spectrometry. Ceramide and hexosylceramide levels were determined from total cell lysates, whereas sphingosine levels were determined in membrane fractions from wild-type and Gaucher fibroblasts (ctrl: control fibroblasts, I: IPTG-induced). A, inset shows the time course of GBA2 expression in bacterial lysates over-expressing GBA2 displayed a prominent ceramide level (C6) that was blocked by NB-DNJ, demonstrating that there is no endogenous GBA1 activity. The drug was directly added to the protein lysates when performing the assay. For C18 ceramide, no difference in activity was observed. However, for C6 ceramide, the drug had a significant effect on GBA2 activity. 100% GBA1 activity was measured in bacterial lysates before (○) and after induction with 1 mM IPTG (■). The dose-response relationship of GBA2 activity to NB-DNJ at pH 6 in E. coli lysates displayed an IC₅₀ of 14.5 ± 2.7 nm (Fig. 5B), which is very similar to the IC₅₀ determined in brain lysates (20.9 ± 1.3 nm) (13). We then assayed the dose-response relationship of GBA2 for sphingosine in bacterial lysates. Sphingosine reduced the GBA2 activity with an IC₅₀ of 25.0 ± 0.2 μM (Fig. 5C). These results indicate that sphingosine directly inhibits GBA2. How-
ever, as described above, not only sphingosine, but also GlcSph accumulates in the absence of GBA1. In fact, GlcSph blocked GBA2 activity in a dose-dependent manner with an IC50 of 1.5 ± 0.1 μM (Fig. 5D). These results demonstrate that both toxic metabolites, GlcSph and sphingosine, inhibit GBA2 activity.

**Structural requirements for the sphingosine-dependent GBA2 inhibition**

Next, we tested other sphingolipid metabolites, structurally similar to sphingosine, regarding their ability to inhibit GBA2 activity. In the cell, sphingosine can be phosphorylated by sphingosine kinases to sphingosine-1-phosphate (S1P), a sphingoid messenger that controls multiple signaling pathways (22). S1P structurally differs from sphingosine, as it bears a negatively charged phosphate headgroup. S1P did not inhibit GBA2 activity, suggesting that the presence of a phosphate group disturbs the sphingosine-dependent inhibition of GBA2 activity (Fig. 5E). Fingolimod, or FTY720, is structurally related to sphingosine and is approved for the treatment of multiple sclerosis (23). FTY720 carries an octylphenyl group in its carbon tail, whereas sphingosine itself only bears a double bond at C4. In vivo, FTY720 is phosphorylated to form FTY720-phosphate, which resembles naturally occurring S1P and also binds to S1P-surface receptors of cells (24). FTY720-inhibited GBA2 activity with an IC50 value of 18.6 ± 0.4 μM (Fig. 5F). Next, we tested whether GBA2 is sensitive to the double bond in the alkyl chain of sphingosine or whether the saturated form of this sphingoid base, sphinganine, also exhibits an inhibitory effect. Sphinganine inhibits GBA2 with an IC50 of 30.6 ± 4.5 μM (Fig. 5G), suggesting that the presence of the double bond in the sphingoid alkyl chain is irrelevant for the inhibitory effect. Finally, we investigated whether GBA2 is sensitive to ceramide, a metabolite of sphingosine. However, ceramide (C6, C8, and C18) concentrations of up to 300 μM did not diminish GBA2 activity (Fig. 5, H–J). Thus, GBA2 seems to be only sensitive to non-acetylated sphingoid bases and their derivatives (GlcSph, sphingosine, sphinganine, and FTY720) and not to complex sphingolipids such as ceramides.

**Sphingosine reversibly blocks GBA2 activity and follows the rule of mixed-type inhibition**

To further characterize the sphingosine-dependent inhibition of GBA2 activity, we tested whether the block is reversible. Hypotonic lysates from bacteria expressing mGBA2 were pre-incubated with 25 μM sphingosine to evoke a half-maximal block of GBA2 activity or with DMSO as a control. After incubation, samples were diluted to a final sphingosine concentration of 3.85 μM. As a control, the sphingosine concentration was maintained at 25 μM. Treatment with 25 μM sphingosine reduced GBA2 activity to 50% of the control values, whereas almost full GBA2 activity was recovered when sphingosine was diluted to 3.85 μM (Fig. 6A). These results indicate that sphingosine reversibly blocks GBA2 activity. To determine the type of reversible inhibition (competitive, non-competitive, uncompetitive, and mixed inhibition), we incubated lysates from bacteria over-expressing mGBA2 with 25 μM sphingosine, competed the inhibitory effect by adding increasing amounts of 4-MUG, and analyzed the enzyme activities according to Michaelis-Menten (Fig. 6B). The maximal GBA2 activity (Vmax) in the presence of sphingosine was reduced to about 50% of the control activity (3.5 ± 0.1 versus 1.9 ± 0.1 relative fluorescence units/min, n = 3), pointing toward a non-competitive inhibition of sphingosine for GBA2 (Fig. 6B). Interestingly, the Km value was also shifted toward higher concentrations (171.3 ± 13.8 versus 304.0 ± 44.3 μM, n = 3) in the presence of sphingosine (Fig. 6B), which does not resemble the classic non-competitive inhibition model. Thus, our data suggest that the inhibition of GBA2 by sphingosine follows the rules of mixed inhibition, where the inhibitor can bind to an allosteric site of the enzyme if it has not bound its substrate yet, as well as to the enzyme-substrate complex. In this case, the Km value is increased, which resembles a lower affinity of the enzyme for its substrate, and Vmax is decreased.

**Discussion**

Here, we provide new insights into the regulation of GBA2 activity, in particular in Gaucher disease. We demonstrate that GBA2 activity depends on GBA1 activity, but not vice versa.
This mechanism applies generally, whenever GBA1 was pharmacologically blocked or genetically deleted, and in every in vitro and in vivo system that we tested, GBA2 activity was reduced. Other reports have also analyzed GBA2 activity in Gaucher disease, but demonstrated an increase in GBA2 activity in brain from GBA1-deficient mice and in fibroblasts from Gaucher disease patients (17, 18). These results are in contrast to our findings, and the reason for this discrepancy is not known. One explanation could be a difference in the experimental set-up, that is, how GBA2 activity was measured. Of note, our experiments and the experiments of others (17, 18) were all performed using the artificial, water-soluble substrate 4-MUG and not using the natural lipid GlcCer, making it difficult to directly transfer the molecular mechanisms to the in vivo situation. However, we have comprehensively analyzed GBA2 expression and activity in different in vitro and in vivo models. In none of them was GBA2 expression or activity higher in the absence of GBA1 activity, arguing against earlier findings as described above.

Our results indicate that GBA2 activity is inhibited by the cytotoxic metabolites sphingosine and GlcSph through direct binding. It has been proposed that sphingosine is generated by GBA2-dependent hydrolysis of GlcSph (12), whose levels are dramatically increased in Gaucher disease patients (6). GlcSph is generated by intralysosomal deacetylation of the accumulating GlcCer and leaves the lysosome through a yet unknown mechanism (7). We first determined sphingosine levels in fibroblasts from control and Gaucher patients using mass spectrometry: sphingosine levels were slightly, albeit not significantly, increased in Gaucher fibroblasts with 1.3 ± 0.8 pmol/μg of protein in type I samples, 2.2 ± 2.3 pmol/μg of protein in type II samples, and 1.2 ± 0.51 pmol/μg of protein in type III samples compared with 1.4 ± 0.6 pmol/μg of protein in control cells. However, after separating the cells into a membrane and cytosolic fraction, sphingosine levels in the membrane fraction of all three types of Gaucher disease showed an elevating trend (Fig. 4A). The IC₅₀ of sphingosine for GBA2 is relatively high (25.0 ± 0.2 μM in mGBA2 expressed in bacteria). This concentration will never be reached in a cell without causing cell death. However, the local sphingosine concentration could be much higher than the global concentration in the cell. The concentration is presumably the highest in membranes directly at the site of production, which, according to the model, is close to GBA2. In line with this model, sphingosine accumulates preferably in the membranes of fibroblasts from Gaucher disease patients. To investigate the inhibition of GBA2 activity by sphingosine in a cellular context in more detail, a quantitative subcellular analysis of the sphingosine localization would be needed. Furthermore, GlcSph, as a cationic amphiphile, is highly cytotoxic, and its accumulation has also been attributed to the neuropathological defects in Gaucher disease (10, 25, 26). We demonstrate that not only sphingosine, but also GlcSph inhibits GBA2 activity. Of note, GBA1 activity has been shown to be inhibited by GlcSph (27). Thus, both cytotoxic metabolites inhibit GBA2 activity in a negative feedback loop to prevent further accumulation.

Direct inhibition of GBA2 activity is the most straightforward explanation to how sphingosine regulates GBA2 activity. However, sphingosine has other properties that could also affect GBA2 activity. Sphingosine is also a "bioactive lipid" (28). It either exerts its effect by directly binding to a protein and/or it indirectly changes the properties of cell membranes and, thereby, protein function. Sphingosine is a surface active agent, which attains its function due to its amphipathic structure: the headgroup carries an amino and two hydroxyl groups, which represent the hydrophilic part, whereas the carbon tail is highly hydrophobic. GBA2 activity is sensitive to detergents (13). Sphingosine forms micelles above a critical micelle concentration of 1 μM at pH 7.4 (29), close to the calculated IC₅₀ for GBA2. Palmitoylcarnitine is a fatty acyl ester with a critical micelle concentration of 10 μM (30) and contains similar surfactant properties as sphingosine without being involved in sphingolipid metabolism. Palmitoylcarnitine also showed a dose-dependent inhibition of GBA2 activity in bacterial lysates with an IC₅₀ of 31.31 ± 2.68 μM (data not shown). Thus, palmitoylcarnitine, but also sphingosine, might act as surfactants, forming protein-detergent complexes with GBA2, dissolving GBA2 from a membrane environment. We have shown that GBA2 is a membrane-associated protein at the cytoplasmatic site of the ER and the cis-Golgi and that the interaction with the membrane, in particular with phospholipids, is crucial for GBA2 activity. After washing the protein off from the membrane, the activity is dramatically reduced, but can be restored when adding back membranes (13). Thus, dissolving GBA2 from the membrane by forming protein-detergent complexes would diminish its activity.

In conclusion, we reveal a sphingosine-dependent regulation of GBA2 activity, which occurs in the absence of GBA1 activity and might also occur in Gaucher disease. Our results add a new chapter to the understanding of the molecular mechanism underlying Gaucher disease pathology, presenting new ideas for the therapy of this severe lysosomal storage disorder.

Experimental procedures

Constructs

The open reading frame of mouse GBA2 (NM_172692) or mGBA1 (NM_001077411.2) was amplified from cDNA using primers containing restriction sites and a Kozak sequence in front of the start codon. The sequence encoding a hemagglutinin (HA) tag was added by PCR at the 3′-end. PCR products were subcloned either into pcDNA3.1 or pcDNA6 (Invitrogen) and their sequence was verified. mGBA2-HA was cloned into an expression vector that additionally expresses eGFP. For expression in E. coli, a His₆ tag was added to the 3′-end of mGBA2 and the construct was cloned into the pET21a vector (Novagen).

Cell lines and culture

Detailed information about the different cell lines used in this study can be found in Table 1. Cell lines from Gaucher and control patients were obtained from Coriell or from TeleThon (31). Mouse embryonic fibroblasts from wild-type and GBA1- or GBA2-deficient mice have been described elsewhere (13). Human fibroblasts were cultured in DMEM, 100 mM sodium pyruvate, 200 mM L-glutamine (all Thermo Fisher Scientific), 15% FCS (Biochrom); HAP1 cells were cultured in Iscove's
**GBA2 in Gaucher disease**

**Table 1**

<table>
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<th>Genotype</th>
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<th>Disease</th>
<th>Mutation</th>
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*NA*, not applicable.

**Purification of recombinant GBA2 from E. coli inclusion bodies to generate polyclonal antibodies**

All steps were performed at 4 °C. Buffers contained protease inhibitor mixture Complete (Roche Life Science). Cells were re-suspended and lysed by sonication (3 × 30 s, Branson sonifier) in 50 mM Tris/HCl, pH 8.0, 200 μg/ml of lysozyme, DNase 1000 units/liter of culture, 500 mM NaCl, 5 mM MgCl₂, and 1 mM DTT. After a 20-min incubation on ice, the suspension was centrifuged for 30 min at 11,000 × g and 4 °C. The pellet was re-suspended in solubilization buffer containing 1% Triton X-100 and 50 mM Tris/HCl, pH 8.0, 0.2 mM EDTA, and 1 mM DTT. The suspension was incubated by end-over-end rotation for 20 min and centrifuged for 15 min at 15,000 × g and 4 °C. The pellet containing the GBA2 inclusion bodies was re-extracted twice in the same way. GBA2 was solubilized from the inclusion bodies by sonication (3 × 30 s, Branson sonifier) in buffer L containing 20 mM imidazole, 20 mM sodium phosphate, 500 mM NaCl, 7 mM urea, pH 7.0, and loaded onto a CoCl₂-activated HisTrap column (GE Healthcare Life Sciences) equilibrated with buffer L. The column was washed with 10 column volumes of buffer L. Recombinant GBA2 was eluted with buffer L containing 500 mM imidazole, collected, and concentrated to ~1.5 mg/ml using an Amicon Ultra-15 Centrifugal Filter Unit with Ultracel-50 membrane (Merck Millipore).

**Affinity purification of polyclonal GBA2 antibody**

Recombinant full-length GBA2 (1.5 mg) was loaded onto a 7.5% SDS gel using a SE400 electrophoresis unit (Hofer). The gel slice containing mGBA2 was cut out and transferred to a PVDF membrane by Western blotting. The blot was incubated for 2 h with 20 ml of the final bleed (rabbit serum), which was diluted with 1 volume of TBS. The blot was washed consecutively with TBS, with TBS containing 0.05% Tween 20 (TBST), with 20 mM Tris/HCl, pH 7.4, and with 20 mM Tris/HCl, pH 7.4,
homogenized in hypotonic buffer (10 mM HEPES, 0.5 mM CaCl₂, and three pulses (20 s each) of sonification in ice-cold water). Tissue supernatants (post-nuclear supernatants) were used for activity assays or Western blotting analysis. Proteins were de-glycosylated using peptide N-glycosidase F (New England Biolabs) according to the manufacturer’s protocol. Protein concentration was determined using the Bradford assay or the bicinchoninic acid (BCA) test kit (Pierce) according to the manufacturer’s protocol. Protein expression levels were normalized to the mean of the housekeeping genes (hB2m, hAlas1).

### Western blotting analysis

Western blotting analysis was performed as described elsewhere (13, 33).

#### β-Glucosidase activity assay

The assay was performed as described elsewhere (13). In brief, the activity of cellular GBAs was analyzed using 4-MUG (Sigma) as a fluorescent substrate (1.67 mM final) at pH 4 and 6. Cleavage of 4-MUG was monitored in real-time in 384-well plates in a Fluostar Omega reader (BMG Labtech) at 29 °C using McIlvaine buffer. We defined the activity of GBA1 as the CBE-blockable activity. As a control, the GBA2 activity in lysates from non-symptomatic (NS) cells was recorded as a change in relative fluorescence units per hour. Each analysis was performed as a quadruplicate in parallel.

### Treatments

Cells on culture plate were treated with CBE (25 μM, C5424, Sigma), NB-DNJ (2 μM, Enzo Life Sciences, BML-SL230), or carmofur (2.9 μM, Cayman Chemical, number 14243) in culture medium at 37 °C for 48 h before analyzing the β-glucosidase activity. As a control, the GBA2 activity in lysates from non-symptomatic (NS) cells was recorded as a change in relative fluorescence units per hour. Each analysis was performed as a quadruplicate in parallel.
GBA2 in Gaucher disease

GBA2 expression in bacteria

Expression of pET21a-mGBA2-His was performed in the E. coli strain BL21 Codon Plus (DE3) RILP (Agilent Technologies, Santa Clara, CA) at 37 °C for 3 h after induction with 1 mM IPTG. mGBA2-His E. coli cultures were centrifuged for 10 min at 11,000 × g and 4 °C, and the pellet from a 30-ml culture was re-suspended in 4.8 ml of hypotonic buffer (1:8 dilution of the initial volume). The cell suspension was sonicated 3 × 20 s in ice-cold water (Branson sonifier) and 20 μl of the protein lysate were used per reaction, if not otherwise stated.

Preparation of membrane and soluble fractions for mass spectrometry

Cells were lysed in cold buffer A (10 mM NaCl, 25 mM HEPES, pH 7.5, 2 mM EDTA, 1:500 mPic) and incubated on ice for 15 min. The protein concentration was determined by BCA. To separate the soluble from the membrane fraction, samples were centrifuged for 30 min at 100,000 × g at 4 °C (TLA-55, Beckmann). The supernatant was transferred into a fresh tube and the membrane pellet was re-suspended in the same volume of buffer B (200 mM NaCl, 50 mM HEPES, pH 7.5, 1:500 mPic).

Quantification of sphingolipids by mass spectrometry

Cells were lysed in hypotonic lysis buffer and used for lipid extraction. Alternatively, the lysate was used for separation of membrane and soluble fractions as described above prior to lipid extraction. Lipids were extracted by adding 500 μl of chloroform/methanol/formic acid (1:1:0.1, v/v/v) and thorough mixing (33). At this point, internal standards were added (35). 250 μl of 1 M KCl, 0.2 M H3PO4 were added, samples were vortexed, and centrifuged at 5,000 rpm for 3 min to obtain phase separation. The lower phase containing the lipids was transferred to a fresh glass vial and the remaining samples were re-extracted by adding 500 μl of chloroform/methanol in a ratio of 2:1 (v/v). Samples were vortexed, centrifuged at 5,000 rpm for 3 min, and the lower phase was combined with the previous extract. Solvents were evaporated under N2 flow and lipids re-suspended in 500 μl of pure chloroform. Small silica columns (Strata-1-Silica, 55 μM, 70 Å containing 100 mg of silica) were derivatized with chloroform for three times. Afterward, samples dissolved in pure chloroform were applied and non-polar lipids (e.g. triacylglycerol, sterols) were eluted with three column volumes of pure chloroform. Hexosylceramides, ceramides, glycosylated long chain bases (e.g. GlcSph), and free long chain bases were eluted with three column volumes of acetone/isopropyl alcohol (1:1, v/v). The acetone/isopropyl alcohol fraction was dried under N2 flow and dissolved in 100 μl of methanol. 50 μl of the sample were dried once more and dissolved in 100 μl of chloroform, methanol, 300 mM ammonium acetate (300:665:35, v/v/v) and subjected to mass spectrometric analysis by nanospray direct infusion Q-TOF MS/MS as described elsewhere (33, 35). The remaining 50 μl of the sample were used for analysis of glycosylated long chain bases using LC-MS/MS with conditions as described elsewhere (37). The relative amounts of the glycosylated long chain bases were determined using d17:1-long chain base as internal standard.

In vivo experiments

Treatment of mice with CBE has been described elsewhere (15). Frozen brains were taken from this study and used for the experiments presented here.


Identification of a feedback loop involving β-glucosidase 2 and its product sphingosine sheds light on the molecular mechanisms in Gaucher disease

Sophie Schonauer, Heinz G. Körschen, Anke Penno, Andreas Rennhack, Bernadette Breiden, Konrad Sandhoff, Katharina Gutbrod, Peter Dörmann, Diana N. Raju, Per Haberkant, Mathias J. Gerl, Britta Brügger, Hila Zigdon, Ayelet Vardi, Anthony H. Futerman, Christoph Thiele and Dagmar Wachten

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