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ToP-DNJ, a Selective Inhibitor of Endoplasmic Reticulum α-Glucosidase II Exhibiting Antiflaviviral Activity

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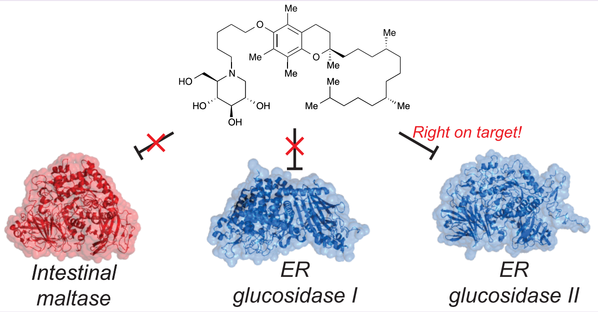
Supporting Information

ABSTRACT: Iminosugars have therapeutic potential against a range of diseases, due to their efficacy as glycosidase inhibitors. A major challenge in the development of iminosugar drugs lies in making a compound that is selective for the glycosidase associated with a given disease. We report the synthesis of ToP-DNJ, an antiviral iminosugar−tocopherol conjugate. Tocopherol was incorporated into the design of the iminosugar in order to direct the drug to the liver and immune cells, specific tissues of interest for antiviral therapy. ToP-DNJ inhibits ER α-glucosidase II at low micromolar concentrations and selectively accumulates in the liver *in vivo*. In cellular assays, the drug showed efficacy exclusively in immune cells of the myeloid lineage. Taken together, these data demonstrate that inclusion of a native metabolite into an iminosugar provides selectivity with respect to target enzyme, target cell, and target tissue.



Iminosugars are characterized by their nitrogen-containing heterocycles and ability to mimic monosaccharides. They have been investigated for their therapeutic potential against a variety of diseases including diabetes, genetic sphingolipidoses, and viral infections, with several iminosugar drugs in clinical use and clinical trials.[1−11] A major challenge for the development of these molecules is that the ubiquity of sugars and sugar processing enzymes throughout the body, which allows iminosugars to be therapeutic with respect to so many diseases, also leads to a variety of side effects.[2] We perceived two ways of improving selectivity: (i) developing a drug that has activity against only the target enzyme and (ii) directing the drug preferentially to target cells and tissues.

Our interests lie in the application of iminosugars as antivirals, particularly for the treatment of hepatitis C virus (HCV) and dengue virus (DENV). The therapeutic effect is theorized to occur via inhibition of the endoplasmic reticulum α-glucosidases I and II (GluI and GluII).[4,6,10,11] These two enzymes are antiviral targets due to their key role in regulating entry into the endoplasmic reticulum quality control (ERQC) pathway. As *N*-linked glycoproteins are being translocated into the ER, a 14-sugar oligosaccharide is transferred *en bloc* onto the nascent polypeptide. The first two steps of glycan processing are carried out by GluI and GluII, sequentially removing the two terminal glucose residues of the oligosaccharide (Figure 1A). The resulting monoglucosylated glycan serves as a "tag" for recognition by calnexin and calreticulin, which mediate interactions with host chaperones that make up ERQC to allow proper glycoprotein folding. GluII acts a second time to remove the final glucose residue, which means that the protein can no longer interact with calnexin and calreticulin. Enveloped viruses that contain *N*-glycosylated envelope and nonstructural proteins rely on this host glycoprotein folding process. Inhibition of GluI and GluII by iminosugars keeps the protein-linked *N*-glycans from being processed to the monoglucosylated stage, preventing these proteins from interacting with ERQC, which in turn can lead to misfolding. Without properly folded viral glycoproteins, morphogenesis and infectivity of the virus are compromised. Iminosugars are effective against a host of viruses including HCV, DENV, HIV, hepatitis B virus, influenza, and others.[6,12]

Because limited high-resolution structural information was available for these enzymes when the project began, a structure-based inhibitor design approach was intractable. Instead, we conceived that cell or tissue targeting could be achieved by conjugation of an iminosugar to a metabolite, thus directing the attached iminosugar according to the metabolite's own distribution. Previously, iminosugars have been successfully targeted to the ER via encapsulation into liposomes;[13] however, degradation of liposomes "on the shelf" made this methodology undesirable for long-term storage or treatment. In contrast, by uniting the pharmacophore and targeting moieties into a single molecule, the stability is defined by that of the molecule itself rather than a vehicle.

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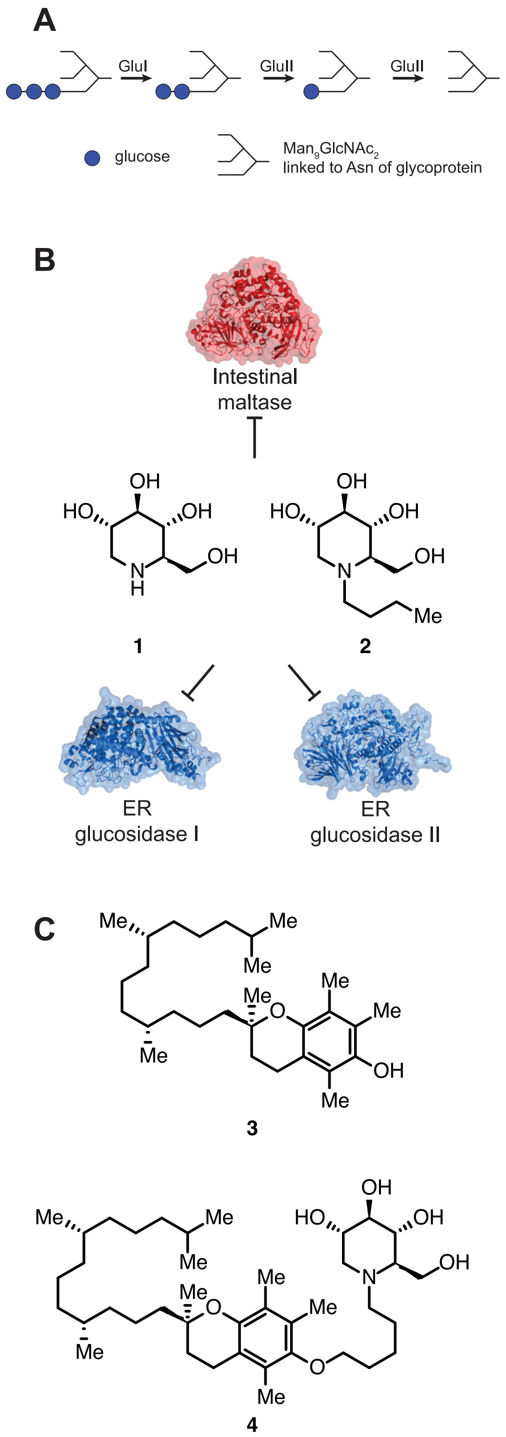


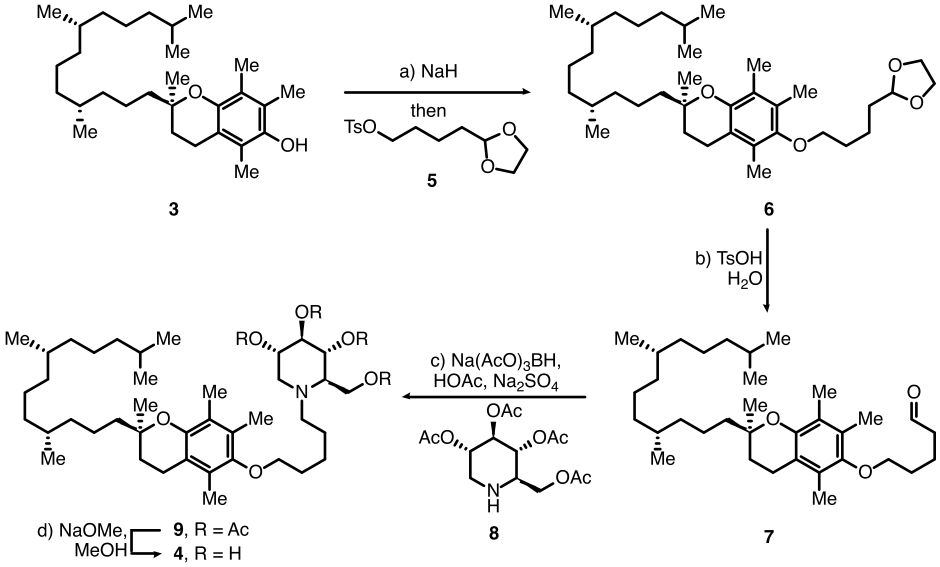
Figure 1. Enzyme targets and structures of iminosugars. (A) Trimming of the *N*-glycan by ER *α*-glucosidases I and II (GluI and GluII). (B) D-1-Deoxynojirimycin **1** and *N*-butyl-D-1-deoxynojirimycin **2** inhibit the ER-resident enzymes GluI (PDB ID 4J5T), GluII (PDB ID 5F0E), and intestinal glucosidases (e.g., maltase/glucoamylase, PDB ID 3TOP), which, like GluII, are members of glycoside hydrolase family 31. (C) D-(+)-*α*-tocopherol **3** and ToP-DNJ **4**.

We selected D-1-deoxynojirimycin (DNJ) **1** (Figure 1B) as the iminosugar component due to the broad-spectrum antiviral activity of **1** and its *N*-alkyl derivatives (e.g., *N*-butyl-DNJ **2**).[6] D-*α*-Tocopherol **3**, a form of vitamin E (Figure 1C), was selected as the metabolite to be conjugated to the iminosugar as it is nontoxic.[14] As **3** accumulates in two places desirable for antiviral therapy, we hoped it could serve as a tissue-targeting moiety. After being absorbed in the gut, **3** is packaged in the liver, the target organ of HCV and a potential reservoir for DENV.[15] Coupling **3** to siRNA directs the conjugate to the liver *in vivo*,[16] though this has never been demonstrated for a small molecule conjugate nor via oral administration. Compound **3** also accumulates in the membranes of immune cells,[17] one of the target cell types of DENV. So that both the DNJ and tocopherol moieties could be recognized independently by biological partners, a 5-carbon chain was employed as a flexible linker, resulting in the target structure 5′-tocopheroxypentyl-DNJ (ToP-DNJ, **4**).

A convergent route (Scheme 1) was designed with eventual exploration of structure−activity relationships (SAR) in mind, with straightforward replacement of any of the 3 subunits (linker, iminosugar, or metabolite) possible to allow optimization of each component. Desymmetrization of 1,5-pentanediol provided linker compound **5** (Supplemental Scheme 1).[18−20] Deprotonation of tocopherol **3** (NaH, DMF, 0 °C) yielded a nucleophilic phenolate anion that attacked alkyl tosylate **5** to give tocopheryl ether **6** (86% yield). With the metabolite attached, the other end of the linker could be unmasked (*p*-TsOH, H_2O) to reveal aldehyde **7** (99% yield). Due to the lipophilicity of the tocopherol moiety, **7** was coupled to tetra-*O*-acetyl DNJ **8**[21] rather than free DNJ **1**, so that the two reactants could be dissolved in a single phase. The reductive amination ($Na(AcO)_3BH$, cat. HOAc, Na_2SO_4) proceeded smoothly to give per-acetylated ToP-DNJ **9** (53% yield), and subsequent removal of the acetyl protecting groups (NaOMe, MeOH) provided **4** (71% yield). Attempts were made to couple **7** directly with DNJ **1**, but the lack of mutual solubility resulted in lower yields of **4**.

With **4** in hand, we examined the biological activities of the lead compound as a proof of concept. To begin characterization of **4**, we addressed whether the addition of the large tocopherol moiety abolished the ability of the iminosugar to inhibit glucosidases. *In vitro* inhibition studies of isolated glucosidases[22] were carried out (Supplemental Table 1 and Supplemental Figure 1). In addition to the targeted enzymes GluI and GluII, the effects of **4** on *α*-glucosidases (intestinal maltase, intestinal isomaltase, intestinal sucrase, and lysosomal glucosidase) and on a *β*-glucosidase (intestinal cellobiase) were analyzed, as off-target inhibition of these can cause undesirable gastrointestinal side effects.[2] The activity of **4** was compared to that of the parent compound **1** and the clinically approved drug **2**,[10] both of which inhibit all of the tested *α*-glucosidases. Surprisingly, **4** showed a remarkable selectivity for GluII. It has a comparable IC_{50} (concentration that gives 50% inhibition) to **1** and **2** with regard to GluII (IC_{50} values 9.0, 13, and 16 μM for **4**, **2**, and **1**, respectively) but shows less than 50% inhibition of the other tested enzymes at the maximum tested concentration of 50 μM. This selectivity for GluII has not been reported for any other DNJ compound and represents a huge step toward developing an antiviral of this class of iminosugars (which requires ER *α*-glucosidase inhibition) without associated gastrointestinal side effects (due to inhibition of the intestinal glucosidases). GluII and the intestinal *α*-glucosidases are all members of glycoside hydrolase family 31; it is therefore difficult to suggest a molecular explanation for the selectivity of **4** toward the ER-resident enzyme. Preliminary comparison of the active site of recently reported crystal structures of GluII[23,24] and that of intestinal maltase and glucoamylase[25,26] does not reveal the molecular origin of selectivity.

Scheme 1. Synthesis of ToP-DNJ 4



After demonstrating inhibition of GluII *in vitro*, **4** was next evaluated for its ability to disrupt activity of the same enzyme in the host cells in which we routinely evaluate compounds for inhibition of HCV and DENV: primary human monocyte-derived macrophages (MDMΦ, for DENV) and the human hepatoma Huh7.5 cell line (for HCV and DENV). Inhibition of GluI and GluII in cell culture is measured by assaying the levels of free oligosaccharides (FOS).[27] In the absence of ER α-glucosidase inhibition, the only glucosylated FOS observed are low levels of Glc$_1$Man$_5$GlcNAc$_1$. In general, when cells are treated with **2**, mono-, di-, and triglucosylated species can be observed indicating that both GluI and GluII are inhibited.[27] Accumulation of mono- and diglucosylated species (Glc$_1$Man$_4$GlcNAc$_1$ and Glc$_2$Man$_4$GlcNAc$_1$, respectively) result from inhibition of GluII, while triglucosylated glycans (Glc$_3$Man$_5$GlcNAc$_1$) serve as a biomarker for inhibition of GluI. In contrast to **2**, **4** demonstrated selectivity in terms of both enzyme and cell type. Glucosylated FOS were observed in naive MDMΦ (Figure 2A) but not in naive Huh7.5 cells. Only monoglucosylated FOS accumulated in **4**-treated MDMΦ, while mono- and triglucosylated FOS were observed in cells similarly treated with **2**. This further confirms the results of *in vitro* enzyme assays that **4** inhibits only GluII, while **2** inhibits both ER-resident glucosidases. In the Huh7.5 cells, no glucosylated FOS were observed, indicating that **4** inhibited neither GluI nor GluII in these cells, while **2** inhibits both enzymes in the same cells (Supplemental Figure 2A).

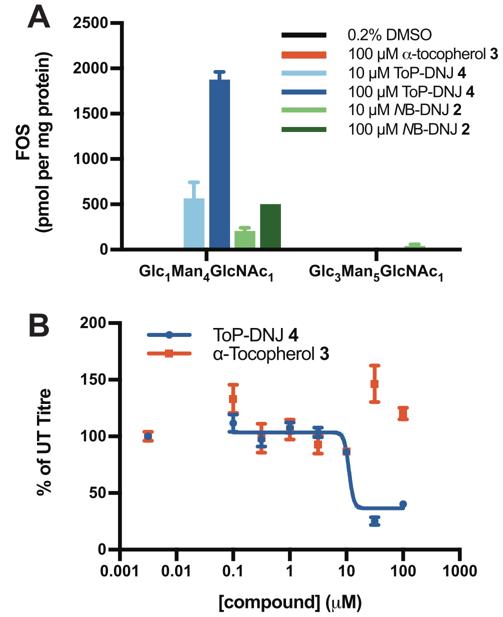


Figure 2. Effects of ToP-DNJ **4** treatment in monocyte-derived macrophages (MDMΦ). (A) Protein-normalized free oligosaccharide levels of naive MDMΦ (1 representative donor). The bar represents the mean; error bars show one standard deviation. (B) Infectious virus titer produced by dengue-infected MDMΦ (7 donors) under ToP-DNJ **4** or α-tocopherol **3** treatment. Compound **4** has an IC$_{50}$ of 12.7 μM, while **3** showed no antiviral effect. The data points represent the mean; error bars show standard error of the mean.

To examine the cell-type selectivity more thoroughly, additional human cell lines were treated with **4** and analyzed for FOS. Glu$_1$Man$_4$GlcNAc$_1$ was detected in HL60 (promyelocytic) cells (Supplemtnal Figure 2B) but not in Jurkat (T lymphocyte, Supplemental Figure 2C) nor Raji (B lymphocyte, Supplemental Figure 2D) cells. The fact that FOS were observed only in the MDMΦ and HL60 cells indicates that **4** affects only myeloid lineage immune cells. The GluII enzyme is the same in all human cells, suggesting that **4** is more effectively absorbed by myeloid lineage cell types than others. This is consistent with our initial hypothesis that the biological uptake of **4** would be influenced by the patterns of the constituent **3**, as immune cells are known to have increased amounts of **3** in their membranes, suggesting that they likely have mechanisms for enhanced uptake of this moiety. This opens up an exciting new strategy for targeting specific host cells, thereby reducing off-target effects typical of iminosugars.

The FOS produced under treatment with **4** in both the primary MDMΦ and HL60 cells included only monoglucosylated species, indicating inhibition of the second reaction catalyzed by GluII. However, no diglucosylated species were detected, raising the question whether **4** inhibits only one of the reactions catalyzed by GluII. In an effort to address this question, we measured the inhibition of GluII *in vitro* using a fluorescently labeled analogue of a native glycan substrate

(Glc$_2$Man$_7$GlcNAc$_1$), rather than α-*p*-nitrophenylglucoside. Compound **4** inhibited both reactions of GluII, with a more potent influence on the first reaction catalyzed by the enzyme (IC$_{50}$ of 14 μM for the conversion of diglucosylated to monoglucosylated versus 56 μM for the conversion of monoglucosylated to nonglucosylated glycan). This suggests that the lack of diglucosylated FOS in the primary MDMΦ and HL60 experiments is due to the kinetics of cellular glycan processing, rather than a property of the inhibitor **4**.

Given the more selective inhibition profile of **4**, it remained to be determined whether it retained the antiviral activity observed for other members of the iminosugar class. Compound **4** was antiviral with respect to DENV in primary MDMΦ cells (Figure 2B), in which GluII is inhibited as shown by FOS assay, but in Huh7.5 cells, in which GluII is not inhibited, neither an anti-DENV nor anti-HCV effect was observed (Supplemental Figure 3). This is consistent with the theory that inhibition of GluII is key to the antiviral effect. The IC$_{50}$ of **4** (12.7 μM) for DENV inhibition in MDMΦ cells (7 donors) is similar to that determined for **2** (6.00 μM)[28] in the same system. Notably, **4** has an antiviral effect in MDMΦ cells in the absence of any GluI inhibition activity, suggesting that GluII inhibition alone is sufficient for an anti-DENV effect.

The *in vitro* and whole cell assays characterized the targeted effects of the conjugated tocopherol on selectivity for specific glucosidases and cell types. However, to see whether it influenced the distribution of the iminosugar in different tissues, biodistribution studies were carried out in **4**-treated mice, with investigations of oral and intravenous administration routes. In both cases, **4** was detected in the highest amounts in the liver (Figure 3A, intravenous (IV) data; orally administered (*per os*, PO), Supplemental Figure 4), whereas **2** is found in the highest amounts in the kidneys and bladder as it is renally excreted.[29,30] The amount of **4** present in the liver did not decrease between the 4 and 24 h time points. In contrast, simple alkylated iminosugars are eliminated from the liver by more than 80% during the same time period.[29] In addition, the plasma terminal half-life of **4** was 8.79 h (Figure 3B), compared to 5 h for **2**.[30] The increase in half-life both in plasma and in the liver means that a single dose will have longer term therapeutic effects than previously investigated iminosugars. Compound **4** has poor oral bioavailability, achieving a maximum blood plasma concentration of 46 nM after 8 h (Figure 3B). However, the absorption of **3** depends on coconsumed nutrients. Consumption of **3** with a lipid-rich meal leads to 10-fold higher plasma levels.[31] Compound **4** might similarly require other hydrophobic molecules for efficient absorption after oral administration. Despite this limitation with regard to oral absorption, the high liver levels of **4** demonstrate that tissue-targeting of small molecules can be accomplished by the incorporation of the tocopherol moiety, regardless of administration route.

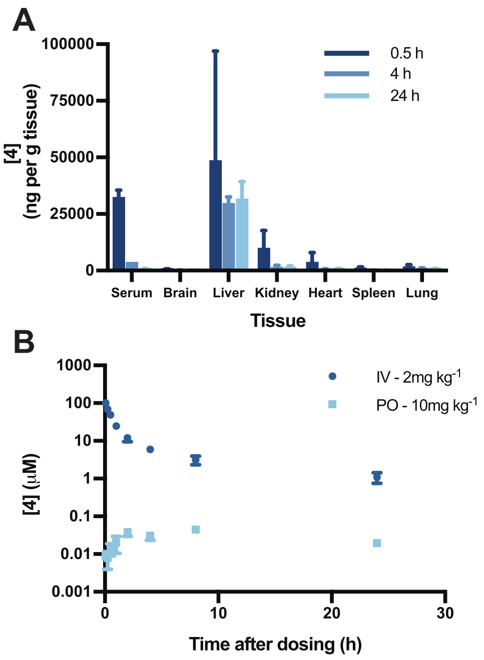


Figure 3. *In vivo* studies of ToP-DNJ **4** in BALB/c mice. (A) The concentration of **4** in all organs after intravenous (IV) administration. (B) Serum concentration of **4** over time (IV and *per os*, PO). On both graphs, the mean of 3 animals is shown; error bars show one standard deviation.

In conclusion, we prepared DNJ−tocopherol conjugate **4**, the first reported DNJ derivative to be a selective inhibitor of GluII. This selectivity was demonstrated both for isolated enzymes and in a whole cell system. By eliminating inhibition of the intestinal glucosidases, **4** could overcome the side effects both in antiviral iminosugar clinical candidates and in FDA-approved **2**. With a selective GluII inhibitor in hand, we discovered that GluI inhibition is not obligate for antiviral activity. Given the cell type specificity of **4** and the correlation of FOS and antiviral effect, it was substantiated that ER α-glucosidase inhibition, and not an alternative effect of DNJ compounds, is the mechanism of action for anti-DENV activity. Furthermore, incorporation of vitamin E into the iminosugar bestowed improved plasma and liver half-lives, as well as cell type dependent activity, which could be exploited for tailor-making drugs for host cells of specific viruses, leaving other cell types less affected. While we continue to study the properties of **4**, investigations are also proceeding to establish SAR for each of these novel iminosugar capabilities, as well as work on further iminosugar−metabolite conjugates.

■ METHODS

Chemistry. Methods for the synthesis of ToP-DNJ **4**, compound characterization, and spectra are described in detail in the Supporting Information.

Biological Assays. Methods for *in vitro* inhibition of isolated enzymes can be found in the Supporting Information. Methods used for evaluating the cellular inhibition of the ER glucosidases, as well as inhibition of HCV and DENV, are detailed in the Supporting Information, which also describes the procedures used in the biodistribution studies.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acschem-bio.7b00870.

Scheme 1 with detailed reagents and conditions, scheme for synthesis of pentyl linker, table of inhibition of isolated enzymes *in vitro*, figures of *in vitro* inhibition of GluII by **4**, free oligosaccharide analysis of cell lines treated with **4**, antiviral activity of **4** in human hepatoma Huh7.5 cell line, and mouse biodistribution of orally-administered **4**, in-depth experimental procedures, and NMR spectra (PDF)

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Notes

The authors declare no competing financial interest.

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