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<td>Wang, Guan-Nan; Murphy, Paul V.</td>
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Bi- to tetravalent glyoclusters: synthesis, structure–activity profiles as lectin inhibitors and impact of combining both valency and headgroup tailoring on selectivity

Guan-Nan Wang, Sabine André, Hans-Joachim Gabius and Paul V. Murphy*

The emerging functional versatility of cellular glycans makes research on the design of synthetic inhibitors a timely topic.

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Bi- to tetravalent glyoclusters: synthesis, structure–activity profiles as lectin inhibitors and impact of combining both valency and headgroup tailoring on selectivity†

Guan-Nan Wang,a Sabine André,b Hans-Joachim Gabiusb and Paul V. Murphys

Received 7th May 2012, Accepted 27th June 2012
DOI: 10.1039/c2ob25870f

The emerging functional versatility of cellular glycans makes research on the design of synthetic inhibitors a timely topic. In detail, the combination of ligand (or headgroup or contact site) structure with spatial parameters that depend on topological and geometrical factors underlies the physiological selectivity of glycan-protein (lectin) recognition. We herein tested a panel of bi-, tri- and tetravalent compounds against two plant agglutinins and adhesion/growth-regulatory lectins (galectins). In addition, we examined the impact of headgroup tailoring (converting lactose to 2′-fucosyllactose) in combination with valency increase in two assay types of increasing biorelevance (from solid-phase binding to cell binding). Compounds were prepared using copper-catalysed azide alkyne cycloaddition from peracyethylated lactosyl or 2′-fucosyllactose azides. Significant inhibition was achieved for the plant toxin with a tetravalent compound. Different levels of sensitivity were noted for the three groups of the galectin family. The headgroup extension to 2′-fucosyllactose led to a selectivity gain, especially for the chimera-type galectin-3. Valency increase established discrimination against the homodimeric proteins, whereas the combination of valency with the headgroup extension led to discrimination against the tandem-repeat-type galectin-8 for chicken galectins but not human galectins-3 and -4. Thus, detailed structure–activity profiling of glyoclusters combined with suitably modifying the contact site for the targeted lectin will help minimize cross-reactivity among this class of closely related proteins.

Introduction

The steadily growing body of evidence on the physiological significance of protein (lectin)-glycan recognition gives reason to aim at lectin-directed rational drug design in order to block clinically unfavourable interactions, e.g. in inflammation, tumour progression or pathogen adhesion.1 Clues to which parameters deserve special attention in the design of (bio)pharmaceuticals come from the delineation of the levels of affinity regulation of glycan binding to lectins.2 The ligand structure (headgroup and aglycone) and the spatial presentation of the ligand in glyoclusters are two key features to be considered in attaining the overall objective. A third is the valency order (monovalent vs. bivalent vs. trivalent etc.). In considering spacing, geometry, topology and inter-ligand distances need to be taken into account. The elegant work on targeting membrane lectins with a sterically rigid presentation of carbohydrate-binding sites, especially the hepatic asialoglycoprotein receptor using a triantennary N-glycan or synthetic cluster glycosides with a matching spatial arrangement, laid the foundation for the concept of the glycoside cluster effect.3 In that case, a numerical increase in valency from one to three reactive headgroups in a neoglycoconjugate led to an enhancement in affinity, mimicking the potency of the type I triantennary N-glycan.4 Since the natural effector activity of lectins, presented in membranes or in solution, is based on binding to structurally and spatially suitable counter-receptors, devising an adequately tailored combination of these two parameters is considered helpful in addressing the challenge to design inhibitors with optimal potency. Given the wide variety of natural ways for lectin-site presentation5 and the diversity of (bio)chemical scaffolds which can be used in glyocluster formation,6 a clear study design will help to discern structure–activity relationships for medically relevant lectins. Following our initial reports on different types of bivalent lactosides,6b we herein explore the effect of stepwise increases in valency, from mono- to tetravalency, as well as changing the structure of the headgroup from lactose to the histo-blood H-type structure – 2′-fucosylactose (Chart 1). In detail, the monovalent control compounds that were investigated are 2′-fucosylactose (FL) 1 and...
a triazole conjugate 2, together with lactose. The set of lactose-
presenting di-, tri- and tetravalent glycoclusters 3–5 and 7 and the
trivalent FL derivative 6, which has the same core scaffold as 4,
complete the compound panel. The testing of this panel was per-
formed in assays involving the same group of lectins in the quest
to define the impact of the given two parameters on bioactivity.

The test panel of lectins investigated herein consists of a plant
toxin (Viscum album L. agglutinin, VAA) and two types of
β-sandwich-fold proteins, i.e. a leguminous lectin (Erythrina
crystagalli agglutinin, ECA) and adhesion/growth-regulatory
glectins. Thus, the synthetic compounds are tested for potency
as anti-toxin (VAA) and for reactivity to lectins sharing the same
fold but differing in positioning the lectin sites (ECA, galectins).
We comprehensively studied all known members of the latter
family from one organism, i.e. the five chicken galectins (CGs),
to spot intrafamily differences and added work on two human
glectins, i.e. Gal-3/-4, for comparison. These lectins’ contact
sites for carbohydrates are presented in three modes of topologi-
cal display: proto-type (non-covalently associated homodimers:
CG-1A/-B/-2), tandem-repeat-type (two different domains co-
valently linked by a peptide: CG-8, Gal-4) and chimera-type (a
single carbohydrate recognition domain connected to a

![Chart 1](chart.png)

Chart 1 Structures of the synthetic compounds 1–7.
collagenase-sensitive stalk and an N-terminal section with two acceptors for serine phosphorylation: CG-3, Gal-3. With regard to the carbohydrate the extension from lactose to the histo-blood H-type structure was expected to have little impact on VAA/ ECA, to slightly prefer CG-1B when compared to CG-1A and to increase the affinity for CG-8, Gal-3 and Gal-4. The respective comparative measurements provide an instructive example for the influence of headgroup/valency tailoring on lectin affinity and selectivity. They were performed in two experimental set-ups. The first is a solid-phase assay, in which extent of lectin binding to a glycoprotein matrix (asialofetuin, ASF, which has up to nine N-acetylactosamine termini on its bi- and triantennary N-glycans; they all can bind to VAA and galectins) was determined. To increase biorelevance, that is to work with cells, an assay was subsequently utilised where blocking of lectin binding to the cell surface was assessed.

Results and discussion

Synthesis

The synthetic routes to the bi-, tri- and tetravalent alkyne precursors to 1–8 are shown in Scheme 1. The dialkyne 9 and tetraalkyne 11 were via the reaction of alkyl bromides 8 and 10 with potassium phthalimide (PhthK)\textsuperscript{14} 1,3,5-Tris(alkynyloxy)benzene 13 was prepared from phloroglucinol 12 and propargyl bromide. The trialkyne 16 was made from the coupling reaction of 14 and 15. Multivalent lactosides were all prepared from the lactose azide 17 (Scheme 2).\textsuperscript{15} Thus alkyne 9, 11, 13, 16, when reacted with 17 using copper(II)-catalysed azide alkyne cycloaddition (CuAAC)\textsuperscript{16} reactions, gave the protected intermediates 18–21. The CuAAC reactions were carried out using the in situ reduction of copper(II) sulphate by sodium ascorbate in aqueous solution using methanol as a co-solvent. As the number of alkynes increased, the completion of CuAAC reaction was found to be more difficult to achieve. Similar to the situation in the synthesis of compounds 19, 20 and 21, either ultrasonic radiation\textsuperscript{17} or heating was required to accelerate the reactions. Both phthali-mido groups and acetyl groups in 18 and 19 were removed using ethylenediamine in ethanol by heating at reflux, giving 3 and 7 after washing the solid product with small amount of methanol. The trivalent lactosides 20 and 21 afforded 4 and 5 after Zemplén deacetylation.

The synthesis of trisaccharide 24 was achieved via glycosidation with the fucosyl donor 23\textsuperscript{18} and acceptor 23 (Scheme 3). For the synthesis of 23 an approach originally described by Matta and co-workers was used.\textsuperscript{19} Two promoter systems NIS–TIOH (46%) and benzenesulfonylpyperidine (BSP)–TF\textsubscript{2}O (70%) were comparatively investigated for the glycosidation to give the trisaccharide 24. In terms of reaction time and yield, the BSP–TF\textsubscript{2}O promoter system turned out to be substantially better for this glycosidation. The anomic configuration of the glycosidic linkage between fucose and lactose residues was assigned based on the size of the coupling constant (J\textsubscript{1,2} = 3.3 Hz) in the \textsuperscript{1}H NMR spectrum. The signal for C-1\textsuperscript{1} occurred at δ 95.2 ppm in the \textsuperscript{13}C-NMR spectrum. Debenzyolation of 24 was carried out using methanolic sodium methoxide, hydrolysis of the acetonide groups using 60% acetic acid at 60 °C and subsequent catalytic hydrogenuolysis provided FL.\textsuperscript{19,20} This trisaccharide was acetylated and the azide group was introduced using SnCl\textsubscript{4} and TMSN\textsubscript{3} to give 27 (Scheme 3). It is worth mentioning that the α-glycosidic linkage was sensitive to the Lewis acid if the benzyl groups were present on the fucose residue while trying to introduce the azide group to form a fucosyllectosyl azide. The use of TMSN\textsubscript{3}–SnCl\textsubscript{4}, 33% HBr in AcOH, and BiBr\textsubscript{3}/TMSBr\textsuperscript{21} all led to the cleavage of this fucosidic bond. In contrast, the fully acetylated FL was found to be more stable.

The CuAAC reaction between fucosyllectosyl azide 27 and Fmoc-protected l-propargylglycine,\textsuperscript{22} which was followed by protecting group removal using initially piperidine and then methanolic sodium methoxide, provided the glycamino acid 2 (Scheme 4). The trivalent fucosyllectoside 6 was prepared via click reaction of 1,3,5-tris(alkynyloxy)benzene 13\textsuperscript{15} and fucosyllectosyl azide 27 and subsequent deacytlation. Having herewith completed the synthetic component of this work, insights into the spatial property of the maximal distance between sugar headgroups within each type of glyocluster were obtained by molecular modelling.

Molecular modelling

The assessment of the distance between the sugar headgroups in the synthetic glyoclusters was set as goal for this part of the study. As a common feature and not in contradiction to the biantennary glycoclusters described, the fructose residues were present on the fucose residue while trying to introduce the azide group to form a fucosyllectosyl azide. The use of TMSN\textsubscript{3}–SnCl\textsubscript{4}, 33% HBr in AcOH, and BiBr\textsubscript{3}/TMSBr\textsuperscript{21} all led to the cleavage of this fucosidic bond. In contrast, the fully acetylated FL was found to be more stable.

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Assaying inhibitory properties on plant lectins

In principle, the solid-phase assay reflects the physiological situation, in which the lectin in solution can bind to surface-presented glycans. This binding can be disrupted by inhibitors. The glycoprotein asialofetuin was adsorbed to the plastic surface of...
microtitre plate wells, and the evaluation of lectin-glycoprotein binding was in each case shown to be saturable and inhibitable by the cognate sugar lactose but not by mannose or glucose. In order to reach optimal sensitivity experimental conditions were defined so that the signal increase associated with increasing lectin concentration and consequently binding to the glycoprotein was in the linear and not saturated range. Titrations with the synthetic products as inhibitors at a constant lectin concentration established curves of decreasing signal intensity. The apparent inhibitory activity fulfilled the expectation raised by the molecular modelling. In order to compare the relative potencies, these curves enabled us to define the concentration of sugar presented by the compounds at which a 50% decrease in optical density (IC50-value) was reached (for an example, please see Fig. 2). In accordance with previous affinity measurements the trisaccharide FL 1 was not found to be more active than lactose (Table 1, see end of document). However, a major avidity increase occurred in the progression to tetravalency for the toxin (Fig. 2, Table 1). This held true for its hololectin constituted by dimers of the toxin (A) and lectin (B) subunits (in which the two accessible Tyr249 sites are separated by 87 Å) and also the isolated B-chain (with a distance between the Tyr249 and Trp38 sites of 62 Å24), all distances thus beyond the range coverable by the glycoclusters 3–7. The Trp38 sites are only 15 Å apart but not fully accessible.24 In contrast, the positioning of contact sites on opposing sides of the leguminous lectin ECA apparently precluded there being an enhancement for the tetravalent compound 7. Previous experience with tetravalent glycoclusters attests that

Scheme 1  Synthesis of alkyne precursors.
not just valency but the geometric mode of ligand presentation matters, giving both functionalized dendritic poly(amidoamine) and pentaerythritol-based compounds exceptional potencies.25

Since the type of glycan display on the matrix (e.g. branching mode of N-glycans) can have an influence on the inhibitory efficiency of glycolusters, it was essential to confirm potency on a more relevant physiological level, i.e. by revealing the efficiency of compounds to protect cells from lectin binding. Thus, we performed cell assays with fluorescently labelled lectin. In this type of assay, the synthetic compounds compete with cell surface glycans for lectin binding. The extent of signal reduction (in terms of percentage of positive cells and mean fluorescence intensity) that results by blocking lectin binding was determined. Assays were routinely performed with aliquots of the same cell suspension, avoiding prolonged culture times and routinely running internal standards (0%/100%-values, inhibition with lactose). As in the case of the solid-phase system, dependence of signals on lectin concentration and presence of cognate sugar was first ascertained, as exemplarily shown for V AA (Fig. 3A and B). Compared to lactose the inhibitory capacity of the test compounds was in most cases only slightly improved (please see documented examples for the bivalent compound 3 and the trivalent compound 4 in Fig. 3C and D), in accord with the solid-phase-based data (Table 1). Tetrapenal compound 7, which reached approximately a 20-fold enhancement (Table 1), was the most potent inhibitor. While 20 mM lactose led to decreases to 50%/23.6 from the control level of 72%/89.3, the presence of 0.5 mM lactose in a glycoluster presentation reduced lectin binding to the cells to 50%/32.9 (Fig. 3B and D). Overall, correlation between the results of the two types of assays (solid phase vs. cell) was thus found. Having started with two plant lectins, we proceeded to measurements with the five CGs. They exhibit sequence variations in their carbohydrate recognition domains and cover the three modes of lectin-site presentation, an attractive model to address the issues on impact and headgroup extension and valency.

Assaying inhibitory properties on chicken galectins

The structure of the headgroup was clearly relevant among this group of lectins (Table 1). A lowered affinity with CG-1A had been indicated by frontal affinity chromatography. The same holds true for human and rat Gal-1. Occurrence of intrafamily differences between CGs was further underscored by slight enhancement of reactivity for CG-8 and reduced sensitivity to α1,2-or α1,3-substitutions seen for CG-1B relative to CG-1A.

Scheme 2 Synthesis of di- to tetravalent lactosides.
The comprehensive profiling of lectin reactivity to \(1\text{–}7\) singled out the chimera-type lectin as the most responsive (Table 1). The CG-3 was especially reactive with FL and found to be susceptible to an increase in valency, with the highest affinity being observed towards \(6\) (Table 1). The proteolytic removal of the collagenase-sensitive stalk, which underlies galectin-3's capacity to form stable aggregates in the presence of oligovalent ligands,\(^{27}\) did not reduce the relative affinity to lactose but did impair the sensitivity to valency increase (comparing lactose and \(1\text{–}7\) for CG-3 and trCG-3). Tri- and tetravalency affected the tandem-repeat-type CG-8 and its separate domains differently, and the increase in length of the linker peptide from nine (CG-8S) to 28.
amino acids (CG-8L) appeared to be associated with a minor
enhancement (Table 1). In terms of achieving selectivity, the
modification to include fucose in the headgroup when combined
with trivalency as seen in 6 leading to the highest inhibition for the
full-length CG-3, less so for CG-8 and its domains. Drawing on
data for human Gal-3 affords a route to further enhancements.
Since the fucose moiety in α1,2-linkage is only weakly involved
in interactions to human Gal-3 relative to the additional α1,3-
substitution in histo-blood group AB-determinants based on
flexible ligand docking,11 a further elaboration to generate a

Table 1  IC₅₀-values of the mono- to tetravalent lactosides
and free lactose (Lac) for blocking binding of biotinylated plant and chicken lectins to surface-immobilized ASF (in mM)

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<th>Lectin inhibitor</th>
<th>VA A (1.5 μg ml⁻¹)</th>
<th>VA A-B (0.5 μg ml⁻¹)</th>
<th>ECA (0.2 μg ml⁻¹)</th>
<th>CG-1A (3 μg ml⁻¹)</th>
<th>CG-1B (1 μg ml⁻¹)</th>
<th>CG-2 (2 μg ml⁻¹)</th>
<th>CG-3 (0.5 μg ml⁻¹)</th>
<th>trCG-3 (2.5 μg ml⁻¹)</th>
<th>CG-8S (3 μg ml⁻¹)</th>
<th>CG-8L (0.5 μg ml⁻¹)</th>
<th>CG-8N (3 μg ml⁻¹)</th>
<th>CG-8C (3 μg ml⁻¹)</th>
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a For structures see Chart 1; titrations were performed using a fixed glycoprotein quantity for coating (0.5 μg per well) with eight concentrations of sugar in duplicates and up to five independent series, reaching an upper limit of 14.8% for the standard deviation (for exemplary titration curves, see Fig. 1); the concentration is always given for lactose, free in solution or conjugated to a scaffold.

b Tendency for stimulation at concentrations above 1 mM; numbers in brackets denote relative potency.
tetrasaccharide rather than a trisaccharide headgroup will be conducive for affinity increase, shown calorimetrically to move $\Delta G$ from $-16.4$ kJ mol$^{-1}$ for lactose and $-19.15$ kJ mol$^{-1}$ for FL to $-24.88$ kJ mol$^{-1}$ for the histo-blood group A-tetrasaccharide (at about 280 K). In inhibition assays, the relative potency, with lactose set to 1, increased by a factor of 2.8 for FL and to 35 by the added $\alpha$1,3-substitution. As noted above for the plant agglutinins, cell assays with the chicken galectins also corroborated the changes in inhibitory potency listed in Table 1. These experiments e.g. illustrated the relative efficiency of the trivalent 6 to block binding of trCG-3 (0.1 mM sugar presented by 6 yielded a decrease from 51%/32.9 (control) to 32%/15.0 compared to 45%/19.7 for 1 mM lactose; Fig. 4A–D) and the N-terminal domain of CG-8 (Fig. 4E and F). In order to ensure that these results from CG-3 can be extrapolated to the human orthologue we next ran experiments under identical conditions with human Gal-3. Because glycoprotein binding of the tandem-repeat-type Gal-4 had been reported to be sensitive to ligand presentation by cyclic scaffolds (calixarenes, cyclooligocaptopeptides), we performed respective experiments with this two-domain protein and its separate domains in parallel.

Assaying inhibitory properties on human galectins

The obtained data document interspecies maintenance of selectivity for respective headgroup tailoring and valency increase in the case of the chimera-type protein (Table 2). The results are also in accord with the 2.8-fold enhancement previously reported for FL in a similar inhibition assay. Binding of Gal-4 proved to be rather susceptible to the presence of the tetravalent compound 6, being less so towards the trivalent compound, so that this structural design appears to hit tandem-repeat-type galectins (Gal-4, CG-8) as well as the chimera-type Gal-3 (Table 2). The strong inhibitory potency of 6 on cell binding, in comparison to the bi- and trivalent substances, is illustrated in Fig. 5, again correlating rather well with the results from the solid-phase assay. The monovalent association of the separate domains of Gal-4 to glycoprotein glycans could also be effectively blocked more strongly than in the case of the lectin domain of Gal-3 (Table 2). Of note, set in relation to the plant toxin, the case of dithiodigalactoside, which shows low-affinity binding, if at all, to human galectins, exemplifies the possibility for markedly different headgroup affinities despite presence of galactose and thus enabling the targeting of the toxin with a galactose-based compound while avoiding side effects that would result from binding to galectins.

Conclusions

The molecular characterization of the counterreceptors for tissue lectins is unlocking the virtues of spatial parameters for generating the high-level selectivity found in nature. In fact, their local density can matter in different contexts up to the presentation of target sites in membrane microdomains. The fundamental importance of this property, that is a particular spatial organization of carbohydrate recognition groups and not just their mere presence, has recently been proven for galectins-1 and -3 in relation to their high-affinity binding to ganglioside GM1 exposed on human neuroblastoma cells by perturbing the integrity of microdomains. This switch-like impact on affinity, together with similar effects on the other levels given in Table 1, prompts the efforts to delineate detailed structure–activity profiles for glyoclusters.

Proceeding from our previous reports on bivalent presentation, we herein delineate special sensitivity of the tandem-repeat and chimera-type galectins for the tested tri- and tetravalent compounds when compared to the group of homodimeric proteins. Synthetic $\alpha$1,3-substitution had even been found to add to the discrimination between galectins-1 and -3 on the level of cell binding. Evidently, the tested natural headgroup elaboration could enhance the respective potency for galectin-3. This result intimates the possibility of such tailoring to allow the attainment of affinity differences between the chimera- and tandem-repeat-type proteins and also within the latter group. Along this line, the identification of distinct natural docking sites for certain lectins, e.g. sulphated glycosphingolipids for galectin-4, and of aglyconic extensions conferring selectivity gains such as the $\beta$-naphthyl sulfone will help achieve stepwise progress. And here choosing the optimum geometry to match an increase in valency can come into play, because the comparison of inhibitory capacity of tetravalent clusters built with different scaffolds (for scaffold development) underlines the fact that geometry can matter markedly. Our results on CG-3/CG-8 and the combination of trivalency with headgroup tailoring encouraged further consideration of the feasibility of this proposal. The same strategy of changing the headgroup could be applied to the toxin, which tolerates $\alpha$2,6-sialylation of lactose in sharp contrast to the galectins, hereby precluding cross-reactivity of an antitoxin compound with the galectins. Giving direction to further work, the detailed analysis of lectin specificity will continue to provide inspirations for the design of the contact region. Equally important, comparative analysis within and between lectin families will be required to track down the most suited glyocluster design to attain optimal selectivity.

Experimental section

General experimental

Unless otherwise noted, all commercially available compounds were used as provided without further purification. Solvents for chromatography were technical grade. Petroleum ether 40–60 °C was used for column chromatography and thin layer chromatography (TLC). NMR spectra were recorded (25 °C) with 500 MHz spectrometer. The frequency is 500 MHz for $^1$H NMR and 125 MHz for $^{13}$C NMR. Data are reported in the following order: chemical shift (δ) in ppm; multiplicities are indicated s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet); coupling constants (J) are given in Hertz (Hz). Chemical shifts are reported relative to internal Me$_4$Si in CDCl$_3$ (d 0.00) or HOAc for D$_2$O (d 4.72, 25 °C) for $^1$H and Me$_4$Si in CDCl$_3$ (d 0.00) or CDCl$_3$ (d 77.0) for $^{13}$C. $^1$H NMR signals were assigned with the aid of COSY and $^{13}$C NMR signals using DEPT, gHSQCAD and/or gHMBCAD. Low- and high-resolution mass spectra were in positive and/or negative mode as indicated in each case. TLC was performed on aluminium sheets precoated with silica gel and spots visualized by UV and charring with H$_2$SO$_4$–EtOH.
Flash chromatography was carried out with silica gel 60 (0.040–0.630 mm) and using a stepwise solvent polarity gradient correlated with TLC mobility. CH₂Cl₂, MeOH, toluene and THF reaction solvents were used as obtained from a Pure Solv™ Solvent Puriﬁcation System. Anhydrous DMF, pyridine, and EtOH were used as purchased.

2-(3,5-Bis(prop-2-ynyloxy)benzyl)isoindoline-1,3-dione 9

To a mixture of potassium phthalimide (408 mg, 2.2 mmol) and bromide 8 (500 mg, 1.8 mmol) in toluene (15 mL) was added 18-crown-6 (49 mg, 0.18 mmol). The mixture was heated at 100 °C for 6 h with stirring under N₂ and then water was added. The organic layer was separated and aqueous layer was extracted with CH₂Cl₂. The organic portions were combined, then dried over Na₂SO₄ and the solvent was evaporated under reduced pressure. Silica gel chromatography (petroleum ether–EtOAc, gradient elution, 3:1 to 1:1) afforded 9 (454 mg, 73%) as an white amorphous solid (73%); ¹H NMR (500 MHz, CDCl₃) δ

7.85 (dd, J = 5.3, 3.0 Hz, 2H), 7.71 (dd, J = 5.3, 3.0 Hz, 2H), 6.67 (d, J = 1.9 Hz, 2H), 6.52 (s, 1H), 4.79 (s, 2H), 4.64 (d, J = 2.1 Hz, 4H), 2.49 (t, J = 2.1 Hz, 2H); ¹³C NMR (125 MHz, CDCl₃) δ 167.9, 158.8, 138.7 (each C), 134.0 (CH), 123.4, 108.1, 101.6 (each CH), 87.2 (C), 75.7 (CH₂), 55.9 (CH₂), 41.5 (CH₃); HRMS-ESI: calcd for C₂₁H₁₆NO₄[M + H]⁺, 346.1079; found, 346.1087.

2-(3,5-Bis(3,5-bis(prop-2-ynyloxy)benzyloxy)benzyl)isoindoline-1,3-dione 11

Compound 11 (56%) was prepared from bromide 10 as described in the preparation of 9 as white solid after column chromatography (petroleum ether–ethyl acetate, 6:1); ¹H NMR
Table 2 IC₅₀-values of the mono- to tetravalent lactosides and free lactose (Lac) for blocking binding of biotinylated human galectins to surface-immobilized ASF (in mM)

<table>
<thead>
<tr>
<th>Lectin inhibitor</th>
<th>Gal-3 (1 μg ml⁻¹)</th>
<th>trGal-3 (10 μg ml⁻¹)</th>
<th>Gal-4 (5 μg ml⁻¹)</th>
<th>Gal-4N (5 μg ml⁻¹)</th>
<th>Gal-4C (10 μg ml⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.16 (2.5)</td>
<td>0.12 (2.5)</td>
<td>0.09 (2.8)</td>
<td>2.4 (1.3)</td>
<td>0.13 (3.1)</td>
</tr>
<tr>
<td>2</td>
<td>0.11 (3.6)</td>
<td>0.08 (3.8)</td>
<td>0.14 (1.8)</td>
<td>2.6 (1.2)</td>
<td>0.18 (2.2)</td>
</tr>
<tr>
<td>3</td>
<td>0.14 (2.9)</td>
<td>0.03 (11)</td>
<td>0.10 (2.5)</td>
<td>0.9 (3.3)</td>
<td>0.18 (2.2)</td>
</tr>
<tr>
<td>4</td>
<td>0.13 (3.1)</td>
<td>0.22 (1.4)</td>
<td>0.07 (3.6)</td>
<td>1.2 (2.5)</td>
<td>0.24 (1.7)</td>
</tr>
<tr>
<td>5</td>
<td>0.08 (5.0)</td>
<td>b</td>
<td>0.05 (5.0)</td>
<td>1.4 (2.1)</td>
<td>0.21 (1.9)</td>
</tr>
<tr>
<td>6</td>
<td>0.02 (20)</td>
<td>0.12 (6.5)</td>
<td>0.04 (13)</td>
<td>0.5 (6.0)</td>
<td>0.06 (6.7)</td>
</tr>
<tr>
<td>7</td>
<td>0.013 (31)</td>
<td>0.27 (1.1)</td>
<td>0.008 (31)</td>
<td>0.16 (19)</td>
<td>0.03 (13)</td>
</tr>
<tr>
<td>Lac</td>
<td>0.4 (1)</td>
<td>0.3 (1)</td>
<td>0.25 (1)</td>
<td>3 (1)</td>
<td>0.4 (1)</td>
</tr>
</tbody>
</table>

For structures see Chart 1; titrations were performed using a fixed glycoprotein quantity for coating (0.5 μg per well) with eight concentrations of sugar in duplicates and up to three independent series, reaching an upper limit of 15.7% for the standard deviation (for exemplary titration curves, see Fig. 1); the concentration is always given for lactose, free in solution or conjugated to a scaffold. Tendency for stimulation at concentrations above 1 mM, numbers in brackets denote relative potency.

Fig. 5 Semilogarithmic representation of fluorescent surface staining of human pancreatic carcinoma cells (Capan-1), reconstituted for expression of the tumor suppressor p16INK4a, by human galectin-4 (for further details, please see legend to Fig. 2). A, B: inhibition of staining with 10 μg ml⁻¹ lectin by 0.5 mM lactose as well as by 0.05 mM lactose presented by the trivalent compound and 0.1 mM lactose in bivalent compound (A) as well as by 20 μM and 7.5 μM lactose presented by the tetravalent compound (B).

Compound (154 mg, 0.23 mmol) was dissolved in CH₂OH–H₂O (5:1, 12 mL), then compound (40 mg, 0.12 mmol), sodium ascorbate (9.2 mg in 1 mL H₂O, 0.047 mmol) and CuSO₄ (3.7 mg in 1 mL H₂O, 0.023 mmol) were subsequently added and the mixture was sonicated for 2 h, whereafter the solvent was removed and the residue was partitioned between CH₂Cl₂ (100 mL) and water (15 mL). The organic portion was washed by water (15 mL ×2), dried by Na₂SO₄ and concentrated. Silica gel chromatography (CH₂Cl₂–CH₃OH, gradient elution, 50:1 to 10:1) gave the title compound as a white solid (234 mg, 95%); Rf 0.2 (CH₂Cl₂–CH₃OH, 10:1). 1H NMR (500 MHz, CDCl₃) δ 6.58 (t, J = 5.4 Hz, 3H, Nff), 3.29 (q, J = 6.6 Hz, 6H, 2.41 (t, J = 6.5 Hz, 6H), 2.26–2.18 (m, 12H), 1.96 (t, J = 2.6 Hz, 3H), 1.79–1.71 (m, 6H), 1.64 (p, J = 6.5 Hz, 6H), 1.60–1.52 (m, 6H). 13C NMR (125 MHz, CDCl₃) δ 173.0 (C), 84.1 (C), 68.6 (CH), 51.4, 37.9, 36.0, 28.0, 26.9, 24.9, 18.2 (each CH₂); HRMS-ESI: calcd for C₉₀H₇₉N₇O₃₈ [M + H]⁺ 513.3805; found, 513.3808.

2-(3,5-Bis((1-(2,3,4,6-tetra-O-acyethyl-β-D-galactopyranosyl)-(1→4)-2,3,6-tri-O-acetyl-β-D-glucopyranosyl)-1H-1,2,3-triazol-4-yl)-methoxy)benzyl]isoindoline-1,3-dione 18

H NMR (500 MHz, CDCl₃) δ 7.85 (dd, J = 5.4, 3.0 Hz, 2H), 7.72 (dd, J = 5.4, 3.0 Hz, 2H), 6.65 (dd, J = 6.1, 2.2 Hz, 6H), 6.54 (t, J = 2.2 Hz, 2H), 6.47 (t, J = 2.2 Hz, 1H), 4.96 (s, 4H), 4.76 (s, 2H), 4.67 (d, J = 2.4 Hz, 8H), 2.52 (t, J = 2.4 Hz, 4H); 13C NMR (125 MHz, CDCl₃) δ 168.0, 159.9, 158.8, 139.3, 138.6 (each C), 134.0 (CH), 132.1 (C), 123.4, 107.6, 106.8, 101.9, 101.6 (each CH), 78.3 (C), 75.7 (CH), 69.8, 56.0, 41.6 (each CH₂); HRMS-ESI: calcd for C₄₂H₃₁NO₃₈Na [M + Na]⁺, 688.1947; found, 688.1947.

YN,Y′N″-(3',3',3'-Nitrilotris(propylene-3,1-diyl))trihept-6-ynamide 16

1-Ethyl-3-(3-dimethylaminopropyl)carbodiimide hydrochloride (EDC·HCl; 606 mg, 3.2 mmol) was added to a mixture of 15 (0.21 mL, 1.6 mmol), tris(3-aminopropyl)amine 14 (0.1 mL, 0.48 mmol), 1-hydroxybenzotriazole and triethylamine (442 μL, 3.2 mmol) in THF (25 mL) and the mixture was stirred at room temperature overnight. THF was removed under reduced pressure. The residue was dissolved in CH₂Cl₂ (150 mL) and washed with saturated NaHCO₃ and brine, dried (Na₂SO₄), filtered, and the solvent was removed under reduced pressure. Silica-gel chromatography (CH₂Cl₂–CH₃OH, gradient elution, 50:1 to 10:1) gave the title compound as a white solid (157 mg, 92%); Rf 0.2 (CH₂Cl₂–CH₃OH, 10:1); 1H NMR (500 MHz, CDCl₃) δ 7.86 (dd, J = 5.4, 3.0 Hz, 2H), 7.72 (dd, J = 5.4, 3.0 Hz, 2H), 6.65 (dd, J = 6.1, 2.2 Hz, 6H), 6.54 (t, J = 2.2 Hz, 2H), 6.47 (t, J = 2.2 Hz, 1H), 4.96 (s, 4H), 4.76 (s, 2H), 4.67 (d, J = 2.4 Hz, 8H), 2.52 (t, J = 2.4 Hz, 4H); 13C NMR (125 MHz, CDCl₃) δ 168.0, 159.9, 158.8, 139.3, 138.6 (each C), 134.0 (CH), 132.1 (C), 123.4, 107.6, 106.8, 101.9, 101.6 (each CH), 78.3 (C), 75.7 (CH), 69.8, 56.0, 41.6 (each CH₂); HRMS-ESI: calcd for C₄₂H₃₁NO₃₈Na [M + Na]⁺, 688.1947; found, 688.1947.

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Compound 18 (100 mg, 60.0 μmol) and ethylenediamine (0.5 mL) in anhydrous ethanol (5 mL) was heated at reflux. After 6 h, the mixture was cooled to room temperature. The precipitate was filtered, washed with methanol (0.5 mL × 3) and dried under vacuum to give 3 as white solid (39 mg, 68%); [α]D20 8.8 (c 1.0, H2O); 1H NMR (500 MHz, D2O) δ 8.33 (s, 2H), 6.71 (s, 2H), 6.65 (s, 1H), 5.80 (d, J = 9.0 Hz, 2H, H-1), 5.28 (s, 4H), 4.52 (d, J = 7.8 Hz, 2H, H-1), 4.07 (t, J = 9.0 Hz, 2H), 3.99–3.75 (m, 20H), 3.70 (dd, J = 10.0, 3.4 Hz, 2H), 3.59 (dd, J = 10.0, 7.8 Hz, 2H); 13C NMR (125 MHz, D2O) δ 158.6 (C), 144.7 (C), 143.5 (C), 124.4, 107.7, 102.8, 101.5, 87.2, 77.7, 77.3, 75.3, 74.5, 72.4, 71.9, 70.9, 68.5 (each CH), 61.3, 61.0, 59.7, 44.4 (each CH2); HRMS-ESI: calcd for C35H32N6O22[M + H]+, 950.3478; found, 950.3441.

2-(3,5-Bis((1-β-D-galactopyranosyl-(1 → 4)-β-D-glucopyranosyl)-(1 → 2,3,6-tri-O-acetyl-β-D-glucopyranosyl)-1H-1,2,3-triazol-4-yl-methoxy)-benzyl)-benzoin-1,3-dione 19

Compound 17 (200 mg, 0.30 mmol) was dissolved in CH3OH (8 mL), to which a solution of compound 11 (50 mg, 0.076 mmol) in CH2Cl2 (2 mL) was added. Then solutions of CuSO4 (4.8 mg dissolved in 1 mL H2O, 30.0 μmol) and sodium ascorbate (12 mg dissolved in 1 mL H2O, 60.0 μmol) were subsequently added and the mixture was sonicated for 2 h, after which it was stirred at 40 °C overnight. Thereafter the solvent was removed and the residue was partitioned between CH2Cl2 (100 mL) and water (15 mL). The organic phase was washed by water (15 mL × 2), dried (Na2SO4) and the solvent was removed under reduced pressure. Silica gel chromatography (CH2Cl2–CH2OH, gradient elution, 80: 1 to 60: 1 to 50: 1) gave 19 as a white solid (172 mg, 69%); [α]D20 +28.0 (c 0.5, CHCl3); 1H NMR (500 MHz, CDCl3) δ 7.84 (dd, J = 5.4, 3.0 Hz, 2H), 7.82 (s, 4H), 7.71 (dd, J = 5.4, 3.0 Hz, 2H), 6.66–6.65 (m, 6H), 6.6 (s, 2H), 6.50 (s, 1H), 5.86 (d, J = 9.0 Hz, 4H, H-1), 5.46–5.39 (m, 8H), 5.37 (d, J = 3.3 Hz, 4H), 5.16 (s, 8H), 5.14 (dd, J = 10.4, 8.0 Hz, 4H), 4.99 (dd, J = 10.4, 3.4 Hz, 4H), 4.96 (s, 4H), 4.77 (s, 2H), 4.55 (s, J = 8.0 Hz, 4H, H-1), 4.49 (s, J = 11.4 Hz, 4H), 4.18–4.08 (m, 12H), 4.02–3.89 (m, 12H), 2.17 (s, 12H), 2.10 (s, 12H), 2.07 (s, 12H), 2.063 (s, 12H), 2.061 (s, 12H), 1.98 (s, 12H); 13C NMR (125 MHz, CDCl3) δ 170.3, 170.2, 170.1, 170.0, 169.5, 169.13, 169.07, 168.0, 159.9, 159.5, 144.6, 139.5, 138.6 (each C), 134.1 (CH), 132.0 (C), 123.4, 121.4, 107.6, 106.6, 101.4, 101.1, 85.6, 76.0, 75.7, 72.6, 70.9, 70.8, 70.5 (each CH), 69.8 (CH2), 69.1 (CH), 66.6 (CH2), 66.0, 61.8, 60.8, 41.6 (each CH2), 20.8, 20.72, 20.67, 20.65, 20.6, 20.5, 20.2 (each CH2); HRMS-ESI: calcd for C41H31N2O4s[M + Na]+, 599.2465; found, 599.2459.

13,5-Tris((1-(β-D-galactopyranosyl-(1 → 4)-β-D-glucopyranosyl)-1H-1,2,3-triazol-4-yl-methoxy)benzene 4

Compound 20 (80 mg, 36.0 μmol) was dissolved in methanol (5 mL). A catalytic amount of NaOMe (0.1 mL of a 0.2 M solution in MeOH) was added to the solution and the resulting mixture was stirred for 1 h at room temperature. Amberlite IR-120 (plus) was added to neutralize (pH = 7), whereafter the resin was filtered by BioGel P-2 gel filtration column to give 4 as an amorphous solid (40 mg, 83%); [α]D20 +6.2 (c 0.9, H2O); 1H NMR (500 MHz, D2O) δ 8.32 (s, 3H), 6.43 (s, 3H), 5.81 (d, J = 9.0 Hz, 3H, H-1), 5.26 (s, 6H), 4.52 (d, J = 7.8 Hz, 3H, H-1), 4.08 (t, J = 9.0 Hz, 3H), 3.96–3.95 (m, 6H), 3.90–3.83 (m, 12H), 3.81–3.76 (m, 9H), 3.70 (dd, J = 10.0, 3.4 Hz, 3H), 3.60 (dd, J = 10.0, 7.8 Hz, 3H, 3H); 13C NMR (125 MHz, D2O) δ 159.4, 143.3 (each C), 124.3, 102.9, 95.8, 87.2, 77.6, 77.3, 75.3, 74.5, 72.4, 71.9, 70.9, 68.5 (each CH), 61.1, 61.0, 59.7 (each CH2); HRMS-ESI: calcd for C51H32N6O6sNa[M + Na]+, 1364.4364; found, 1364.4332.
Compound 21 was prepared from lactoside 17 and compound 16 as described for the preparation of 20, using ultrasonic radiation instead of heating. The title compound was obtained (92%) as an amorphous solid after chromatography (CH₂Cl₂-CH₂OH, gradient elution, 80 : 1 to 30 : 1); [α]D<sup>20</sup> = −14.4 (c 1.0, CHCl₃); <sup>1</sup>H NMR (500 MHz, CDCl₃) δ 7.75 (s, 3H), 7.16 (s, 3H), 5.83 (d, J = 8.4 Hz, 3H, H-1′), 5.44–5.54 (m, 6H), 5.37 (d, J = 3.1 Hz, 3H), 5.13 (dd, J = 10.2, 3.3 Hz, 3H), 4.58 (d, J = 7.9 Hz, 3H, H-1′), 4.51 (d, J = 11.9 Hz, 3H), 4.18–4.08 (m, 9H), 4.05–3.86 (m, 9H), 3.31 (d, J = 4.8 Hz, 6H), 2.96 (m, 6H), 2.72 (t, J = 6.5 Hz, 6H), 2.25 (s, 6H), 2.17 (s, 9H), 2.11 (s, 9H), 2.074 (s, 9H), 2.066 (s, 9H), 2.06 (s, 9H), 1.98 (s, 9H), 1.89 (m, 6H), 1.86 (s, 9H), 1.69 (s, 12H); <sup>13</sup>C NMR (125 MHz, CDCl₃) δ 173.9, 170.4, 170.3, 170.1, 170.0, 169.5, 169.2, 161.9, 148.3 (each C), 119.6, 101.1 (CH-1′), 85.4 (CH-1′), 75.9, 75.6, 72.7, 70.9, 70.8, 70.5, 69.1, 66.6 (each CH); 61.8, 60.8, 50.9, 35.6, 28.9, 25.8, 25.0, 24.5 (each CH₂); 20.9, 20.74, 20.67, 20.65, 20.64, 20.5, 20.3 (each CH₃); HRMS-ESI: calcd for C₁₀₈H₁₅₄N₁₃O₅₄ [M + H]+, 2496.9704; found, 2496.9739.

N,N′,N″-(3,3′,3″)-Nitrilotris(propane-3,1-diyl))tris(5-(1β-D-galactopyranosyl)-(1→4)-3β-N,O-acetyl-β-D-galactopyranosyl)-1H-1,1,3-triazol-4-yl)pentamidine 5

Compound 21 (100 mg, 40 mmol) was dissolved in methanol (5 mL) to which a catalytic amount of NaOMe (0.5 mL of a 2 M solution in MeOH) was added and the resulting solution was stirred for 4 h at room temperature. The solvent was removed and the residue was purified by BioGel P-2 gel filtration column to give 5 as an amorphous solid (50 mg, 79%); [α]D<sup>20</sup> = −5.6 (c 1.0, H₂O); <sup>1</sup>H NMR (500 MHz, D₂O) δ 8.02 (s, 3H), 5.74 (d, J = 9.2 Hz, 3H, H-1′), 4.53 (d, J = 8.0 Hz, 3H, H-1′), 4.04 (t, J = 9.2 Hz, 3H, H-2′), 3.97–3.76 (m, 27H), 3.70 (d, J = 9.6, 2.9 Hz, 3H), 3.60 (d, J = 9.6, 8.0 Hz, 3H), 3.14 (t, J = 6.6 Hz, 6H), 2.74 (t, J = 6.8 Hz, 6H), 2.43–2.40 (m, 6H), 2.25 (t, J = 6.7 Hz, 6H), 1.65–1.57 (m, 18H); <sup>13</sup>C NMR (125 MHz, D₂O) δ 176.4, 148.3 (each C), 122.1 (CH), 102.8 (CH-1′), 87.1 (CH-1′), 77.6, 77.3, 75.3, 74.5, 72.5, 71.9, 70.9, 68.5 (each CH), 61.0, 59.7, 50.3, 37.4, 35.3, 27.7, 24.9, 24.7, 24.1 (each CH₃); HRMS-ESI: calcd for C₆₇H₁₁₁N₁₃O₃₃Na[M + Na]+, 1636.7305; found, 1636.7290.

O-(2,3,4-Tri-O-acetyl-α-L-fucopyranosyl)-(1→2)-O-(3,4,6-tri-O-acetyl-β-D-galactopyranosyl)-(1→4)-1,2,3,6-tetra-O-acetyl-α-L-glucopyranose 26<sup>96</sup>

To compound 24 (2.12 g, 2.33 mmol) in anhydrous MeOH, NaOMe (0.5 mL of a 2 M solution in MeOH) was added and the resulting mixture was stirred for 1 h at room temperature. Amberlite IR-120 (plus) was added to neutralize (pH = 7), and the solvent was removed under reduced pressure to afford a colourless oil. This residue was dissolved inaq 60% acetic acid (30 mL) and heated for 6 h at 60 °C. The reaction mixture was diluted with toluene and the volatile components removed. Then to a solution of the residue in THF–H₂O–AcOH (4 : 2 : 1, 14 mL), 10% Pd–C (50 mg) was added. The suspension was stirred under an atmosphere of hydrogen for 2 days at ambient temperature. When the reaction was completed, the mixture was filtered over Celite and concentrated. Toluene (3 × 30 mL) was evaporated from the residue to remove the acetic acid and water. Then fuscosylactose 19 was dissolved in pyridine–acetic anhydride (2 : 1, 30 mL) and then stirred overnight under an atmosphere of nitrogen at ambient temperature. The solvent was then removed and the residue was partitioned between CH₂Cl₂ (100 mL) and water (25 mL). The organic phase was washed with water (25 mL × 2), dried (Na₂SO₄) and the solvent was removed. Chromatography (petroleum ether–EtOAc, gradient elution, 4 : 1 to 3 : 1) gave 26 as a white foam (1.67 mg, 79%); R<sub>f</sub> 0.35 (petroleum ether–EtOAc, 1.5 : 1), which were a mixture of anomers (β : α = 1 : 1); selected <sup>1</sup>H NMR (500 MHz, CDCl₃) data for the β anomer: δ 5.69 (d, J = 8.2 Hz, 1H, H-1′), 5.37 (d, J = 3.4 Hz, 1H, H-1′), 5.20 (t, J = 9.5 Hz, 1H), 5.09 (dd, J = 9.7, 8.3 Hz, 1H); selected <sup>13</sup>C NMR data for the α anomer: δ 6.30 (d,
1 Hz, 1H, H-1”), 5.05 (dd, J = 10.4, 3.7 Hz, 1H); overlapped 1H NMR data for both β and α anomer: 5.31–5.27 (m, 4H), 5.18–5.12 (m, 2H), 5.00–4.96 (m, 4H), 4.50–4.38 (m, 6H), 4.27 (dd, J = 12.3, 5.3 Hz, 2H), 4.18–4.12 (m, 2H), 4.10–4.03 (m, 3H), 3.91–3.80 (m, 7H), 2.18–1.97 (19s, 60H), 1.24–1.21 (2d, J = 6.5 Hz, 6H); mixture 13C NMR (125 MHz, CDCl3) data for both α and β anomers: δ 171.1, 170.7, 170.65, 170.6, 170.5, 170.3 (2s), 170.1, 170.0 (2s), 169.8, 169.7, 169.6, 169.3, 168.8, 168.7 (each C), 102.0, 99.9, 95.7, 73.9, 73.8, 73.4, 73.3, 71.7, 71.11, 70.9, 70.9, 70.8, 70.7, 70.3, 69.2, 69.1, 68.1, 68.0, 67.5, 67.3, 67.0, 65.0, 64.9 (each CH), 62.1, 61.9, 61.0, 60.8 (each CH2), 21.1, 21.0, 20.9, 20.8, 20.7, 20.65, 20.6, 20.5, 15.6 (each CH3); selected 13C NMR data for the α-anomer: δ 89.0 (CH, C-1); Selected 13C NMR data for the β-anomer: δ 91.5 (CH, C-1); HRMS-ESI: calculated for C35H52N3O25Na2[M + Na]+, 931.2695; found, 931.2686.

O-(2,3,4-Tri-O-acetyl-α-L-fucopyranosyl)-(1 → 2)-O-(3,4,6-tri-O-acetyl-β-D-galactopyranosyl-(1 → 4)-2,3,6-tri-O-acetyl-β-D-glucopyranosyl azide 27

Compound 26 (1.35 g, 1.49 mmol) was dissolved in CH2Cl2 (30 mL, anhydrous) under an atmosphere of N2. To this solution was added TMSN3 (0.54 mL, 4.46 mmol) followed by the drop-wise addition of SnCl4 (88 μL, 0.57 mmol) and CuSO4 (1.6 mg, 0.013 mmol) and CuCl (15 mg, 0.1 mmol), and the mixture was stirred at 45 °C overnight, after which the solvent was removed under reduced pressure, chromatography using (CH2Cl2 → MeOH, 15 : 1 to 1 : 0.5) gave the acetylated intermediate as a white foam (83 mg, 60% from 50 mg, water (15 mL x 2)). Removal of the protect- 35 groups from this protected compound (39 mg, 0.013 mmol), after lyophilization, as a white solid (20 mg, 82%); HRMS-ESI: calculated for C35H52N3O25Na2[M + Na]+, 649.2181; found, 649.2176.

O-(2,3,4-Tri-O-acetyl-α-L-fucopyranosyl)-(1 → 2)-O-(3,4,6-tri-O-acetyl-β-D-galactopyranosyl-(1 → 4)-β-D-glucopyranosyl)-(1H-1,2,3-triazol-4-yl) methoxy-benzene 6

Azide 27 (90 mg, 101 μmol) was dissolved in CH2OH–H2O (2 : 1, 15 mL), then 135 (8.0 mg, 33.7 μmol), sodium ascorbate (0.4 mg dissolved in 1 mL H2O, 20.2 μmol) and CuSO4 (1.6 mg dissolved in 1 mL H2O, 10.1 μmol) were subsequently added and the mixture was stirred at 45 °C overnight, after which the solvent was removed and the residue was participated by CH2Cl2 (50 mL) and water (15 mL). The organic phase was washed by water (15 mL x 2), dried by Na2SO4 and concentrated. Chromatography (CH2Cl2–CH2OH, gradient elution, 80 : 1 to 70 : 1 to 60 : 1) gave the acetylated intermediate as a white foam (83 mg, 85%), Rf 0.55 (CH2Cl2–CH2OH, 20 : 1). Removal of the protect- ing groups from this protected compound (39 mg, 0.013 mmol), as for the formation of 4, gave 6, after lyophilization, as a white solid (20 mg, 82%); [α]D20 = 50.5 (c 0.2, D2O); 1H NMR (500 MHz, D2O) δ 8.22 (s, 3H), 7.80 (d, 1H), 7.50 (d, 1H), 7.20 (d, 1H), 6.90 (d, 1H), 6.50 (d, 1H), 6.30 (d, 1H); 13C NMR (125 MHz, CDCl3) δ 179.8 (C), 144.3 (C), 123.1, 100.2, 99.3, 87.3, 78.1, 76.2, 75.2, 74.9, 74.3, 73.5, 72.0, 71.6, 69.9, 61.8, 61.6, 69.9 (each CH), 61.1, 59.8 (each CH2), 55.5 (CH), 29.6 (CH3), 15.2 (CH3). HRMS-ESI: calculated for C35H52N3O25Na2[M + Na]+, 649.2181; found, 649.2176.

(5S)-2-Amino-3-[(α-L-fucopyranosyl)-(1 → 2)-β-D-glucopyranosyl)-(1 → 4)-β-D-glucopyranosyl)-(1H-1,2,3-triazol-4-yl)propanoic acid 2

To a solution of glycoside 27 (106 mg, 0.12 mmol) and Fmoc-protected i-proparglyllicine (41 mg, 0.12 mmol)15 in tert- butanol (2 mL) and water (4 mL) was added a solution of CuSO4 (0.04 M, 0.6 mL, 0.024 mmol) and sodium ascorbate (0.08 M, 0.6 mL) in H2O. The mixture was stirred overnight, water (6 mL) was added, and the product was extracted with CH2Cl2 (2 x 25 mL). The combined organic layers were washed with brine, dried over Na2SO4, and evaporated under reduced pressure. Chromatography using (CH2Cl2–MeOH, 15 : 1 to 10 : 1) give the intermediate as a white foam 131 mg (90%), Rf 0.2 (CH2Cl2–MeOH, 15 : 1). The residue (131 mg, 0.11 mmol) was treated with 20% piperidine in DMF (v/v, 5 mL), then stirred for 20 min and solvent was finally removed under reduced pressure. The crude product was dissolves in MeOH (5 mL), and NaOMe (2 M, 0.05 mL) was added. The mixture was stirred for 1 h. The mixture was concentrated and passed through BioGel P-2 gel filtration column with water to give 2 (45 mg, 67%) as an amorphous solid; [α]D20 = 48.8 (c 0.5, H2O); 1H NMR (500 MHz, D2O) δ 8.06 (s, 1H), 7.55 (d, J = 9.2 Hz, 1H, H-1), 5.35 (d, J = 3.1 Hz, 1H, H-1″), 4.61 (d, J = 7.8 Hz, 1H, H-1″), 4.27 (q, J = 6.7 Hz, 1H, H-4″), 4.07 (t, J = 9.2 Hz, 1H, H-2), 4.01–3.97 (m, 2H), 3.93–3.90 (m, 2H), 3.78–3.71 (m, 10H), 3.67–3.64 (m, 1H), 3.16 (dd, J = 14.8, 5.2 Hz, 1H), 3.08 (dd, J = 14.8, 6.9 Hz, 1H), 1.28 (d, J = 6.6 Hz, 3H); 13C NMR (125 MHz, D2O) δ 179.8 (C), 144.3 (C), 123.1, 100.2, 99.3, 87.3, 78.1, 76.2, 75.2, 74.9, 74.3, 73.5, 72.0, 71.6, 69.9, 61.8, 61.6, 69.9 (each CH), 61.1, 59.8 (each CH2), 55.5 (CH), 29.6 (CH3), 15.2 (CH3). HRMS-ESI: calculated for C35H52N3O25Na2[M + Na]+, 649.2181; found, 649.2176.

Molecular modelling

Structures were first built using Maestro version 6.0 (Schrodinger Inc., LLC, New York, USA). Constraints were then applied
during an energy minimization (OPLSAA force field, gas phase, PRCG method to convergence) of each structure using Macro-model version 8.5 (Schrodinger Inc.) so as to generate an extended conformation for each structure. This approach enabled estimation of the maximum distances that could potentially be adopted between the lactose headgroups in 3, 4, 5 and 7. In the case of 4 the angles defined by the three glucose anomeric carbon atoms were constrained at 60°, for 5 the angles between the glucose anomeric carbon atoms of two of the lactose residues and the nitrogen atom at the centre of the scaffold were constrained at 120°. In the case of 7 the angles between three of the glucose anomeric carbons were constrained to 90°. Distance constraints had to be applied between the glucose anomeric carbons in order to maximize the spacing between the headgroups. Torsions were adjusted using Maestro if necessary to help generate the extended structures. The final modeled structures obtained are shown in Fig. 1. The distances between the headgroups for these structures are given in the main text.

**Lectin purifications and quality controls**

Using extracts of dried plant material or bacterial pellets from recombinant production, affinity chromatography over lactosylated Sepharose 4B obtained by divinyl sulfone activation was performed as crucial step, following a standard procedure.9,25d,36 The B-chain of the toxin was obtained after in situ cleavage of the disulfide bond linking the AB-chains by extensive treatment with β-mercaptoethanol, removal of the A-chain by column washes and covalent deactivation of the sulphydryl group in the resin-bound B-chain by iodoaceticamide treatment, trCG-3/Gal-3 by purifying the cloned product or collagene treatment of the full-length protein.37 One- and two-dimensional gel electrophoresis and gel filtration as well as haemagglutination assays were routinely performed to ensure purity, quaternary structure and activity.25,37 Biotinylation with the N-hydroxysuccinimide ester derivative (Sigma, Munich, Germany) under activity-preserving conditions followed a standard protocol, with incorporation yields measured by mass spectrometric analysis.7b,5a

**Inhibition assays**

Microtiter plate wells were coated with ASF (0.5 μg per well in 50 μl phosphate-buffered saline) overnight at 4 °C and residual sites for binding protein were blocked with 100 μl buffer containing 1% (w/v) carbohydrate-free bovine serum albumin for 1 h at 37 °C. Following washing the series of steps comprising incubation with biotinylated lectin, washing, application of the streptavidin-peroxidase conjugate (0.5 μg ml−1; Sigma), washing and signal development with the chromogenic substrates o-phenylenediamine (1 μg ml−1)/hydrogen peroxide (1 μl ml−1) was completed with readings of the optical density at 490 nm as described.6a,25a Assays were routinely done in triplicates with up to five independent series, standard deviations for percentage of bound lectin as parameter not exceeding 16.2%.

Assays with the human B-lymphoblastoid/pancreatic carcinoma and the Chinese hamster ovary cell lines followed an optimized protocol ensuring interstudy comparison.6a,25c–f Aliquots of cell suspensions at the same passage were routinely processed at least in duplicates, with at least three independent series, by washing to thoroughly remove serum components and then incubation with lectin-containing solution at 4 °C for 30 min. in the loading step, later with streptavidin-R-phycocerythin (1:40; Sigma) in the labeling step. Controls included omission of the loading step to measure the level of lectin-independent background staining and application of non-cognate sugar to track down osmolarity effects. Following normalization of values based on the internal controls the standard deviations of measurements did not exceed 12.7%

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**References**

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