Synthesis of a novel photoactivatable glucosylceramide cross-linker

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Abstract The biosynthesis of glucosylceramide (GlcCer) is a key rate-limiting step in complex glycosphingolipid (GSL) biosynthesis. To further define interacting partners of GlcCer, we have made a cleavable, biotinylated, photoreactive GlcCer analog in which the reactive nitrene is closely apposed to the GlcCer head group, by substituting the native fatty acid with D, L-2-aminohexadecanoic acid. Two amino-GlcCer diastereomer cross-linkers (XLA and XLB) were generated. XLB proved an effective lactosylceramide (LacCer) synthase substrate while XLA was inhibitory. Both probes specifically bound and cross-linked the GlcCer binding protein, glycolipid transfer protein (GLTP), but not other GSL binding proteins (Shiga toxin and cholera toxin). GlcCer inhibited GLTP cross-linking. Both GlcCer cross-linkers competed with microsomal nitrobenzoxadiazole (NBD)-GlcCer anabolism to NBD-LacCer. GLTP showed marked, ATP-dependent enhancement of cell-free intact microsomal LacCer synthesis from endogenous or exogenous liposomal GlcCer, supporting a role in the transport/membrane translocation of cytosolic and extra-Golgi GlcCer. GLTP was specifically labeled by either XLA or XLB GlcCer cross-linker during this process, together with a (the same) small subset of microsomal proteins. These cross-linkers will serve to probe physiologically relevant GlcCer-interacting cellular proteins.—Budani, M., M. Mylvaganam, B. Binnington, and C. Lingwood. **Synthesis of a novel photoactivatable glucosylceramide cross-linker.** ***J. Lipid Res.*** **2016.** 57: **1728–1736.**

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Glycosphingolipid (GSL) accumulation is the basis of the pathology of lysosomal GSL storage diseases (1). In addition, aberrant GSL synthesis plays a key cofactor role in the pathology of many other human diseases (1), and in models of such disease, GSL blockade ameliorates symptoms (2–4). Understanding the synthesis of complex GSL is therefore crucial in generating the means for selective therapeutic correction of GSL levels.

Glycosyltransferase knockout studies in mice identify central roles for GSLs in embryology and differentiation, particularly in the peripheral and central nervous system (5). However, differences are observed for the same deletion in different studies (6–8), indicating that other factors in the regulation of GSL biosynthesis remain to be determined. One such factor is the relationship between the synthesis of the acidic and the several neutral GSL subclasses from lactosylceramide (LacCer) (9). GSL synthesis is complicated by the fact that the common precursor, glucosylceramide (GlcCer), is made on the outer membrane of the Golgi (10, 11), while complex GSL synthesis occurs within the Golgi luminal membrane. The mechanism by which GlcCer translocation is achieved is still largely a matter of conjecture (12). Phosphatidylinositol-four-phosphate adapter protein 2 (FAPP2)-facilitated cytosolic GlcCer traffic is implicated in neutral GSL synthesis, while vesicular GlcCer traffic is involved in ganglioside biosynthesis (13). We have proposed the Golgi located MDR1(multidrug resistance protein 1) pump as a potential mechanism for flipping GlcCer into the Golgi (14), but its role remains ill-defined and is unlikely the only mechanism. Furthermore, GlcCer is emerging as an important factor in intracellular membrane traffic (15) and membrane order (16).

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Abbreviations: 2A-GlcCer, 2-aminohexadecanoyl glucosyl sphingosine; AEBSF, 4-(2-aminoethyl)benzenesulfonyl fluoride hydrochloride; BOC anhydride, di-tert-butyl dicarbonate; BOP, benzotriazole-1-yl-oxy-tris-(dimethylamino)-phosphonium hexafluorophosphate; CBE, conduritol β epoxide; CTB, cholera toxin B subunit; DCM, dichloromethane; DMF, dimethylformamide; Gal, galactose; Gb_3, globotriaosylceramide; GlcCer, glucosylceramide; GLTP, glycolipid transfer protein; GSL, glycosphingolipid; LacCer, lactosylceramide; LCS, LacCer synthase; NBD, nitrobenzoxadiazole; SA-HRP, streptavidin horseradish peroxidase conjugate; sulfo-SBED, sulfo-*N*-hydroxysuccinimidyl-2-(6-[biotinamido]-2-(*p*-azido benzamido)-hexanoamido) ethyl-1,3′-dithioproprionate; t-BOC, *tert*-butyloxycarbonyl; TEA, triethylamine; TFA, trifluoroacetic acid; VTB, verotoxin-1 B subunit.

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GlcCer synthesis and trafficking are, in addition, regulated by statin-sensitive prenylation mechanisms (17).

As a means to address the mechanism by which GlcCer is trafficked intracellularly and translocated into the Golgi lumen, we have designed a novel GlcCer-based photoaffinity probe, using a 2-amino fatty acid derivative (18). The cross-linker is converted to LacCer and competes with nitrobenzoxadiazole (NBD)-GlcCer for GSL synthesis in cell free studies and thus provides a potential means to define GlcCer binding proteins, which should include any GlcCer flippase.

MATERIALS AND METHODS

Reagents

Sulfo-*N*-hydroxysuccinimidyl-2-(6-[biotinamido]-2-(*p*-azido benzamido)-hexanoamido) ethyl-1,3′-dithioproprionate (sulfo-SBED) biotin label transfer reagent (no-weigh format) and streptavidin horseradish peroxidase conjugate (SA-HRP) were purchased from Thermo Scientific. GlcCer (glucocerebrosides) was purchased from Matreya LLC. 2-Aminohexadecanoic acid, di-*tert*-butyl dicarbonate (BOC anhydride), $Mg(OAc)_2$, UDP-galactose (UDP-Gal), pyridine, ethyl acetate, trifluoroacetic acid (TFA), NaOH, HCl, triethylamine (TEA), acetic acid, acetic anhydride, dimethylformamide (DMF), dichloromethane (DCM), benzotriazole-1-yl-oxy-tris-(dimethylamino)-phosphonium hexafluorophosphate (BOP), sucrose, sodium bicarbonate, and cholera toxin B subunit (CTB) were purchased from Sigma-Aldrich. Succinimidyl 6-(*N*-(7-nitrobenz-2-oxa-l,3-diazol-4-yl)amino)hexanoate (NBD-X SE) was purchased from AnaSpec Inc. MEM, Dulbecco's PBS 1X (D-PBS), FBS, and trypsin (0.05%)/EDTA were purchased from Wisent Inc. 4-(2-Aminoethyl)benzenesulfonyl fluoride hydrochloride (AEBSF), protease inhibitor cocktail, Tris, $MgCl_2$, and BSA were purchased from BioShop. Chloroform, methanol, silica gel 60, and KCl were purchased from Caledon Laboratory Chemicals. C-18 silica gel and conduritol β epoxide (CBE) were purchased from Toronto Research Chemicals Inc. Precoated TLC sheets (Polygram SIL G/UV_{254}) were purchased from Machery-Nagel. Sep-Pak Vac 6 cc (1 g) certified C18 cartridges were purchased from Waters. DU145 cells were kindly supplied by Dr. N. Fleshner, University of Toronto. ^{3}H-UDP-Gal was purchased from American Radiolabeled Chemicals. Glycolipid transfer protein (GLTP) was kindly provided by Dr. Thorsten Lang, Department of Membrane Biochemistry at the Life & Medical Sciences (LIMES) Institute, University of Bonn, Germany. Verotoxin-1 B subunit (VTB) was made as described (19).

Lyso-GlcCer

Twelve milligrams of GlcCer was dried under nitrogen and low heat and then lyophilized overnight. GlcCer was deacylated in 11.5 ml 1 M NaOH/methanol at 70°C for 4 days (20). Reaction products were neutralized with concentrated HCl, and dried by rotary evaporation. The reaction products were dissolved in water and desalted with C-18 reversed phase silica gel column chromatography and then purified with normal phase silica gel column chromatography (80% yield).

Tert-butyloxycarbonyl (t-BOC) protection of 2-aminohexadecanoic acid

To protect the amino function of 2-aminohexadecanoic acid before coupling to lyso-GlcCer, a mole ratio of 1:1.5:2 of 2-aminohexadecanoic acid (121.9 mg), BOC anhydride, and sodium bicarbonate were initially dissolved in CH_3OH/water (3.4:1, v/v), then stirred for 2 days at room temperature (21). Products were dried under vacuum, dissolved in ethyl acetate and extracted twice with water using a separating funnel. Reaction product, 2-((*tert*-butoxycarbonyl)amino)hexadecanoic acid, was purified by silica gel column chromatography (19% yield), and analyzed by negative TOF mass spectrometry.

Lyso-GlcCer coupling to 2-((*tert*-butoxycarbonyl)amino) hexadecanoic acid

Lyso-GlcCer and 2-((*tert*-butoxycarbonyl)amino)hexadecanoic acid were dried overnight in a P_2O_5 desiccator. The 2-((*tert*-butoxycarbonyl)amino)hexadecanoic acid (32.4 μmol) and BOP reagent (27 μmol) were dissolved in dry solvent mixture (DMF/DCM/TEA, 5:5:1) and incubated at −60°C for 10 min under nitrogen; lyso-GlcCer (10.8 μmol) dissolved in dry solvent mixture was added to the reaction and incubated for 1.5 h at −60°C under nitrogen (22). The reaction was allowed to warm to −30°C and then quenched with water. Reaction products were thoroughly dried, desalted by C-18 reversed phase silica gel column chromatography, and then purified by silica gel column chromatography (83% yield).

t-BOC deprotection

The t-BOC protected 2A-GlcCer analog was dried, lyophilized overnight, dissolved in TFA/water (1:1, v/v), and then stirred at room temperature for 7 h (21). HCl was added to the reaction products to protonate the trifluoroacetate salt and then dried under nitrogen without heat. Products 2-aminohexadecanoyl glucosyl sphingosine (2A-GlcCer) isomers A and B were purified by silica gel column chromatography, and purified products (59% A and B combined yield) were compared by TLC $CHCl_3/CH_3OH$/water (65:25:4, v/v/v). The two products were analyzed by positive TOF mass spectrometry.

Acetylation of 2A-GlcCer amino analog

Both 2A-GlcCer A and B analogs, were dissolved in acetic anhydride-pyridine (1:1, v/v), incubated at 37°C for 2 h, and dried (23). To deacetylate the sugar only, products were dissolved in TEA/methanol/water (1:1:1, v/v/v) and incubated at 37°C overnight (23). Starting materials and *N*-acetyl products were compared by TLC in $CHCl_3/CH_3OH$/water (65:25:4, v/v/v) and then purified by silica gel column chromatography. Each product was analyzed by positive TOF mass spectrometry.

2A-GlcCer analog coupling to trifunctional photoactivatable cross-linker, sulfo-SBED

Both 2A-GlcCer A (1.3 mg) and 2A-GlcCer B (0.6 mg) analogs were dissolved separately in DMF and incubated in the dark at room temperature with 1 mg sulfo-SBED per analog for 3 h (supplier's protocol). Reaction products, termed 2A-GlcCer XLA and 2A-GlcCer XLB (abbreviated XLA and XLB) were desalted using C18 Sep-Pak, purified by silica column chromatography (33% and 31% yield for XLA and XLB, respectively), and characterized by positive TOF mass spectrometry.

Preparation of crude microsomes

The DU145 prostate cancer cell line was chosen to study because these cells express a full complement of neutral and acidic GSLs. Near-confluent DU145 cells, maintained with MEM supplemented with 10% FBS, were washed with D-PBS, detached by trypsin, collected in an equal volume of FBS to inhibit trypsin, and washed twice with ice-cold D-PBS (360 *g*, 4°C), and pellets were stored at −80°C. Cell pellets were suspended in one volume of ice-cold homogenization buffer (10 mM Tris-HCl pH 7.4, 10 mM KCl, 1.5 mM $MgCl_2$, 0.5 M sucrose), and homogenized with

30 strokes of a Dounce homogenizer. Nuclei and debris were pelleted at 1,000 *g* for 10 min at 4°C. The supernatant was collected and centrifuged at 10,000 *g* for 10 min at 4°C. The supernatant (crude microsomes) was collected, and protein concentration measured. The protease inhibitor AEBSF was added to 0.1 mM, and 200 μg aliquots were stored at −80°C. This microsome preparation method is designed to retain cytosolic factors and minimize their dilution and is a modification of that used by De Rosa et al. (9); DTT was omitted to avoid reduction of the cleavable disulfide bond in XLA and XLB.

LacCer synthase (LCS) assays

Detergent-containing assay to measure LCS activity. Triton X-100 (0.3%) and 20 μg C16:0 GlcCer, XLA or XLB were dried under nitrogen, suspended, and sonicated in 20 mM cacodylate, pH 6.8, 10 mM $MnCl_2$, and 1 mM $MgCl_2$ and incubated with 130 μg DU145 microsomes and 0.5 μCi ^{3}H-UDP-Gal at 37°C for 3 h (24).

Detergent-free assay to assess GlcCer translocation. The detergent-free radiolabeled LCS assay is a modification of that of Chatterjee and Castiglione (24). Bovine GlcCer (20 μg) was dried and sonicated in water, incubated with 20 mM cacodylate, pH 6.8, 10 mM $MnCl_2$ and 1 mM $MgCl_2$, 2 μM GLTP, 5 μM ATP, 120 μg intact DU145 microsomes, and 0.5 μCi ^{3}H-UDP-Gal (100 μl final volume) at 37°C for 3 h.

For both LCS assays, phospholipids were saponified at room temperature for 2 h with 1 M NaOH in methanol. Each reaction was neutralized with equal normal $HCl_{(aq)}$ and 23 mM NH_4OAc. Chloroform was added to form a Folch partition ($CHCl_3$/CH_3OH/water, 2:1:0.6, v/v/v), the GSL-containing lower phase was washed with theoretical upper phase ($CHCl_3$/CH_3OH/water, 1:47:48, v/v/v), and the lower phase was extracted and dried under nitrogen. Samples were dissolved in 20 μl 2:1 $CHCl_3$/CH_3OH, and half was separated by TLC $CHCl_3$/CH_3OH/water (65:25:4, v/v/v), along with a standard, ^{14}C-Gal-labeled GSLs from vero cells. The TLC plate was sprayed with En3Hance and exposed to film at −80°C.

NBD-GlcCer LCS assay. For synthesis of NBD-GlcCer, lyso-GlcCer (2.5 mg) and NBD-X SE (3.2 mg) were dissolved in 1.1 ml of DMF/TEA (9:1, v/v) and stirred at room temperature for 3 h (25). NBD-GlcCer (80% conversion) was purified by silica gel column chromatography and stored at −20°C in chloroform. For the detergent-free NBD-LCS assay, the LCS assay is a modification of the method of Chatterjee and Castiglione (24). Primarily intact, right-side-out microsomes were used. Bovine NBD-GlcCer (1 μg), and XLA or XLB (20 μg) were dried under nitrogen, dissolved in water, sonicated, and diluted to a total volume of 100 μl containing 1 mM $MnCl_2$, 1 mM $Mg(OAc)_2$, 20 mM cacodylate pH 6.8, protease inhibitor cocktail (50 μM AEBSF, 40 nM aprotinin, 25 μM bestatin, 75 nM E-64, 1 μM leupeptin, 0.5 μM pepstatin A), 0.5 mM UDP-Gal, 0.25 mM CBE, and 100 μg DU145 microsomes. Enzyme reactions were incubated at 37°C as indicated and stopped by addition of 1 ml of $CHCl_3$/CH_3OH (2:1, v/v) and 100 μl water for Folch partition as above. Half of each sample was separated by TLC $CHCl_3$/CH_3OH/water (80:20:2, v/v/v). The dried plate was imaged using a Typhoon FLA 9500 Fluorescent imager (473 nm excitation wavelength, 250 V, 50 μm pixel size).

Cross-linking assay

For purified protein cross-linking, XLA or XLB were dried, dissolved in 2 μl of ethanol (0.75 μM final concentration), incubated at 37°C for a few minutes, and then diluted in warm TBS. Equal mass of GLTP (2 mM), gelatin, VTB, and CTB in TBS were incubated with cross-linker at room temperature for 1 h. For microsomal protein cross-linking, XLA or XLB were dried in 1.5 ml microtubes under air, dissolved in water, sonicated, and stored at −20°C until use. Thawed cross-linker micelles (0.1 μg) were preincubated with 2 mM GLTP and 13 μg GlcCer micelles or water of equal volume at 37°C for 1 h. GLTP, cross-linkers, and GlcCer samples were incubated with 1 mM $MnCl_2$, 1 mM $Mg(OAc)_2$, 20 mM cacodylate pH 6.8, protease inhibitor cocktail, 0.5 mM UDP-Gal, 0.25 mM CBE, and 100 μg DU145 microsomes at 37°C for 1 h. Purified and microsomal proteins were cross-linked with Spectroline Model EB-280C UV (302 nm) from a distance of 5 cm for 15 min. Samples were analyzed by SDS-PAGE, stained with Coomassie blue, or by Western blot using SA-HRP.

RESULTS

Design and synthesis of 2A-GlcCer XL (XLA and XLB) photoactivatable cross-linkers

The 2A-GlcCer XL was designed to closely mimic native GlcCer with two hydrophobic chains for membrane association, a cleavable disulfide bond, photoactivatable aryl azide in the proximity to the head group, and a biotin tag for affinity isolation. An overview of 2A-GlcCer XL synthesis is shown in **Fig. 1**. GlcCer was deacylated to lyso-GlcCer, desalted on a C-18 reverse phase silica gel column, and purified. The amino function of 2-aminohexadecanoic acid was protected with t-BOC, which increases yield of the subsequent BOP reaction by preventing polymerization of the 2-amino fatty acid. TLC staining with ninhydrin was used to monitor t-BOC protection reaction progression (**Fig. 2A**). 2-Aminohexadecanoic acid contains both D and L forms, which appears to run as two distinct bands when separated by TLC. After t-BOC protection the D, L isomers may have closely resolved to appear as one band. Product was purified on silica column and was confirmed by negative TOF mass spectrometry to have the expected mass of t-BOC protected 2-aminohexadecanoic acid [2-((tert-butoxycarbonyl)amino)hexadecanoic acid], 371.3 amu. Lyso-GlcCer was coupled to 2-((tert-butoxycarbonyl)amino)hexadecanoic acid to produce the product t-BOC-protected 2A-GlcCer. Reaction progression was monitored by TLC compared with C16:0 GlcCer analog and lyso-GlcCer by orcinol staining (Fig. 2B). t-BOC-protected 2A-GlcCer was deprotected, the two products (A and B) were purified and compared by TLC (Fig. 2C), and 2A-GlcCer A and B were confirmed as isomers by positive TOF mass spectrometry with a mass of 714.6 amu.

Diastereomers are not usually so well resolved by TLC (Fig. 2C). Therefore, the amino group on the fatty acid moiety of the 2A-GlcCer analogs was acetylated, to probe whether the TLC separation of the two isomers is due to differential intramolecular hydrogen bonding. After acetylation, the separation of the two isomers was much reduced, suggesting that polarity of isomer A is due to an NH intramolecular hydrogen bond (Fig. 2D). Both acetylated isomers A and B had an expected mass of 756.6 amu. 2A-GlcCer A and B analogs were separately coupled to sulfo-SBED to synthesize the biotinylated cross-linkers

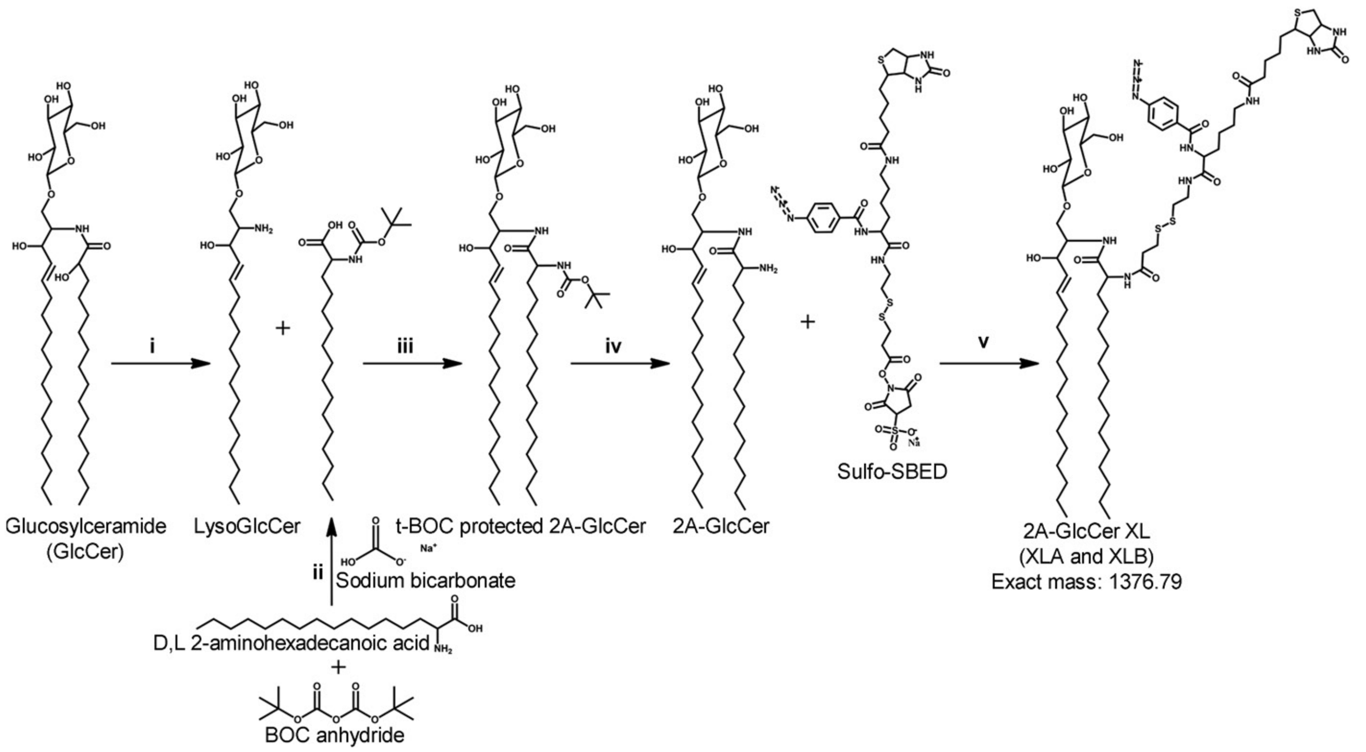

Fig. 1. Overview of 2A-GlcCer XL (XLA and XLB) synthesis. GlcCer was deacylated in 1 M NaOH/methanol at 70°C for 4 days (i). The amino function of 2-aminohexadecanoic acid was protected with t-BOC (ii). Mole ratio of 1:1.5:2 of 2-aminohexadecanoic acid, BOC anhydride, and sodium bicarbonate dissolved in CH_3OH/water (3.4:1, v/v) stirred for 2 days at room temperature. Lyso-GlcCer was coupled to t-BOC-protected 2-aminohexadecanoic acid (iii). BOP reagent (27.0 μmol) and t-BOC-protected 2-aminohexadecanoic acid (32.4 μmol) were dissolved in 5:5:1 DMF/DCM/TEA and incubated at −60°C for 10 min under nitrogen, and lyso-GlcCer (10.8 μmol) in 5:5:1 DMF/DCM/TEA was added to the reaction and incubated for 1.5 h at −60°C under nitrogen. t-BOC-protected 2A-GlcCer was deprotected (iv). t-BOC-protected 2A-GlcCer was dissolved in TFA/water (1:1, v/v) and stirred at room temperature for 7 h. 2A-GlcCer isomers A and B were purified. The 2A-GlcCer analogs were coupled to sulfo-SBED (v). Both 2A-GlcCer A and B analogs were dissolved separately in DMF and incubated in the dark at room temperature with 1 mg sulfo-SBED per analog for 3 h.

2A-GlcCer XLA and 2A-GlcCer XLB (abbreviated XLA and XLB). XLA and XLB were purified (Fig. 2E) and confirmed by positive TOF mass spectrometry to have the expected mass of 1,376.8 amu (**Fig. 3**).

Cross-linker characterization

GLTP binding. To determine the selectivity of XLA and XLB, cross-linking to known GlcCer binding protein GLTP was compared with GSL binding proteins VTB and CTB, and non-GSL binding protein gelatin. Selectivity was established by incubating 0.75 μM XLA or XLB with an equal mass of GLTP, VTB, CTB, and gelatin. Western blot with SA-HRP shows GLTP (25 kDa) was preferentially cross-linked by both XLA or XLB compared with gelatin and other GSL binding proteins (**Fig. 4A**, left panel). SDS-PAGE gel stained with Coomassie blue shows an equal quantity of GLTP, VTB, CTB, and gelatin present in cross-linking reactions (Fig. 4A, right panel). XLA and XLB cross-linking competition for GLTP was also investigated by addition of excess GlcCer. Western blot with SA-HRP shows GLTP cross-linking was reduced by half in the presence of excess GlcCer for both XLA and XLB compared with cross-linker alone, confirming GlcCer competes with both cross-linkers as ligands for GLTP binding (Fig. 4B).

LCS substrates. XLA and XLB were assessed as LCS substrates, in a ^{3}H-UDP-Gal LCS assay with DU145 microsomes in detergent (**Fig. 5A**). Exogenous C16:0 GlcCer standard was used as a positive substrate control, which generated a tritiated product coincident with the lower band of the LacCer standard. XLB gave a product which comigrated with the upper band of the LacCer standard. The product was greater than that derived from C16:0 GlcCer, but no LCS product was observed for XLA. Thus, XLB is a highly efficient substrate for LCS, whereas XLA is not an LCS substrate. The orcinol-stained TLC plate confirmed the putative substrate XLA was not degraded during the incubation period (Fig. 5B).

LCS competition. A detergent-free substrate competition LCS assay was used to determine whether NBD-GlcCer and XLA or XLB compete for LCS and putative GlcCer flippases. NBD-LacCer synthesis was reduced in the presence of either XLA or XLB, consistent with substrate competition (Fig. 5C). Competition with NBD-GlcCer breakdown by β-glucocerebrosidase was not completely avoided, even in the presence of the inhibitor, CBE. Because the LCS is in the Golgi lumen and this assay retains an intact (Golgi) membrane, it provides a potential index of Golgi luminal access to exogenous GlcCer, including translocation.

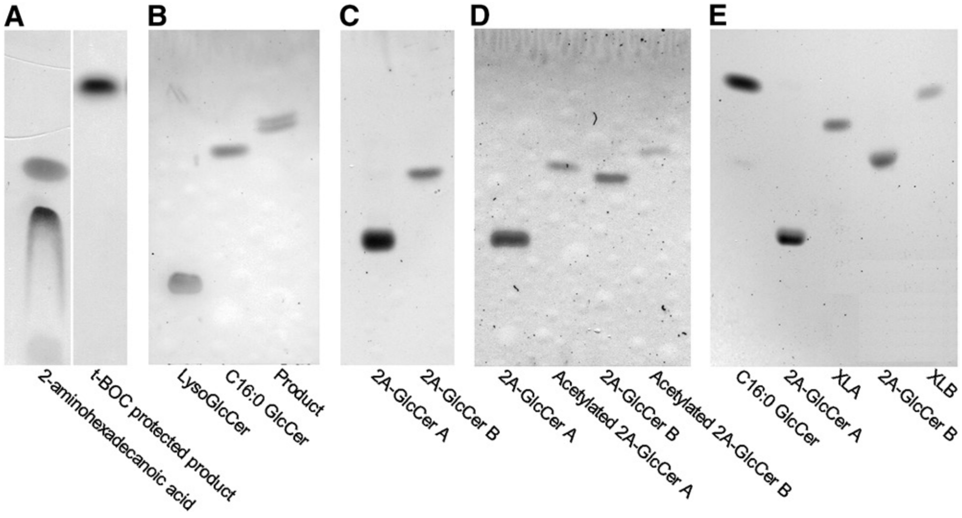

Fig. 2. XLA and XLB synthesis reactions were monitored by TLC. A: t-BOC protection of 2-aminohexadecanoic acid. TLC of 2-aminohexadecanoic acid, and reaction products were stained with ninhydrin. B: Lyso-GlcCer coupling reaction to t-BOC-protected 2-aminohexadecanoic acid. TLC of reaction products compared with C16:0 GlcCer analog and lyso-GlcCer stained with orcinol. C: TLC stained with orcinol of purified products from t-BOC deprotection reaction. D: 2A-GlcCer acetylation suggests intramolecular hydrogen bonding in isomer A. 2A-GlcCer A and B compared with acetylated products by TLC, stained with orcinol. Discrepancy of resolved acetylated products is significantly reduced. E: TLC stained with orcinol of purified biotinylated cross-linkers 2A-GlcCer XLA and XLB compared with precursors and C16:0 GlcCer.

GLTP delivery of GlcCer into microsomal membranes

Because GLTP has been used to transfer GSLs to model membranes to modify glycolipid composition (26), we rationalized that GLTP could be used to insert XLA and XLB into microsomal membranes. However, first we needed to establish whether GLTP delivery of GlcCer could increase LacCer synthesis. We used ^{3}H-UDP-Gal incorporation in detergent-free microsomes to monitor LacCer and globotriaosylceramide (Gb_3) synthesis from endogenous (**Fig. 6A**) or exogenous (Fig. 6B) GlcCer, in the presence and absence of GLTP and ATP. GLTP markedly increased LacCer synthesis (and subsequent Gb_3 synthesis) both from endogenous and exogenous GlcCer. This effect was significantly enhanced in the presence of ATP. ATP alone had little effect on LacCer synthesis but reduced the observed GLTP-increased radiolabeling of GlcCer. LacCer and Gb_3 synthesis were significantly increased by exogenous GlcCer supply. In the absence of ATP, however, exogenous GlcCer had no LacCer/Gb_3 stimulatory effect.

XLA and XLB cross-linking to microsomal proteins

XLA and XLB cross-linking was assessed in DU145 microsomes ± GLTP to deliver and insert the cross-linker into the microsomal membranes (**Fig. 7**). XLA or XLB were preincubated ± GLTP and then incubated with microsomes for 1 h before cross-linking with UV light for 15 min. Western blot with SA-HRP shows GLTP did not enhance cross-linking of microsomal proteins compared with XLA or XLB alone. Several protein bands of interest near 45, 50, 55, 100, and above 170 kDa were cross-linked by both XLA and XLB. GLTP was also cross-linked during the reaction. GLTP cross-linking was reduced in the presence of microsomes, as well as a cross-linked protein at 70 kDa present in GLTP only control (also seen in Fig. 4B).

DISCUSSION

XLA and XLB were designed with two alkyl chains to closely mimic native GlcCer. The $2NH_2$ fatty acid moiety of 2A-GlcCer provides a primary amine for coupling to the biotin-labeled cross-linker sulfo-SBED. The position of the amine maintains the hydrophilicity of the polar head group of the analog once coupled to sulfo-SBED and is appropriately positioned to cross-link head group binding proteins. The methods involved in synthesizing XLA/XLB are versatile and can easily be interchanged with lyso forms of different GSLs, different fatty acid chain lengths, and different cross-linkers.

After coupling the protected fatty acid to lyso-GlcCer, TLC separated two products. These are isomers resulting from the D and L forms of 2-aminohexadecanoic acid used in the coupling reaction with lyso-GlcCer. The two isomers of protected 2A-GlcCer analog were deprotected in the same reaction, which resulted in two compounds that ran very differently on TLC but with identical mass, which has not been previously observed. This effect is likely the result of an intramolecular hydrogen bond between the primary amine and the hydroxyl group of the sphingosine moiety in one of the isomers. To address this possibility, the primary amines of the two products were acetylated. Acetylation of the amine function considerably reduced the TLC separation, indicating an intramolecular H-bond from the amino group of isomer A was responsible for the TLC separation. Both isomers were coupled to sulfo-SBED

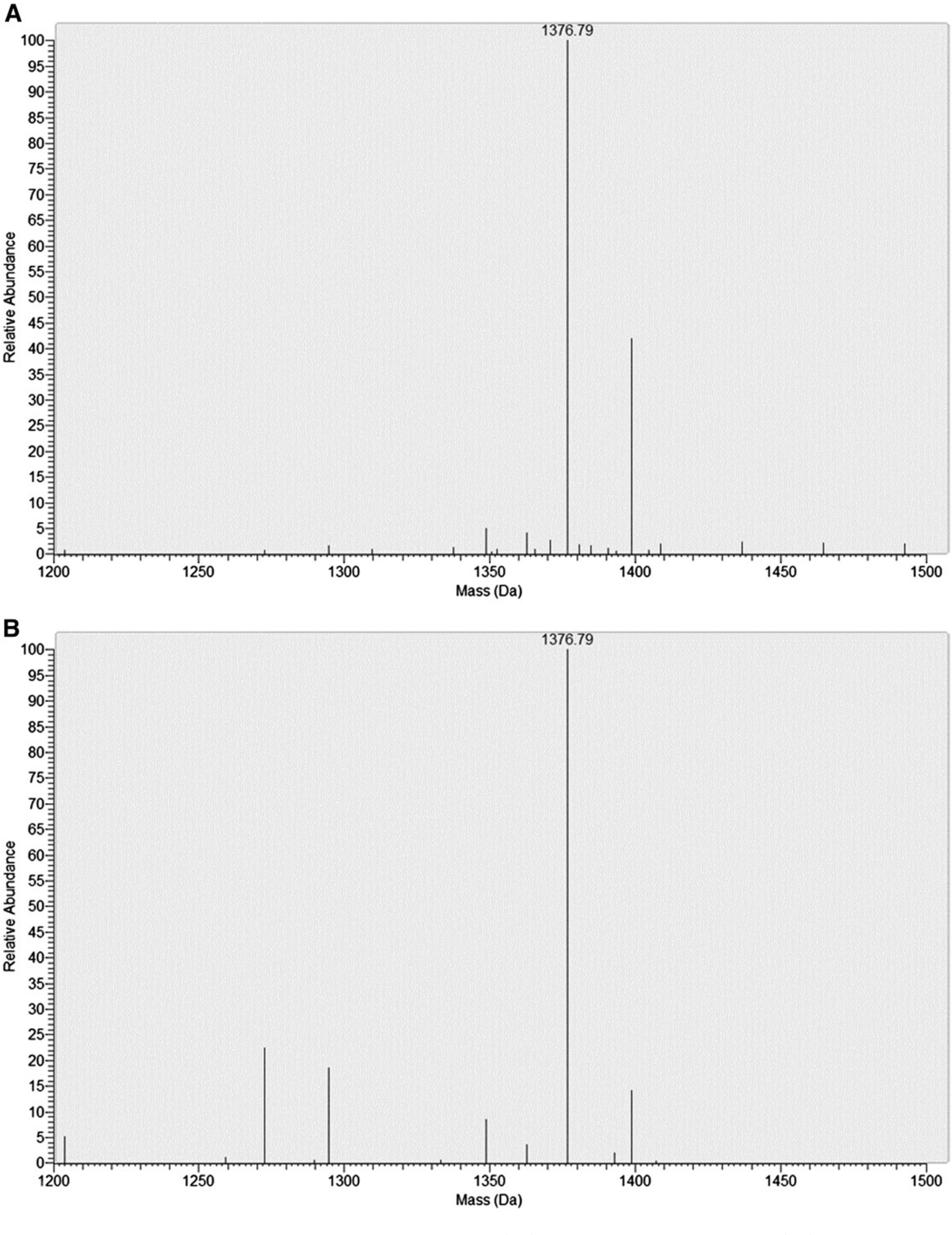

Fig. 3. Positive TOF of purified XLA and XLB. A: XLA with mass of 1,376.79 Da. B: XLB with mass of 1,376.79 Da.

to synthesize XLA and XLB, which show interesting differential activity in vitro.

The specificity of XLA and XLB cross-linking was shown using the known GlcCer binding protein GLTP. Recombinant GLTP was preferentially cross-linked by both cross-linkers as compared with GSL binding proteins VTB and CTB. Cross-linking GLTP with XLA and XLB decreased in the presence of GlcCer, which supports a common binding site on GLTP (for XLA/B and GlcCer) and also suggests GLTP can be used to transfer cross-linker into membranes.

The ^{3}H-LCS assay in detergent showed only XLB was converted into its LacCer form, not XLA. However, XLA still decreased NBD-LacCer synthesis when incubated with NBD-GlcCer in a detergent-free LCS assay, showing retained competition for LCS or putative flippases. Without detergent, the intact microsomal membrane remains a barrier, requiring substrate membrane translocation prior to luminal LacCer synthesis. Microsomal conversion of exogenous liposomal GlcCer to LacCer thus provides an index of GlcCer "flippase" activity. NBD-LacCer synthesis in intact

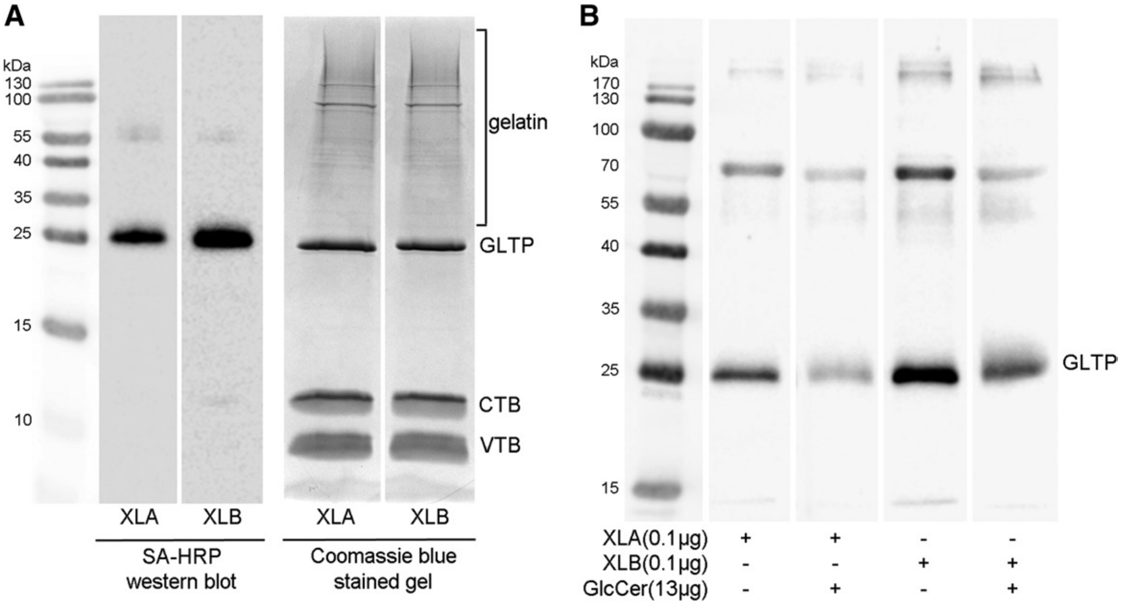

Fig. 4. XLA and XLB preferentially cross-links and shows substrate competition for GLTP. A: XLA or XLB (0.75 μM) was incubated with an equal mass of GLTP (2 mM), VTB, CTB, and gelatin. XLA and XLB were cross-linked to interacting proteins with UV light for 15 min. Western blot with SA-HRP shows GLTP was preferentially cross-linked, gel stained with Coomassie blue shows the presence of equal amounts of GLTP, VTB, CTB, and gelatin. B: GLTP, XLA, or XLB were incubated with or without GlcCer for 1 h at 37°C before cross-linking with UV light for 15 min. Representative Western blot with SA-HRP shows GlcCer reduces GLTP cross-linking for both XLA and XLB.

cell microsomes similarly suggests NBD-GlcCer is translocated by a GlcCer flippase prior to conversion by LCS. NBD-GlcCer has been shown to be a substrate for MDR1-mediated membrane flipping (27). Interestingly, the microsomal cytosolic β-glucosidase-mediated breakdown to NBD-Cer was less effectively blocked, particularly by XLA. The altered orientation of the acyl chain isoform in XLA may restrict access to the 4’OH of the glucose moiety required for LCS action. XLB is a very good substrate for LCS, more effective than C16:0 GlcCer in our in vitro assay; in contrast, XLA acts as an LCS inhibitor, rather than an active substrate. This provides a dramatic example of lipid modulation of GSL function (28, 29).

The role of GLTP in GSL synthesis was clearly shown in the cell-free microsomal system. In the absence of detergent, GLTP strongly promoted LacCer synthesis from both endogenous and exogenous GlcCer. This is consistent with the correlation between GLTP and cellular GlcCer levels (30). The GLTP-dependent increase we observed was amplified by ATP, but ATP alone did not affect LacCer synthesis. Conversion to Gb_3 was similarly stimulated by GLTP/ATP. GLTP does not appear to be ATP dependent, suggesting an

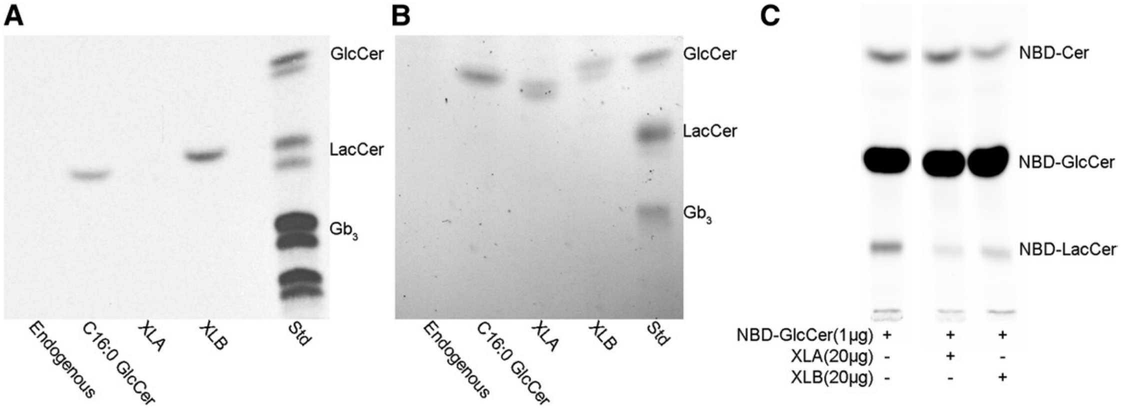

Fig. 5. Evaluation of GlcCer cross-linker substrate activity for LCS. A: DU145 microsomes were incubated with no exogenous GlcCer, semi-synthetic C16:0 GlcCer, XLA or XLB in the presence of Triton X-100 and ^{3}H-UDP-Gal. Analysis of reaction products by TLC followed by fluorography. TLC shows formation of a product consistent with LacCer from C16:0 GlcCer and XLB but not XLA. ^{14}C-Gal-labeled GSLs from vero cells are in “Std” lane. B: A portion of each sample from A was analyzed by orcinol-stained TLC to confirm XLA was not degraded during the incubation period. C: NBD-LacCer synthesis in DU145 crude microsomes; NBD-GlcCer and XLA or XLB were incubated with intact microsomes for 3 h at 37°C. TLC analysis of fluorescent NBD products revealed some glucocerebrosidase (GBA) 2/GBA3-mediated (32) breakdown to NBD ceramide. Conversion of NBD-GlcCer into NBD-LacCer was reduced in the presence of excess XLA or XLB, suggesting competition for GlcCer translocase or LCS or both.

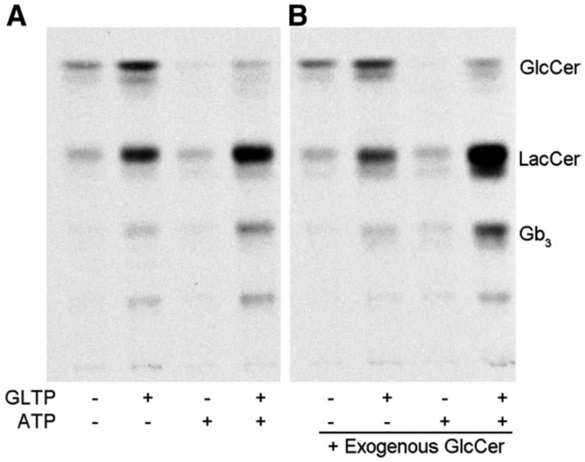

Fig. 6. Effect of GLTP and ATP on cell-free microsomal GSL biosynthesis. Membrane intact DU145 cell microsomes were incubated with ^{3}H-UDP-Gal at 37°C for 3 h ±5 mM ATP, ± GLTP in the absence or presence of exogenous liposomal GlcCer. GSLs were extracted, separated by TLC, and radiolabeled species detected by fluorography. A: Synthesis of LacCer from endogenous GlcCer. B: Synthesis of LacCer from exogenous GlcCer. The effect of ATP shows the UDP-Gal<->UDP-Glc epimerase responsible for labeling GlcCer is inhibited by ATP. GLTP markedly increases LacCer synthesis both from endogenous and exogenous GlcCer. Epimerase-mediated GlcCer labeling is also increased. Addition of both ATP and GLTP results in the greatest increase in LacCer synthesis, particularly from exogenous GlcCer when increased Gb_3 synthesis is also readily apparent.

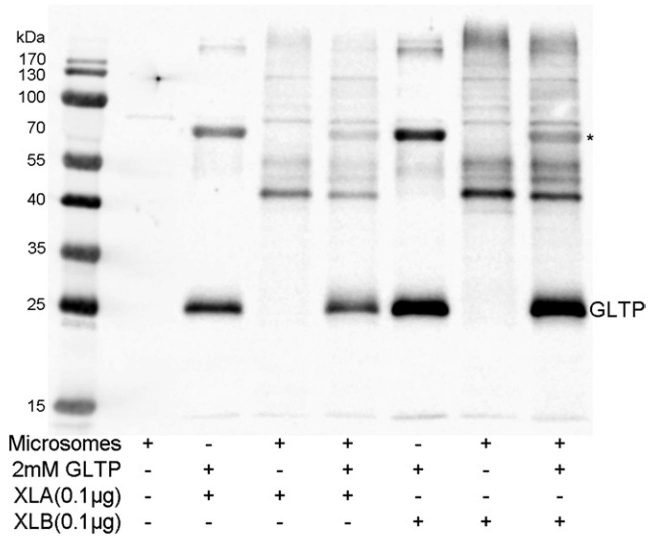

Fig. 7. XLA and XLB cross-linking not enhanced by delivery with GLTP to DU145 microsomes. XLA or XLB preincubated with GLTP, were incubated with microsomes for 1 h before cross-linking with UV light for 15 min. Western blot with SA-HRP shows GLTP did not enhance cross-linking of proteins compared with only XLA or XLB. However, there are several cross-linked proteins that could be GlcCer binding proteins or putative flippases. Band at 70 kDa (*) is in GLTP control without microsomes.

additional ATP-dependent step (e.g., an ATP-dependent translocator). The effect of GLTP/ATP was most marked for exogenous GlcCer, consistent with a primary effect on the mobilization of extra-Golgi GlcCer for LacCer (and Gb_3) synthesis. This suggested that using GLTP to deliver XLA and XLB to microsomal membranes would enhance cross-linking to GlcCer binding proteins and putative flippases.

XLA and XLB were cross-linked in DU145 microsomes using GLTP to deliver and insert the cross-linker into the microsomal membranes, as GLTP has been previously used to insert and extract GSLs in model membranes (26, 31), and our studies show GLTP enhancement of microsomal GSL synthesis. Recombinant GLTP was cross-linked by both XLA and XLB in DU145 microsomes, but cross-linking of microsomal proteins was not enhanced by GLTP delivery. This would suggest translocation is not the rate-limiting step. Cross-linking of the 70 kDa species was reduced in microsomes compared with GLTP alone, suggesting that this could be a GlcCer-donating species. Several microsomal proteins were consistently cross-linked in both micelle- and GLTP-delivered cross-linking. Our future studies are directed toward the characterization of these putative GlcCer binding proteins and flippases and their potential role in GSL synthesis.

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REFERENCES

1. Lingwood CA. 2011. Glycosphingolipid functions. Cold Spring Harb. Perspect. Biol. **3:** a004788.
2. Zhao, H., M. Przybylska, I. H. Wu, J. Zhang, P. Maniatis, J. Pacheco, P. Piepenhagen, D. Copeland, C. Arbeeny, J. A. Shayman, et al. 2009. Inhibiting glycosphingolipid synthesis ameliorates hepatic steatosis in obese mice. *Hepatology*. **50:** 85–93.
3. Marshall, J., K. A. McEachern, W. L. Chuang, E. Hutto, C. S. Siegel, J. A. Shayman, G. A. Grabowski, R. K. Scheule, D. P. Copeland, and S. H. Cheng. 2010. Improved management of lysosomal glucosylceramide levels in a mouse model of type 1 Gaucher disease using enzyme and substrate reduction therapy. *J. Inherit. Metab. Dis.* **33:** 281–289.
4. Natoli, T. A., L. A. Smith, K. A. Rogers, B. Wang, S. Komarnitsky, Y. Budman, A. Belenky, N. O. Bukanov, W. R. Dackowski, H. Husson, et al. 2010. Inhibition of glucosylceramide accumulation results in effective blockade of polycystic kidney disease in mouse models. *Nat. Med.* **16:** 788–792.
5. Allende, M. L., and R. L. Proia. 2014. Simplifying complexity: genetically resculpting glycosphingolipid synthesis pathways in mice to reveal function. *Glycoconj. J.* **31:** 613–622.
6. Biellmann, F., A. J. Hulsmeier, D. Zhou, P. Cinelli, and T. Hennet. 2008. The Lc3-synthase gene B3gnt5 is essential to pre-implantation development of the murine embryo. *BMC Dev. Biol.* **8:** 109.
7. Togayachi, A., Y. Kozono, Y. Ikehara, H. Ito, N. Suzuki, Y. Tsunoda, S. Abe, T. Sato, K. Nakamura, M. Suzuki, et al. 2010. Lack of lacto/neolacto-glycolipids enhances the formation of glycolipid-enriched microdomains, facilitating B cell activation. *Proc. Natl. Acad. Sci. USA*. **107:** 11900–11905.
8. Kuan, C. T., J. Chang, J. E. Mansson, J. Li, C. Pegram, P. Fredman, R. E. McLendon, and D. D. Bigner. 2010. Multiple phenotypic changes in mice after knockout of the B3gnt5 gene, encoding Lc3 synthase–a key enzyme in lacto-neolacto ganglioside synthesis. *BMC Dev. Biol.* **10:** 114.
9. De Rosa, M. F., D. Sillence, C. Ackerley, and C. Lingwood. 2004. Role of multiple drug resistance protein 1 in neutral but not acidic glycosphingolipid biosynthesis. *J. Biol. Chem.* **279:** 7867–7876.

10. Futerman, A. H., and R. E. Pagano. 1991. Determination of the intracellular sites and topology of glucosylceramide synthesis in rat liver. *Biochem. J.* **280:** 295–302.
11. Jeckel, D., A. Karrenbauer, K. N. Burger, G. van Meer, and F. Wieland. 1992. Glucosylceramide is synthesized at the cytosolic surface of various Golgi subfractions. *J. Cell Biol.* **117:** 259–267.
12. D'Angelo, G., E. Polishchuk, G. Di Tullio, M. Santoro, A. Di Campli, A. Godi, G. West, J. Bielawski, C. C. Chuang, A. C. van der Spoel, et al. 2007. Glycosphingolipid synthesis requires FAPP2 transfer of glucosylceramide. *Nature.* **449:** 62–67.
13. D'Angelo, G., T. Uemura, C. C. Chuang, E. Polishchuk, M. Santoro, H. Ohvo-Rekila, T. Sato, G. Di Tullio, A. Varriale, S. D'Auria, et al. 2013. Vesicular and non-vesicular transport feed distinct glycosylation pathways in the Golgi. *Nature.* **501:** 116–120.
14. Lala, P., S. Ito, and C. A. Lingwood. 2000. Transfection of MDCK cells with the MDR1 gene results in a major increase in globotriaosyl ceramide and cell sensitivity to verocytotoxin: role of P-gp in glycolipid biosynthesis. *J. Biol. Chem.* **275:** 6246–6251.
15. Shen, W., A. G. Henry, K. L. Paumier, L. Li, K. Mou, J. Dunlop, Z. Berger, and W. D. Hirst. 2014. Inhibition of glucosylceramide synthase stimulates autophagy flux in neurons. *J. Neurochem.* **129:** 884–894.
16. Varela, A. R., A. M. Goncalves da Silva, A. Fedorov, A. H. Futerman, M. Prieto, and L. C. Silva. 2013. Effect of glucosylceramide on the biophysical properties of fluid membranes. *Biochim. Biophys. Acta.* **1828:** 1122–1130.
17. Binnington, B., L. Nguyen, M. Kamani, D. Hossain, D. L. Marks, M. Budani, and C. A. Lingwood. 2016. Inhibition of Rab prenylation by statins induces cellular glycosphingolipid remodeling. *Glycobiology.* **26:** 166–180.
18. Schwarzmann, G., M. Wendeler, and K. Sandhoff. 2005. Synthesis of novel NBD-GM1 and NBD-GM2 for the transfer activity of GM2-activator protein by a FRET-based assay system. *Glycobiology.* **15:** 1302–1311.
19. Ramotar, K., B. Boyd, G. Tyrrell, J. Gariepy, C. Lingwood, and J. Brunton. 1990. Characterization of Shiga-like toxin I B subunit purified from overproducing clones of the SLT-I B cistron. *Biochem. J.* **272:** 805–811.
20. Basta, M., M. Karmali, and C. Lingwood. 1989. Sensitive receptor-specified enzyme-linked immunosorbent assay for *Escherichia coli* verocytotoxin. *J. Clin. Microbiol.* **27:** 1617–1622.
21. Williams, R. M., P. J. Sinclair, D. E. DeMong, D. Chen, and D. Zhai. 2003. Asymmetric synthesis of N-tert-butoxycarbonyl α-amino acids. Synthesis of (5S,6R)-4-tert-butoxycarbonyl-5,6-diphenylmorpholin-2-one (4-morpholinecarboxylic acid, 6-oxo-2,3-diphenyl-, 1,1-dimethylethyl ester, (2S,3R). *Org. Synth.* **80:** 18–30.
22. Kamani, M., M. Mylvaganum, R. Tian, B. Binnington, and C. Lingwood. 2011. Adamantyl glycosphingolipids provide a new approach to the selective regulation of cellular glycosphingolipid metabolism. *J. Biol. Chem.* **286:** 21413–21426.
23. Mylvaganam, M., L. J. Meng, and C. A. Lingwood. 1999. Oxidation of glycosphingolipids under basic conditions: Synthesis of glycosyl 'serine acids' as opposed to 'ceramide acids'. Precursors for neoglycoconjugates with increased ligand binding affinity. *Biochemistry.* **38:** 10885–10897.
24. Chatterjee, S., and E. Castiglione. 1987. UDPgalactose:glucosylceramide beta 1 → 4-galactosyltransferase activity in human proximal tubular cells from normal and familial hypercholesterolemic homozygotes. *Biochim. Biophys. Acta.* **923:** 136–142.
25. Karlström, A., and P. Å. Nygren. 2001. Dual labeling of a binding protein allows for specific fluorescence detection of native protein. *Anal. Biochem.* **295:** 22–30.
26. Rao, C. S., T. Chung, H. M. Pike, and R. E. Brown. 2005. Glycolipid transfer protein interaction with bilayer vesicles: modulation by changing lipid composition. *Biophys. J.* **89:** 4017–4028.
27. Eckford, P. D. W., and F. J. Sharom. 2005. The reconstituted P-glycoprotein multidrug transporter is a flippase for glucosylceramide and other simple glycosphingolipids. *Biochem. J.* **389:** 517–526.
28. Lingwood, C. A. 1996. Aglycone modulation of glycolipid receptor function. *Glycoconj. J.* **13:** 495–503.
29. Watkins, E. B., H. Gao, A. J. Dennison, N. Chopin, B. Struth, T. Arnold, J. C. Florent, and L. Johannes. 2014. Carbohydrate conformation and lipid condensation in monolayers containing glycosphingolipid Gb3: influence of acyl chain structure. *Biophys. J.* **107:** 1146–1155.
30. Kjellberg, M. A., and P. Mattjus. 2013. Glycolipid transfer protein expression is affected by glycosphingolipid synthesis. *PLoS One.* **8:** e70283.
31. Zhai, X., W. E. Momsen, D. A. Malakhov, I. A. Boldyrev, M. M. Momsen, J. G. Molotkovsky, H. L. Brockman, and R. E. Brown. 2013. GLTP-fold interaction with planar phosphatidylcholine surfaces is synergistically stimulated by phosphatidic acid and phosphatidylethanolamine. *J. Lipid Res.* **54:** 1103–1113.
32. Yamaji, T., and K. Hanada. 2015. Sphingolipid metabolism and interorganellar transport: localization of sphingolipid enzymes and lipid transfer proteins. *Traffic.* **16:** 101–122.