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Graphical Abstract

Biocatalyzed synthesis of difuranosides and their ability to trigger production of TNF-α
Ilona Chlubnová, Blanka Králová, Hana Dvořáková, Vojtěch Spiwok, Dominik Filipp, Caroline Nugier-Chauvin, Richard Daniellou and Vincent Ferrières

F better than CH₂OH or CH₃

OC₆H₁₇ better than OpNP

Improved biological properties when n increases
Biocatalyzed synthesis of difuranosides and their ability to trigger production of TNF-α

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ABSTRACT

Transglycosylation reactions biocatalyzed by the native arabino-furanosidase Araf51 and using D-galactosyl, D-fucosyl and 6-deoxy-6-fluoro-D-galactosyl derivatives as donors and acceptors provided di- to pentahexofuranosides. The immunostimulatory potency of these compounds, and more especially their ability to induce production of TNF-α, was evaluated on the murine macrophage cell line, Raw 264.7. The results obtained showed concentration-dependent and most importantly, structure-dependent responses. Interestingly, oligoarabinofuranosides belonging to the oligopentafuranoside family displayed concentration-, chain length and aglycon-dependent bioactivities irrespective of their fine chemical variations. Thus, neo-oligofuranosides in D-Galf series, as well as their D-Fuf and 6-fluorinated counterparts are indeed potential sources of immunostimulating agents.

Keywords: Carbohydrates Furanosides Immunostimulation

1. Introduction

Rare hexofuranosides occur in many microorganisms but are absent from the mammalian kingdom and invertebrates. That is why they constitute nowadays a source of inspiration to develop new treatments to fight pathogenic microorganisms for which the biosynthesis of these carbohydrates is vital.1-4 Indeed, immunological, antiviral and antiparasitic properties of furanosyl-containing compounds are increasingly evidenced.5-13 In this context, many efforts have been investigated to prepare and to mimic glycofuranosyl conjugates by both conventional chemical approaches and original enzymatic tools. Considering the latter, two classes of biocatalysts can be exploited. The usefulness of furanosyl transferases is dampened by its limited access to both these enzymes as well as the required UDP- or polyprenyl-furanosyl donors. On another hand, glycosyl hydrolases are more easily available and robust, therefore are more interesting as alternative synthetic tools, provided they are used under kinetic conditions, i.e. as a synthetic catalyst and not as a hydrolytic one. Surprisingly, reported results in this domain focused on only two arabino-furanosidases: AbfD3 produced by Thermocellum xylanilyticus,14-17 and an enzyme exploited by our group Araf51 from Clostridium thermocellum.18-21 AbfD3 led to disaccharides and allowed Araf transfer to xylobiose and xylotriose. As for Araf51, we have demonstrated that it is involved in autocondensation reactions yielding di- to pentasaccharides. Both enzymes catalyzed the synthesis of furanosyl-containing glycosides starting from p-nitrophenyl L-arabinofuranosides (pNP Araf) but also from structurally related D-galacto- (D-Galf) and D-fucofuranosyl (D-Fuf) series: AbfD3 led to disaccharides and allowed Araf transfer to xylobiose and xylotriose, while Araf51 was involved in the transfer of di- to pentasaccharides in autocondensation reactions.

The higher synthetic potential of native Araf51 was demonstrated for autocondensation reactions20 and in transglycosylation with pyranosidic acceptors.22 Herein, this potency was applied in transglycosylation involving two furanoidic substrates, D-galactofuranosyl donor and various furanosidic acceptors [D-Galf, D-Fuf, 6-deoxy-6-fluoro-D-galactofuranoside (6-F-D-Galf)], Figure 1. The choice of D-Galf as the donor was based on its occurrence in glycoconjugates of numerous pathogenic species.22-25 As for the furanosidic acceptors, we examined the ability of the enzyme to accept...
structural analogues of β-D-Galf in the +1-subsite as well as the possible effect on the enzyme regioselectivity in the absence of a hydroxyl function on C-6 of the acceptor. Regarding the enzyme preferences toward formation of the (1→6) linkage in β-D-Galf series, we were interested in the effect of restriction of C-6 participation in the bond formation. To this end, β-D-Galf moiety was modified at C-6 by the replacement of the hydroxyl group with either hydrogen (β-D-Fucf), or fluorine (6-F-β-D-Galf). Moreover, the set of furanosic acceptors were also represented by an octyl group at the anomeric position. First, we anticipated that the alkoxyl chain is a more inferior leaving group in comparison to the nitrophenolate, hence octyl furanosides would mainly play the role of acceptors. Second, numerous studies have highlighted the importance of alkyl chains in various biological activities. Using alkyl furanosides as acceptors will therefore allow the direct synthesis of glycolipidomimetics. Finally, immunological properties of the neo-oligosfuranosides will be assessed, with a particular focus on the expression of tumor necrosis factor-α (TNF-α).

Transglycosylation was first performed with Oct β-D-Galf as the acceptor (Table 1, family A). Using size exclusion chromatographic purification, fractions of disaccharides (entries 1 and 2, 45%), trisaccharides (entries 3 and 4, 18%), tetrasaccharides (entry 5, 2%), and pentasaccharides (entry 6, 1%) were obtained. As expected, autocondensation of the donor pNP β-D-Galf proceeded simultaneously resulting in a 34% yield of pNP glycosides. After 90 minutes, the conversion of pNP β-D-Galf was nearly complete with only 4% of the donor remaining.

While the donor molecule was nearly entirely consumed, only 55% of acceptor Oct β-D-Galf was transformed. The detailed molar balance of reaction products clearly indicates that the acceptor Oct β-D-Galf simultaneously acted as a donor. Overall, an octyl aglycon initially intended as a protecting group turned out to be a good leaving group in the Ara51-mediated transglycosylation. The nature of the superior nucleofugality of the p-nitrophenate group versus the octanolate anion has shown not to be determinant enough. Besides tryptophan residue in the +1-subsite of Ara51 (Trp17) forming a hydrophobic stacking with an acceptor, the funnel of the +1-subsite is furnished with a number of other aromatic/hydrophobic residues which could provide a complementary environment, facilitating the leaving of the alkoxyl chain.

Next, transglycosylation was performed in the presence of Oct β-D-Fucf. After purification, mainly di- and trisaccharides were isolated at 20% (Table 1, entries 7-9, family B) and 11% yields (entries 10-12), respectively. It is noteworthy that (i) the conversion of pNP β-D-Galf in the presence of Oct β-D-Fucf proceeded much slower than in the case of Oct β-D-Galf (48% vs. 96 % after 90 min), (ii) the conversion of Oct β-D-Fucf (42%) was comparable to that of the donor pNP β-D-Galf, in contrast to the transglycosylation reaction with Oct Galp as acceptor, (iii) the degree of hydrolysis was very low, with a yield of less than 3% of the products. Therefore, these observations indicate that the presence of Oct β-D-Fucf reduces pNP β-D-Galf autocondensation. Because of the low solubility of Oct β-D-Fucf in water, the corresponding kinetic parameters could not be determined. Nevertheless, we hypothesized that the acceptor Oct β-D-Fucf is significantly retained within the donor –I-subsite, thus limiting the access of the donor pNP β-D-Galf. To corroborate this hypothesis, analysis of isolated products revealed the presence of a furanosyl residue at the non-reducing end of a number of resulting saccharides. This clearly demonstrated that Ara51 is able to use Oct β-D-Fucf simultaneously and efficiently as a donor and an acceptor.

Finally, transglycosylation with Oct 6-F-β-D-Galf (entries 15-18, family C) as the acceptor was characterized by the slow rate of the reaction: (i) conversion of pNP β-D-Galf reached only 43% after 90 minutes and (ii) Oct 6-F-β-D-Galf was barely converted to the reaction products, its consumption did not exceed 20%. Nevertheless, there was a very low degree of hydrolysis (2%), and similarly to the reaction with Oct β-D-Fucf, pNP β-D-Galf acted as a better acceptor than Oct 6-F-β-D-Galf. It is interesting to note that pNP β-D-Galf residue was more frequently found in the reducing position of products. Taking together the very low degree of hydrolysis and pNP β-D-Galf autocondensation as well as the unwillingness of Oct 6-F-β-D-Galf to participate in the formation of transglycosylation products, this implies that the presence of fluorine has an inhibitory effect on enzyme activity.

It seems that 6-F-β-D-Galf residue is strongly retained in the donor subsite resulting in a more rapid process of the transfer of the β-D-Galf residue to an acceptor.

Table 1. Oligosfuranosides produced with Ara51.

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>Oligosaccharides (Yield)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OH</td>
<td>Adi1 Galp-Galf/OCP (2%)</td>
</tr>
<tr>
<td>2</td>
<td>(Oct β-D-Galf)</td>
<td>Adi2 Galp-Galp/OCP (19%)</td>
</tr>
<tr>
<td>3</td>
<td>Atri1</td>
<td>Galp-Galp/OCP (8%)</td>
</tr>
<tr>
<td>4</td>
<td>Atri2</td>
<td>Galp-Galp/OCP (9%)</td>
</tr>
<tr>
<td>5</td>
<td>Atetra</td>
<td>Galp-Galp/OCP (2%)</td>
</tr>
<tr>
<td>6</td>
<td>Apenta</td>
<td>Galp-Galp/OCP (1%)</td>
</tr>
<tr>
<td>7</td>
<td>H</td>
<td>Bd1 Galp-Galp/OCP (12%)</td>
</tr>
<tr>
<td>8</td>
<td>(Oct β-D-Fucf)</td>
<td>Bd2 Galp-Galp/OCP (4%)</td>
</tr>
<tr>
<td>9</td>
<td>Btri1</td>
<td>Galp-Galp/OCP (4%)</td>
</tr>
<tr>
<td>10</td>
<td>Btri2</td>
<td>Galp-Galp/OCP (5%)</td>
</tr>
<tr>
<td>11</td>
<td>Btri3</td>
<td>Galp-Galp/OCP (1%)</td>
</tr>
<tr>
<td>12</td>
<td>F</td>
<td>Cd1 Galp-Galp/OCP (13%)</td>
</tr>
<tr>
<td>13</td>
<td>(Oct</td>
<td>Cd2 6-F-Galp/OCP (3%)</td>
</tr>
<tr>
<td>14</td>
<td>6-F-β-D-Galf)</td>
<td>Cd3 6-F-Galp/OCP (6%)</td>
</tr>
<tr>
<td>15</td>
<td>Cd4</td>
<td>6-F-Galp/OCP (3%)</td>
</tr>
<tr>
<td>16</td>
<td>Ctrl1</td>
<td>6-F-Galp/OCP (1%)</td>
</tr>
</tbody>
</table>

Further chromatographic separation led to disaccharides 1-11 (Figure 2) which were identified by mass spectrometry and their structures elucidated by 1D and 2D NMR. The β-configuration of the newly formed furanosic linkages were based on a small H1-
H2 coupling constant less than 1.0 Hz. The five-membered ring size of the transferred glycosyl entity was deduced from the latter value, which is specific to furanosides,28 and from 13C NMR data, i.e. 107.4 ppm for C1, a value that also corroborates the β-configuration, and a chemical shift upper to 80 ppm for C-4.29 Finally, the regioselectivity of the glycosidic coupling was established by comparing the chemical shifts of the carbon atoms of the reducing entity with those of the starting acceptor since O-glycosylation results in downfield chemical shifts.30 For instance, δ(13C) increased from 81.6 ppm to 87.5 ppm in compound 1 while δ(13C) rose 6.2 ppm (from 62.9 ppm to 69.1 ppm) in disaccharide 2. For disaccharides 4 and 10, downfield chemical shifts from 76.6 ppm to 82.3 ppm, and from 62.8 ppm to 69.1 ppm, corroborated (1→3) and (1→6) new glycosidic linkages, respectively.

To evaluate the immunomodulatory potency of enzymatically synthesized neofuranosides, these molecules were incubated with the murine macrophage cell line, Raw 264.7. All glycoconjugates were tested at concentrations of 1, 10, 100 and 1000 ng/mL. E. coli lipopolysaccharide (LPS) was used as a positive control. After 18 hours of incubation, the production of tumor necrosis factor-α (TNF-α) in the culture medium was assessed using TNF-α-specific ELISA. While in the unstimulated control sample, Raw 264.7 secreted only background levels of TNF-α (4.4 ± 3.4 pg/mL, not shown), these levels in positive control samples stimulated with 100 ng/mL of LPS reached 880 ± 53 pg/mL. Importantly, significant TNF-α responses (up to 800 pg/mL) were elicited upon stimulation with the indicated oligofuranosides when used at concentrations of 100 and 1000 ng/mL (Figure 3). It is of note that only trace and non-stimulatory levels of LPS were detected in the samples used, as admixing LPS inhibitor polymyxin B to cell cultures resulted in the production of comparable levels of TNF-α (data not shown).

TNF-α protein levels produced by regioisomers of galactofuranosides (A) and their structural analogues fucofuranosides (B) or 6-deoxy-6-fluorogalactofuranosides (C) clearly demonstrated that certain structural features play an important role in their bioactivity. First, as depicted in figure 3, oligofuranosides bearing a pNP aglycon exhibited a weaker effect on TNF-α production than that induced by octyl oligosaccharides, provided that the number of glycosyl units was equivalent. Nevertheless, oligofuranosides from families A (Galf) and C (Galf, 6-F-Galf) are better inducers of the production of target cytokine than those of family B (Galf, Fucf). Second, although more noticeable with the octyl series, the length of the carbohydrate chain was of great importance since biological activity significantly increased with the number of furanosyl rings, irrespectively to the nature of the glycosyl units (Gal f, Fucf, or 6-F-Galf). This chain length-dependent activity has been previously described with synthetic oligoarabinofuranosides.20 Third, fluorine-containing di- or trisaccharides C seem to be much more efficient than their hydroxylated or deoxy counterparts. Indeed, the disaccharide 11 displayed a similar biological effect than the tested pentasaccharide (TNF-α>200 pg/mL), which represents approximately 2.5-times greater immunostimulatory potential. While it is difficult to predict the impact of the number of fluorine atoms as well as the position of fluorinated units along the octyl oligofuranoside on the biological activity, adding a furanosidic unit can significantly increase the production of TNF-α which reached 600 pg/mL for the fraction 6-F-Galf/6-F-Galf-OC8H17.

To conclude, a set of original oligofuranosides which are structurally-related to D-galactofuranose and possess chemical modulations on the primary position was obtained using native type Ara51. This biocatalyst allowed the synthesis of D-Gal derivatives but also oligomers derived from D-fucofuranose and 6-deoxy-6-fluoro-D-galactofuranose. In each case, the transglycosylation process constituted a major reaction with a very low degree of hydrolysis. Importantly, the octyl furanosides first designed as acceptors also played the role of donors, probably thanks to a good recognition within the –I sub-site. All of the compounds were tested on Raw264.7 cells in order to evaluate their immunostimulatory activity. They significantly upregulate TNF-α secretion in a concentration-, chain length-
and aglycon-dependent fashion. Importantly, the presence of an alkyl chain and/or of fluorine atoms significantly increased biological activity. Consequently, both arabinofuranosyl and galactofuranosyl derivatives are compounds of interest for their immunostimulatory properties and further studies are currently underway to evaluate their potential as adjuvants in vaccine development.

**Acknowledgments**

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**Supplementary Material**

Experimental details, NMR data and description of biological tests are available in Supplementary material.

**References and notes**