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Synthesis of Substituted Mono- and Diindole C-Nucleoside Analogues from Sugar Terminal Alkynes by Sequential Sonogashira/Heteroannulation Reaction

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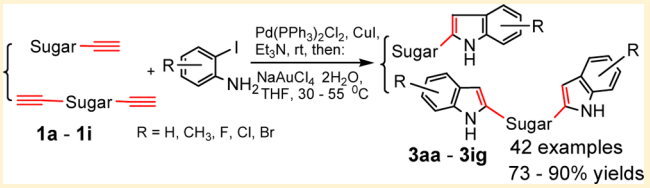
Supporting Information

ABSTRACT: The synthesis of substituted mono- and diindole C-nucleoside analogues has been achieved in good to excellent yields by sequential Sonogashira coupling/$NaAuCl_4$-catalyzed heteroannulation reactions of substituted 2-iodoanilines with various sugar terminal alkynes in one pot. The method is general, mild, and efficient and suitable for a wide range of sugar substrates, and 42 examples are given. The amino group of the substituted 2-iodoanilines is unprotected. The sugar terminal alkynes include furanosides, pyranosides, and acyclic glycosides with free hydroxyl groups, sensitive functional subtituents, and various protecting groups having different steric hindrance.



INTRODUCTION

Heteroaryl C-nucleosides have received much attention due to their interesting biological activities and their use in the extension of the genetic alphabet.[1] Indole represents an important artificial DNA base because of its structural similarity to guanine and adenine.[1g,2] It is also a very crucial charge transport trap in DNA, especially for C-2- or C-3-substituted indole C-nucleosides.[3] Figure 1 shows α-*C*-mannosyltryptophan discovered in Trp7 of ribonuclease 2[4] and two C-2-substituted indole C-nucleoside analogues isolated recently from the roots of *Isatis indigotica*, which display significant cytotoxic activities against human liver cancer HepG2 cells, human myeloid leukemia HL-60, and human myeloid leukemia Mata.[5] The methods for the synthesis of C-2- and C-3-substituted indole derivatives are well documented.[6] Catalytic heteroannulation of functionalized 2-alkynylaniline derivatives is the most efficient approach for the synthesis of C-2-substituted indole derivatives.[6a−j,7] Many kinds of catalysts were reported for these cyclizations, and transition-metal-promoted heteroannulations have been achieved.[6g−j,8] Base-promoted heteroannulations of 2-alkynylphenylamines and their N-protected derivatives have also been established.[6i,k,9] I_2 and iodinating reagent were successfully used for electrophilic cyclizations to synthesize C-2-substituted 3-iodoindoles.[10]

Among the approaches used for the synthesis of C-2- and C-3-substituted indole C-nucleoside analogues, the most common method is the addition of N-protected lithioindoles onto sugar lactones or lactols followed by reduction.[11] C-Glycosylation of indole derivatives with glycosyl donors promoted by boron trifluoride−diethyl etherate[12] or trifluoromethanesulfonic anhydride[13] has also been employed. Recently, catalytic heteroannulation of sugar 2-alkynylanilines has been developed. Minehan and co-workers reported a concise route to a natural indole C-nucleoside analogue[5] by Sonogashira coupling of sugar alkyne with 2-iodo-3-nitrophenol, nitro group reduction, and subsequent heteroannulation of sugar 2-alkynylaniline promoted by potassium *tert*-butoxide.[14] Hocek's group synthesized 1-α- and 1-β-(indol-2-yl)-2′-deoxyribose C-nucleosides based on the Sonogashira reaction of 1α- and 1β-ethynyldeoxyribose and 2-haloanilines followed by a Pd-complex-catalyzed cyclization.[15] Isobe reported the synthesis of C-2-substituted indole C-nucleoside analogues by a Pd-mediated Sonogashira coupling of sugar alkynes with *N*-tosyl-2-iodoaniline, a Cu-mediated Castro cyclization, and subsequent removal of the *N*-tosyl group by tetrabutylammonium fluoride.[16] In view of the biological importance of C-2-substituted indole C-nucleoside analogues, and our interest in the syntheses of biologically active carbohydrate analogues[17] as well as C-substituted sugar analogues,[18] we describe herein a general, mild, and efficient synthesis of C-2-substituted mono- and diindole C-nucleoside analogues from various sugar alkynes.

RESULTS AND DISCUSSION

Terminal alkynes serving as building blocks for the synthesis of substituted indoles by Sonogashira coupling with substituted 2-haloanilines have been reported, and most substrates were

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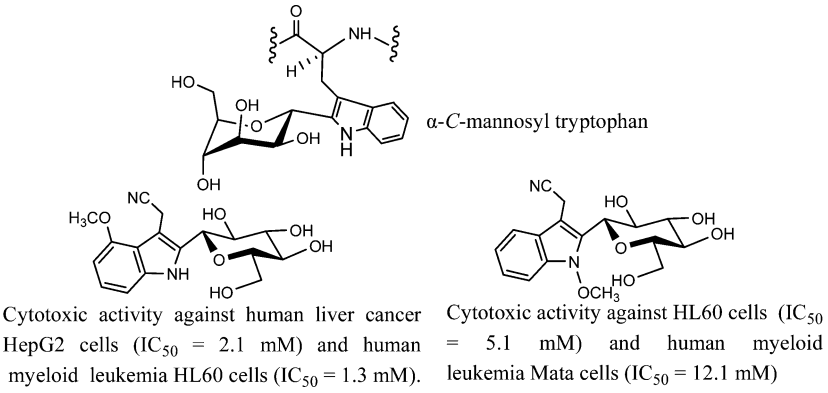
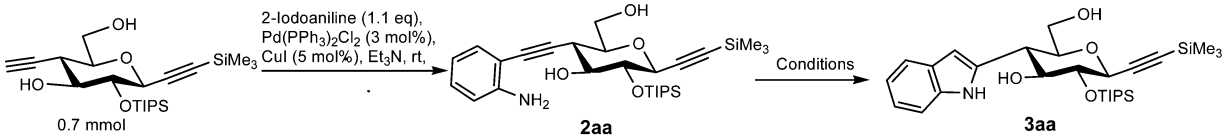


Figure 1. Examples of naturally occurring indole C-nucleoside analogues.

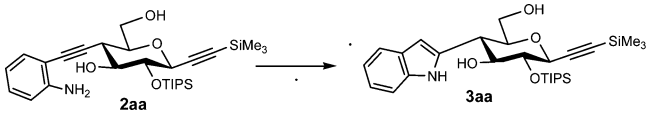
Scheme 1. Synthesis of 2aa and 3aa



phenylacetylene.[6e−o] To find a general reaction system tolerant of various functional groups and structural diversity of sugar alkynes in one pot, at the outset, **1a**[19] (Scheme 1) with sterically bulky triisopropylsilyl, unprotected hydroxyl groups and a sensitive trimethylsilylethynyl group was deliberately used as a model to perform the Sonogashira coupling/heteroannulation reaction. In the optimization studies, the two-step reactions were examined, respectively. Sonogashira coupling reaction of **1a** with 2-iodoaniline was performed under classical conditions in the presence of $Pd(PPh_3)_2Cl_2$, CuI, and Et_3N in degassed solvent. The influence of solvent, the amount of catalyst, and temperature on the reaction was examined in detail. When the reaction was carried out in THF, the coupling product sugar-substituted 2-ethynylaniline **2aa** (Scheme 1) was obtained in 85% yield. The change of solvent to MeCN and CH_2Cl_2 gave rise to **2aa** in 80% and 88% yields, respectively. In these cases, the undesired homocoupling product 1,3-diyne was not observed. The best result was obtained using 1.1 equiv of 2-iodoaniline, 1.0 equiv of **1a**, 3 mol % of $Pd(PPh_3)_2Cl_2$, and 5 mol % of CuI in pure degassed Et_3N. The coupling reaction was complete within 5 h at rt, and **2aa** was attained in 95% isolated yield. Heteroannulation product **3aa** was not obtained under these conditions. After the coupling reaction of **1a** with 2-iodoaniline was accomplished, an attempt to carry out a tandem reaction by increasing the temperature to 60 °C gave **3aa** only in 18% yield.

The second task was the development of the high yielding heteroannulation of **2aa** (Table 1). Although many examples for the intramolecular heteroannulation of 2-alkynylaniline to indole were reported,[6a−j,7] elevated temperature and prolonged reaction time in strong basic or Lewis acidic media are not suitable for the sugar-substituted alkynylaniline possessing complex structure and sensitive functional substituents. To get a general and efficient catalytic system for heteroannulation of various sugar 2-ethynylanilines, many catalysts were scanned using isolated **2aa** as starting material, and some results are listed in Table 1. Strong bases such as *t*-BuOK in THF and $NaNH_2$ in DMF at 50 °C gave **3aa** in very low yields of 12% and 15% (entries 1 and 2). In the two cases, TLC indicated that

Table 1. Heteroannulation of Sugar 2-Ethynylaniline 2aa under Various Conditions[a]



entry	catalyst	solvent	*T* (°C)	time (h)	yield (%)[b]
1	*t*-BuOK	THF	50	6	12
2	$NaNH_2$	DMF	50	5	15
3	$ZnCl_2$	toluene	80	4.5	20
4	$InBr_3$	toluene	80	3	22
5	$Cu(OTf)_2$	toluene	80	3	28
6	$CuCl_2$	$(CH_2Cl)_2$	80	3.5	20
7	$Pd(MeCN)_2Cl_2$	MeCN	60	5	38
8	$PdCl_2$	DMF	60	5.5	30
9	$NaAuCl_4{\cdot}2H_2O$[c]	THF	50	4.5	86
10	$NaAuCl_4{\cdot}2H_2O$	EtOH	50	5	70

[a]Conditions: 0.4 mmol of sugar 2-ethynylaniline **2aa**, 5 mol % of catalyst, 6 mL of solvent. [b]Isolated yield. [c]3 mol %.

most of **2aa** decomposed. The change of catalyst to a Lewis acid gave better results. The use of $ZnCl_2$ in toluene at 80 °C afforded **3aa** in 20% yield, and $InBr_3$ gave a similar result (entries 3 and 4). A slight increase in yield, to 28%, was obtained in toluene by the use of $Cu(OTf)_2$ (entry 5). When $Pd(MeCN)_2Cl_2$ was used in MeCN at 60 °C, **3aa** was obtained in 38%, which was better than that using $PdCl_2$ (entries 7 and 8). Fortunately, $NaAuCl_4{\cdot}2H_2O$ was found to be an efficient catalyst for heteroannulation of **2aa** to indole C-nucleoside. In the presence of 3 mol % of $NaAuCl_4{\cdot}2H_2O$, the best yield of **3aa** (86%) was achieved in THF at 50 °C (entry 9).

After obtaining the optimal conditions for the two steps, we carried out Sonogashira coupling/heteroannulation reaction in one pot. When the coupling of **1a** with 2-iodoaniline was finished under the optimal conditions, Et_3N was removed. THF and 3 mol % of $NaAuCl_4{\cdot}2H_2O$ were then added, and the mixture was stirred for 4.5 h at 50 °C to afford **3aa** in 83% yield. To examine the electronic effect of the substituents of 2-

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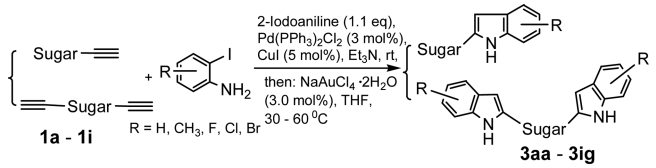
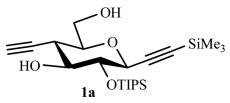
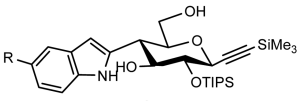
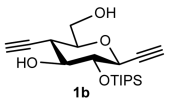
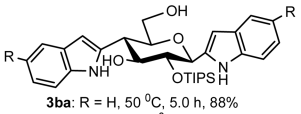
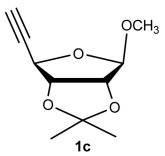
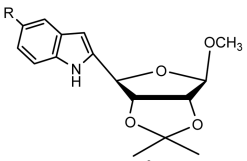
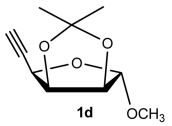
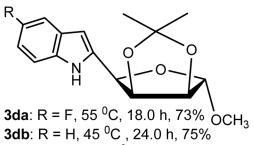
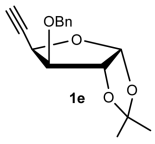
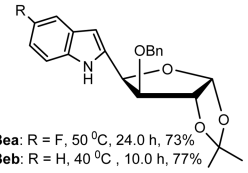
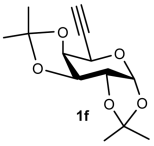
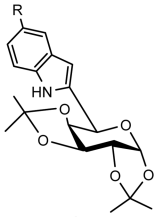
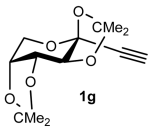
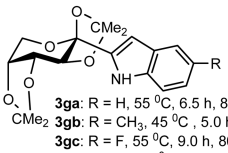
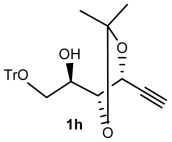
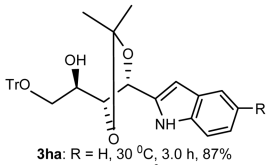
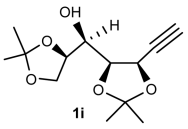
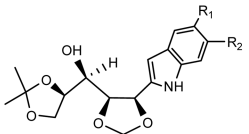
Table 2. Synthesis of Mono- and Diindole C-Nucleoside Analogues via Sequential Sonogashira Coupling/Heteroannulation Reactions of Various Terminal Sugar Alkynes with Substituted 2-Iodoanilines



Entry	Terminal sugar alkynes	Product, Temperature, Time, Yield[a]
1		 **3aa**: R = H, 50 °C, 5.0 h, 83% **3ab**: R = CH_3,50 °C, 4.0 h, 87% **3ac**: R = F, 50 °C, 10.0 h, 78% **3ad**: R = Cl, 50 °C, 8.0 h, 80% **3ae**, R = Br, 50 °C, 7.5 h, 85%
2		 **3ba**: R = H, 50 °C, 5.0 h, 88% **3bb**: R = CH_3,50 °C, 4.0 h, 90% **3bc**: R = F, 50 °C, 8.0 h, 84% **3bd**: R = Cl, 50 °C, 7.5 h, 87% **3be**, R = Br, 50 °C, 6 h, 85%
3		 **3ca**: R = Cl, 50 °C, 8.0 h, 83% **3cb**: R = H, 50 °C, 4.0 h, 85% **3cc**: R = CH_3, 50 °C, 3.0 h, 90% **3cd**: R= F, 50 °C, 10.0 h, 80% **3ce**: R= Br, 50 °C, 7.5 h, 83%
4		 **3da**: R = F, 55 °C, 18.0 h, 73% **3db**: R = H, 45 °C , 24.0 h, 75% **3dc**: R = CH_3, 50 °C, 24.0 h, 78%
5		 **3ea**: R = F, 50 °C, 24.0 h, 73% **3eb**: R = H, 40 °C , 10.0 h, 77%
6		 **3fa**: R = H, 45 °C, 8.0 h, 82% **3fb**: R = CH_3, 45 °C , 5.0 h, 85% **3fc**: R = F, 55 °C, 9.0 h, 80% **3fd**: R = Cl, 55 °C, 8.0 h, 84% **3fe**: R = Br, 50 °C, 7.5 h, 87%
7		 **3ga**: R = H, 55 °C, 6.5 h, 82% **3gb**: R = CH_3, 45 °C , 5.0 h, 88% **3gc**: R = F, 55 °C, 9.0 h, 80% **3gd**: R = Cl, 55 °C, 8.0 h, 85% **3ge**: R = Br, 55 °C, 7.5 h, 85%
8		 **3ha**: R = H, 30 °C, 3.0 h, 87% **3hb**: R = CH_3, 45 °C , 5.0 h, 90% **3hc**: R = F, 45 °C, 4.0 h, 83% **3hd**: R = Cl, 35 °C, 4.0 h, 89% **3he**: R = Br, 30 °C, 5.0 h, 87%
9		 **3ia**: R_1 = R_2 = H, 30 °C, 4.0 h, 88% **3ib**: R_1 = CH_3, R_2 = H, 25 °C, 3.0 h, 90% **3ic**: R_1 = F, R_2 = H, 45 °C, 5.0 h, 86% **3id**: R_1 = H, R_2 = F, 55 °C, 3.5 h, 84% **3ie**: R_1 = Cl, R_2 = H, 35 °C, 5.0 h, 85% **3if**: R_1 = H, R_2 = Cl, 50 °C, 4.0 h, 90% **3ig**: R_1 = Br, R_2 = H, 30 °C, 5.0 h, 88%

[a]Isolated yield.

iodoaniline on the reactions and to obtain different substituted indole patterns for nucleobase surrogate, 2-iodoanilines with electron-donating, electron-neutral, and electron-withdrawing substituents were used to react with **1a**. Fortunately, in all cases the sequence proceeded smoothly to give the corresponding products in high yields (Table 2, entry 1). Next, sugar terminal diyne **1b** (entry 2) having a sterically bulky triisopropylsilyl group and two unprotected hydroxyl groups was used to react with some substituted 2-iodoanilines to test this protocol. The corresponding diindole C-nucleoside analogues with electron-neutral, electron-donating, and electron-withdrawing substituents in the indole rings were afforded in high yields.

To investigate the scope and generality of this method further, other sugar alkynes, including sugars in furanose, pyranose, and acyclic forms with various protecting groups and free hydroxyl groups, having different steric hindrance were employed in reactions with various substituted 2-iodoanilines. These results are also summarized in Table 2. The substituted 2-iodoaniline having an electron-donating substituent gave a slightly higher yield than that having an electron-neutral or electron-withdrawing substituent. This is the same as the cases for **1a** and **1b** as described. The steric hindrance of the sugar alkynes also affects the Sonogashira coupling/heteroannulation reaction. For the furanoside alkynes **1c**–**e** (Table 2, entries 3–

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5), **1c** with *trans*-isopropylidene next to ethynyl exhibited a clean reaction and afforded C-nucleoside analogues **3ca−ce** in excellent yields (83−90%). Alkynes **1d** and **1e** (entries 4 and 5) with *cis*-isopropylidene and benzyloxy next to ethynyl, respectively, gave the corresponding products in slightly lower yields (73−78%), probably due to increased steric hindrance. In these two cases, the starting material cannot be converted completely. Increasing the temperature and prolonging the reaction time caused decomposition of the starting material. However, the pyranoside alkynes **1f** and **1g** (entries 6 and 7) with *cis*- and *trans*-isopropylidenes next to ethynyl, respectively, proceeded very smoothly, and the corresponding products were obtained in 80−88% yields. Then we turned our attention to acyclic alkynes. Alkynes **1h** and **1i** (entries 8 and 9) were used to perform the Sonogashira coupling/heteroannulation reactions. Both acyclic alkynes are much more reactive than the furanoside and pyranoside ones, probably because the acyclic chains are more flexible and have less steric hindrance, leading to the corresponding substituted indole acyclic C-nucleoside analogues in excellent yields. The structures of all the new compounds (**3aa−ig**) were characterized by ^{1}H NMR, ^{13}C NMR, DEPT-135, ^{19}F NMR, 2D NMR, HRMS, and IR spectra.

CONCLUSIONS

We have developed a new approach to synthesize substituted mono- and diindole C-nucleoside analogues by the sequential Sonogashira coupling/heteroannulation reactions of substituted 2-iodoanilines with sugar terminal alkynes. Various substituted indoles as isosteric surrogates of the structurally similar guanine and adenine have been coupled to the sugars. This method is simple, mild, and efficient, and the desired products were obtained in good to excellent yields. The scope and generality have been examined, and 42 examples are given. The sugar alkynes include furanosides, pyranosides, and acyclic glycosides derived from various inexpensive and abundant natural sugars. The reaction conditions are tolerant of various structurally complex sugars having sterically bulky groups, unprotected hydroxyl groups, sensitive substituents, and various protecting groups. The modification and biological study of these C-nucleoside analogues are in progress.

EXPERIMENTAL SECTION

Synthesis of 3,7-Anhydro-1,1,2,2-tetradehydro-1,2,6-trideoxy-6-*C*-ethynyl-4-*O*-(triisopropylsilyl)-1-*C*-(trimethylsilyl)-D-glycero-D-gulo-octitol (1a).[19] A solution of $AgNO_2$ (10.7 g, 69.5 mmol) in MeOH/H_2O 25:8 (33 mL) was added to a solution of protected 1,4-dideoxy-1,4-diethynyl-β-D-glucopyranose[19] (11.6 g, 23.3 mmol) in MeOH (120 mL). The mixture was stirred at rt for 4 h. Then it was cooled to 0 °C, treated with saturated KCN solution (18 mL), carefully neutralized with 2 N HCl (ca. 35 mL), and evaporated to remove MeOH. The residue was dissolved in EtOAc (80 mL) and washed with water (2 × 15 mL). The organic phase was dried over Na_2SO_4 and evaporated to dryness to give **1a** (8.9 g, 90%) as a white solid. R_f = 0.5 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); mp: 136−138 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.97 (d, 1H, *J* = 9.2 Hz), 3.94−3.93 (m, 1H), 3.77−3.71 (m, 1H), 3.63 (t, 1H, *J* = 8.4 Hz), 3.57−3.51 (m, 1H), 3.48−3.44 (m, 1H), 2.58−2.52 (m, 1H), 2.47 (s, 1H), 2.22 (d, 1H, *J* = 2.4 Hz), 2.08 (s, 1H), 1.30−1.10 (m, 21H), 0.17 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 102.3, 91.4, 80.2, 79.0, 77.0, 75.3, 73.0, 72.1, 63.6, 37.6, 18.5, 13.2, 0.3.

Synthesis of 3,7-Anhydro-1,1,2,2-tetradehydro-1,2,6-trideoxy-6-*C*-ethynyl-4-*O*- (triisopropylsilyl)-D-glycero-D-gulo-octitol (1b).[19] A 0.5 N NaOH solution (3 mL) was added to a solution of protected 1,4-dideoxy-1,4-diethynyl-β-D-glucopyranose[19] (1.0 g, 2.0 mmol) in MeOH (30 mL). The mixture was stirred at rt until TLC indicated the completion of the reaction. Then it was neutralized with 1 N HCl (1.5 mL) and evaporated to remove MeOH. The residue was dissolved in EtOAc (30 mL) and washed with water (2 × 5 mL). The organic phase was dried over Na_2SO_4 and evaporated to dryness to give **1b** (0.64 g, 90%) as a white solid. R_f = 0.5 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); mp: 113−115 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.97 (dd, 1H, *J* = 9.2 Hz, *J* = 2.2 Hz), 3.94−3.91 (m, 1H), 3.82−3.71 (m, 1H), 3.66 (t, 1H, *J* = 9.0 Hz), 3.58−3.53 (m, 1H), 3.50−3.46 (m, 1H), 2.60−2.54 (m, 1H), 2.50 (s, 1H), 2.49 (d, 1H, *J* = 2.1 Hz), 2.23 (d, 1H, *J* = 2.4 Hz), 2.09 (s, 1H), 1.26−1.09 (m, 21H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 81.1, 80.2, 79.0, 76.7, 75.1, 74.8, 73.1, 71.3, 63.4, 37.7, 18.4, 13.0.

General Procedure for the Preparation of 1c−g.[20] A solution of CBr_4 (2 equiv) in dry CH_2Cl_2 was added to a mixture of zinc (3 equiv), PPh_3 (3 equiv), and dry CH_2Cl_2 at 0 °C. Then sugar aldehyde[20c,i] (1.0 equiv) in dry CH_2Cl_2 was added dropwise for 10 min. The mixture was stirred at rt until TLC indicated the complete conversion of sugar aldehyde. Then it was evaporated, and the residue was purified by column chromatography (silica gel, 6:1−3:1, petroleum ether/EtOAc) to give a syrup.

A 2.5 M *n*-butyllithium solution in dry THF (2.5 equiv) was added to a solution of the syrup (1.0 equiv) in dry THF at −45 °C. The mixture was stirred until TLC indicated the completion of the reaction. It was quenched by water (*ca.* 2.5 equiv) and evaporated. The residue was dissolved in EtOAc, washed with water. The organic phase was dried over Na_2SO_4 and evaporated. The residue was purified by column chromatography (silica gel, 5:1−3:1, petroleum ether/EtOAc) to give **1c−g**.

*1-O-Methyl-5,6-dideoxy-2,3-O-isopropylidene-β-D-ribo-hex-5-ynofuranoside (**1c**).*[20c,d] White solid, 457 mg, 68% yield; R_f = 0.5 (silica gel F_{254}, 6:1, petroleum ether/EtOAc); mp: 63−64 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.97 (s,1H), 4.78 (d, 1H, $J_{3,2}$ = 6.0 Hz), 4.68 (d, 1H, *J* = 2.8 Hz), 4.58 (d, 1H, *J* = 6.0 Hz), 3.27 (s, 3H), 1.34, 1.20 (2s, each 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 112.5, 109.2, 85.3, 85.1, 81.5, 74.6, 74.1, 54.1, 26.2, 24.8.

*1-O-Methyl-5,6-dideoxy-2,3-O-isopropylidene-α-D-lyxo-hex-5-ynofuranoside (**1d**).*[20c,d] Yellow solid, 486 mg, 74% yield; R_f = 0.5 (silica gel F_{254}, 6:1, petroleum ether/EtOAc); mp: 45−46 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.90 (s, 1H), 4.72 (d, 1H, *J* = 4.0 Hz), 4.60 (dd, 1H, *J* = 5.6 Hz, *J* = 4.0 Hz), 4.53 (d, 1H, *J* = 5.6 Hz), 3.32 (s, 3H), 1.50, 1.32 (2s, each 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 113.4, 107.2, 84.8, 80.6, 77.4, 76.6, 70.6, 55.0, 26.3, 25.3.

*3-O-Benzyl-5,6-dideoxy-1,2-O-isopropylidene-α-D-xylo-hex-5-ynofuranose (**1e**).*[20c−g] Colorless oil, 438 mg, 72% yield; R_f = 0.6 (silica gel F_{254}, 4:1, petroleum ether/EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40−7.27 (m, 5H), 5.96 (d, 1H, *J* = 3.6 Hz), 4.83 (t, 1H, *J* = 2.4 Hz, *J* = 2.8 Hz), 4.81 (d, 1H, *J* = 12.4 Hz), 4.74 (d, 1H, *J* = 12.4 Hz), 4.58 (d, 1H, *J* = 3.6 Hz), 4.02 (d, 1H, *J* = 2.8 Hz), 2.64 (d, 1H, *J* = 2.4 Hz), 1.49, 1.31 (2s, each 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.4, 128.5, 128.0, 127.8, 112.0, 104.7, 82.8, 82.4, 77.6, 76.6, 72.6, 70.7, 26.8, 26.2.

*6,7-Dideoxy-1,2:3,4-di-O-isopropylidene-α-D-galacto-hept-6-ynopyranose (**1f**).*[20c,d,g] Colorless oil, 583 mg, 76% yield; R_f = 0.7 (silica gel F_{254}, 4:1, petroleum ether/EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.51 (d, 1H, *J* = 4.8 Hz), 4.60−4.58 (m, 2H), 4.29−4.25 (m, 2H), 2.51 (d, 1H, *J* = 2.0 Hz), 1.48, 1.47, 1.32, 1.27 (4s, each 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 109.9, 108.9, 96.4, 78.8, 74.5, 72.6, 70.6, 70.1, 60.0, 26.1, 25.9, 24.7, 24.3.

*1,2-Dideoxy-3,4:5,6-di-O-isopropylidene-β-D-arabino-hept-1-yn-3-ulo-3,7-pyranose (**1g**).*[20h,i] Colorless oil, 532 mg, 80% yield; R_f = 0.7 (silica gel F_{254}, 4:1, petroleum ether/EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.53 (dd, 1H, *J* = 2.0 Hz, *J* = 8.0 Hz), 4.43 (d, 1H, *J* = 2.0 Hz), 4.18−4.15 (m, 1H), 3.73−3.67 (m, 2H), 2.58 (s, 1H), 1.46, 1.45, 1.40, 1.29 (4s, each 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 109.6, 109.5, 95.8, 81.8, 75.7, 72.4, 70.4, 70.2, 61.2, 26.1, 26.0, 24.6, 24.2.

General Procedure for the Preparation of 1h and 1i.[21,22] A mixture of sugar hemiacetal (10.0 mmol), anhydrous K_2CO_3 (4.1 g, 30.0 mmol), and dry MeOH (20 mL) was refluxed, to which Ohira's reagent (6.7 g, 35.0 mmol) in dry MeOH (20 mL) was added

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dropwise over 6−8 h. TLC indicated completion of the reaction. The mixture was evaporated to dryness, and water (30 mL) was added. The solution was extracted with EtOAc (4 × 10 mL). The combined organic phases were dried over Na_2SO_4 and evaporated. The residue was purified by column chromatography (silica gel, 6:1−4:1, petroleum ether/EtOAc) to give **1g** or **1i**.

*3,4-Isopropylidene-6-O-triphenylmethyl-1,2-dideoxy-D-ribo-hex-1-ynitol (**1h**).*[22,23] Colorless oil, 3.6 g, 85% yield; R_f = 0.6 (silica gel F_{254}, 4:1, petroleum ether/EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50−7.28 (m, 15H), 4.73−4.71 (dd, J = 6.4 Hz, 1H), 4.25−4.22 (t, J = 6.0 Hz, 1H), 3.91 (s, 1H), 3.35−3.34 (d, J = 5.2 Hz, 2H), 2.53 (d, J = 3.6 Hz, 1H), 2.49 (d, J = 2.0 Hz), 1.52 (s, 3H), 1.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.7, 128.7, 127.9, 127.2, 110.8, 99.8, 87.1, 82.0, 74.4, 70.9, 66.9, 64.4, 26.9, 26.1.

*3,4:6,7-Di-O-isopropylidene-1,2-dideoxy-D-manno-hex-1-ynitol (**1i**).*[22−24] Colorless oil, 2.2 g, 86% yield; R_f = 0.7 (silica gel F_{254}, 5:1, petroleum ether/EtOAc); ^{1}H NMR (400 Hz, $CDCl_3$) δ 4.68 (dd, 1H, J = 1.4 Hz, J = 7.6 Hz), 4.30 (dd, 1H, J = 7.6 Hz, J = 1.6 Hz), 4.02−4.14 (m, 3H), 3.58 (br s, 1H), 2.56 (d, 1H, J = 1.4 Hz), 2.23 (d, 1H, J = 7.6 Hz), 1.53, 1.45, 1.44, 1.38 (s, each 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 110.1, 109.5, 80.8, 80.6, 76.2, 74.9, 69.8, 66.8, 66.6, 26.8, 26.6, 26.2, 25.3.

Synthesis of 3,7-Anhydro-1,1,2,2-tetradehydro-1,2,6-trideoxy-6-C-[(2- aminophenyl)ethynyl]-4-*O*-(triisopropylsilyl)-1-*C*-(trimethylsilyl)-D-glycero-D-gulo-octitol (2aa). A mixture of 2-iodoaniline (90 mg, 0.77 mmol), $Pd(PPh_3)_2Cl_2$ (15 mg, 0.021 mmol), CuI (7 mg, 0.035 mmol), and Et_3N (3 mL) was degassed. Then sugar alkyne **1a** (297 mg, 0.70 mmol) in Et_3N (3 mL) was injected with a syringe. The mixture was stirred at room temperature until TLC indicated completion of the reaction. It was evaporated to remove Et_3N. The residue was purified by column chromatography (silica gel, 3:1, petroleum ether/EtOAc) to give **2aa** (342 mg, 95%) as a brown oil: R_f = 0.5 (silica gel F_{254}, 3:1, petroleum ether/EtOAc). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.22 (dd, 1H, J = 1.1 Hz, J = 7.6 Hz, H-6′), 7.11−7.07 (m, 1H, H-5′), 6.68 (d, 1H, J = 7.9 Hz, H-4′), 6.65 (d, 1H, J = 7.4 Hz, H-7′), 3.99 (d, 1H, J = 9.3 Hz, H-3), 3.97 (d, 1H, J = 2.4 Hz, H-8a), 3.78 (dd, 1H, J = 5.8 Hz, J = 11.7 Hz, H-8b), 3.68 (t, J = 8.5 Hz, J = 10.2 Hz, H-5), 3.54−3.49 (m, 1H, H-7), 2.78 (t, 1H, J = 10.3 Hz, H-6), 1.29−1.10 (m, 21H, $Si(CH(CH_3)_2)_3$), 0.18 (s, 9H, $Si(CH_3)_3$); ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.04 (C-8′), 132.21 (C-6′), 129.79 (C-5′), 118.14 (C-4′), 114.67 (C-7′), 107.64 (C-3′), 102.61 (C-2), 90.66 (C-1), 91.23 (C-1′), 81.59 (C-2′), 79.30 (C-7), 77.20 (C-5), 75.36 (C-4), 72.12 (C-3), 63.77 (C-8), 38.84 (C-6), 18.47 ($Si(CH(CH_3)_2)_3$), 13.17 ($Si(CH(CH_3)_2)_3$), −0.28 ($Si(CH_3)_3$) ppm; HRMS (ESI) calcd for $C_{28}H_{46}NO_4Si_2$ $[M + H]^+$ 516.2965, found: 516.2960.

General Procedure for the Synthesis of 3aa−ig. A mixture of substituted 2-iodoaniline (0.77 mmol), $Pd(PPh_3)_2Cl_2$ (0.021 mmol), CuI (0.035 mmol), and Et_3N (3 mL) was degassed. Then sugar alkyne (0.70 mmol) in Et_3N (3 mL) was injected with a syringe. The mixture was stirred at room temperature until TLC indicated the completion of the reaction. It was evaporated to remove Et_3N. THF (8 mL) and $NaAuCl_4{\cdot}2H_2O$ (0.021 mmol) were then added, and the mixture was stirred at 25−55 °C. After TLC indicated completion of the reaction, the mixture was evaporated. The residue was purified by column chromatography (silica gel, 3:1−1:1, petroleum ether/EtOAc) to give the products **3aa−ig**.

*3,7-Anhydro-6-C-(indol-2-yl)-1,1,2,2-tetradehydro-1,2,6-trideoxy-4-O-(triisopropylsilyl)-1-C-(trimethylsilyl)-D-glycero-D-gulo-octitol (**3aa**).* Brown foam, 299 mg, 83% yield; mp: 56−57 °C; R_f = 0.7 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −26.3° (*c* 0.66, $CHCl_3$); IR (KBr): 3421, 3133, 2963, 2865, 1664, 1622, 1455, 1290, 1253, 1141, 1112, 1070, 1021, 883, 803 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.49 (s, 1H, NH), 7.56 (d, 1H, $J_{4',5'}$ = 8.0 Hz, H-4′), 7.31 (d, 1H, $J_{7',6'}$ = 8.0 Hz, H-7′), 7.18−7.08 (m, 2H, H-5′, H-6′), 6.34 (s, 1H, H-3′), 4.12 (d, 1H, $J_{3,4}$ = 8.4 Hz, H-3), 3.82−3.80 (m, 2H, H-4, H-5), 3.70 (d, 1H, $J_{8a,8b}$ = 12.0 Hz, H-8a), 3.58 (br d, J = 10.4 Hz, H-7), 3.37 (dd, 1H, $J_{8b,7}$ = 4.0 Hz, $J_{8b,8a}$ = 12.0 Hz, H-8b), 3.06 (t, 1H, $J_{6,7}$ = $J_{6,5}$ = 10.0 Hz, H-6), 2.38 (s, 2H, 2OH), 1.30−1.11 (m, 21H, $Si(CH(CH_3)_2)_3$), 0.21 (s, 9H, $Si(CH_3)_3$) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 135.8 (C-7a′), 135.0 (C-2′), 128.5 (C-3a′), 122.0 (C-6′), 120.3 (C-4′), 120.2 (C-5′), 111.0 (C-7′), 102.7 (C-2), 99.4 (C-3′), 91.3 (C-1), 80.0 (C-7), 77.4 (C-5), 75.7 (C-4), 72.2 (C-3), 63.2 (C-8), 44.4 (C-6), 18.5 ($Si(CH(CH_3)_2)_3$), 13.2 ($Si(CH(CH_3)_2)_3$), −0.2 ($Si(CH_3)_3$) ppm; HRMS (ESI) calcd for $C_{28}H_{46}NO_4Si_2$ $[M + H]^+$ 516.2965, found: 516.2962.

*3,7-Anhydro-6-C-(5-methylindol-2-yl)-1,1,2,2-tetradehydro-1,2,6-trideoxy-4-O-(triisopropylsilyl)-1-C-(trimethylsilyl)-D-glycero-D-gulo-octitol (**3ab**).* Brown foam, 322 mg, 87% yield; mp: 92−93 °C; R_f = 0.7 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −30.8° (*c* 0.50, $CHCl_3$); IR (KBr) 3425, 3132, 2966, 2864, 1664, 1623, 1400, 1293, 1254, 1141, 1071, 1023, 882, 778 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.35 (s, 1H), 7.34 (s, 1H), 7.20 (d, 1H, J = 8.4 Hz), 6.98 (d, 1H, J = 8.4 Hz), 6.25 (s, 1H), 4.12 (d, 1H, J = 8.8 Hz), 3.81−3.78 (m, 2H), 3.70 (d, 1H, J = 12.0 Hz), 3.60−3.56 (m, 1H), 3.37 (br d, 1H, J = 8.4 Hz), 3.03 (t, 1H, J = 10.2 Hz), 2.43 (s, 3H), 2.33, 2.27 (2br s, each 1H), 1.28−1.11 (m, 21H), 0.20 (s, 9H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 135.0, 134.2, 129.4, 128.8, 123.6, 120.0, 110.7, 102.8, 99.0, 91.2, 80.0, 77.4, 75.7, 72.2, 63.3, 44.5, 21.5, 18.5, 13.2, −0.2 ppm; HRMS (ESI) calcd for $C_{29}H_{48}NO_4Si_2$ $[M + H]^+$ 530.3122, found: 530.3125.

*3,7-Anhydro-6-C-(5-fluoroindol-2-yl)-1,1,2,2-tetradehydro-1,2,6-trideoxy-4-O-(triisopropylsilyl)-1-C-(trimethylsilyl)-D-glycero-D-gulo-octitol (**3ac**).* Brown foam, 291 mg, 78% yield; mp: 63−64 °C; R_f = 0.7 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −30.7° (*c* 0.52, $CHCl_3$); IR (KBr) 3422, 3335, 3133, 2961, 2865, 1626, 1487, 1454, 1400, 1291, 1253, 1119, 1069, 1022, 849, 813 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.49 (s, 1H), 7.22−7.17 (m, 2H), 6.92−6.86 (m, 1H), 6.30 (s, 1H), 4.12 (d, 1H, J = 8.4 Hz), 3.82−3.79 (m, 2H), 3.74 (d, 1H, J = 11.4 Hz), 3.61−3.58 (m, 1H), 3.38 (dd, J = 3.6 Hz, J = 11.4 Hz), 3.08 (t, 1H, J = 10.2 Hz), 2.36 (s, 1H), 2.26 (s, 1H), 1.29−1.11 (m, 21H), 0.20 (s, 9H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.2 (d, $^1J_{C\text{-}F}$ = 233.0 Hz), 137.0, 132.3, 128.9 (d, $^3J_{C\text{-}F}$ = 10.0 Hz), 111.6 (d, $^3J_{C\text{-}F}$ = 10.0 Hz), 110.3 (d, $^2J_{C\text{-}F}$ = 26.0 Hz), 105.1 (d, $^2J_{C\text{-}F}$ = 24.0 Hz), 102.6, 99.5 (d, $^4J_{C\text{-}F}$ = 4.0 Hz), 91.4, 80.0, 77.4, 75.8, 72.2, 63.2, 44.2, 18.5, 13.2, −0.2 ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −124.4 (dt, J_1 = 9.2 Hz, J_2 = 4.1 Hz) ppm; HRMS (ESI) calcd for $C_{28}H_{45}FNO_4Si_2$ $[M + H]^+$ 534.2871, found 534.2869.

*3,7-Anhydro-6-C-(5-chloroindol-2-yl)-1,1,2,2-tetradehydro-1,2,6-trideoxy-4-O-(triisopropylsilyl)-1-C-(trimethylsilyl)-D-glycero-D-gulo-octitol (**3ad**).* Brown foam, 308 mg, 80% yield; mp: 39−40 °C; R_f = 0.7 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −39.0° (*c* 0.54, $CHCl_3$); IR (KBr) 3413, 3335, 3134, 2927, 2863, 1665, 1618, 1583, 1464, 1311, 1252, 1140, 1113, 1065, 1022, 848, 805 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.53 (s, 1H, NH), 7.51 (d, 1H, J = 1.6 Hz), 7.22 (d, 1H, J = 8.4 Hz), 7.10 (dd, 1H, J = 1.6 Hz, J = 8.4 Hz), 6.28 (s, 1H), 4.12 (d, 1H, J = 8.8 Hz), 3.84−3.80 (m, 2H), 3.76 (d, 1H, J = 13.2 Hz), 3.60 (dd, 1H, J = 2.8 Hz, J = 10.4 Hz), 3.39 (dd, 1H, J = 3.4 Hz, J = 12.0 Hz), 3.60 (dd, 1H, J = 2.8 Hz, J_7 = 10.4 Hz), 3.39 (dd, 1H, J = 3.4 Hz, J = 12.0 Hz), 3.10 (t, 1H, J = 10.4 Hz), 2.34 (s, 1H), 2.22 (s, 1H), 1.28−1.11 (m, 21H), 0.20 (s, 9H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.7, 134.2, 129.6, 125.8, 122.3, 119.7, 112.0, 102.5, 99.0, 91.5, 80.0, 77.4, 75.9, 72.2, 63.2, 44.1, 18.5, 13.2, −0.2 ppm; HRMS (ESI) calcd for $C_{28}H_{45}ClNO_4Si_2$ $[M + H]^+$ 550.2576, found 550.2579.

*3,7-Anhydro-6-C-(5-bromoindol-2-yl)-1,1,2,2-tetradehydro-1,2,6-trideoxy-4-O-(triisopropylsilyl)-1-C-(trimethylsilyl)-D-glycero-D-gulo-octitol (**3ae**).* Brown foam, 353 mg, 85% yield; mp: 96−97 °C; R_f = 0.7 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −34.4° (*c* 0.50, $CHCl_3$); IR (KBr) 3423, 3134, 2964, 2864, 1664, 1621, 1449, 1400, 1312, 1256, 1141, 1109, 1070, 1022, 882, 802 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.56 (s, 1H), 7.66 (s, 1H), 7.23 (dd, 1H, J = 1.6 Hz, J = 8.6 Hz), 7.17 (d, 1H, J = 8.6 Hz), 6.28 (s, 1H), 4.12 (d, 1H, J = 8.4 Hz), 3.81−3.79 (m, 2H), 3.74 (d, 1H, J = 12.4 Hz), 3.60−3.58 (m, 1H), 3.36 (br d, 1H, J = 9.2 Hz), 3.09 (t, 1H, J = 10.0 Hz), 2.36 (s, 1H), 2.26 (s, 1H), 1.27−1.11 (m, 21H), 0.20 (s, 9H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.6, 134.4, 130.3, 124.8, 122.8, 113.3, 112.4, 102.5, 98.9, 91.5, 80.0, 77.4, 75.8, 72.2, 63.2, 44.0, 18.5, 13.2, −0.2 ppm; HRMS (ESI) calcd for $C_{28}H_{45}BrNO_4Si_2$ $[M + H]^+$ 594.2070, found 594.2072.

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*2-[4-Deoxy-2-O-triisopropylsilyl-4-C-(indol-2-yl)-β-D-glucopyranosyl]indole (**3ba**).* Brown foam, 329 mg, 88% yield; mp: 74−75 °C; R_f = 0.7 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −20.2° (*c* 0.53, $CHCl_3$); IR (KBr) 3556, 3409, 2962, 2864, 1664, 1619, 1545, 1455, 1400, 1291, 1262, 1130, 1070, 1017, 848, 792 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.91, 8.74 (2s, each 1H, 2NH), 7.64−7.59 (m, 2H, H-4, H-4″), 7.31−7.28 (m, 2H, H-7, H-7″), 7.23−7.11 (m, 4H, H-5, H-5″, H-6, H-6″), 6.54 (s, 1H, H-3), 6.35 (s, 1H, H-3″), 4.45 (d, 1H, $J_{1',2'}$ = 8.8 Hz, H-1′), 4.06 (t, 1H, $J_{2',1'} = J_{2',3'}$ = 8.8 Hz, H-2′), 3.96−3.91 (m, 1H, H-3′), 3.67−3.59 (m, 2H, H-5′, H-6′a), 3.33 (dd, 1H, $J_{6'b,5'}$ = 2.8 Hz, $J_{6'b,6'a}$ =11.6 Hz, H-6′b), 3.21 (t, 1H, $J_{4',3'} = J_{4',5'}$ = 10.4 Hz, H-4′), 2.50 (s, 1H, OH), 0.88−0.80 (m, 21H, $Si(CH(CH_3)_2)_3$) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.2, 135.9, 135.6, 135.4 (C-2, C-7a, C-2″, C-7a″), 128.6, 128.0 (C-3a, C-3a″), 122.3, 122.0 (C-6, C-6″), 120.8, 120.3, 120.2, 119.9 (C-4, C-5, C-4″, C-5″), 111.1, 111.0 (C-7, C-7″), 102.9 (C-3), 99.4 (C-3″), 79.7 (C-5′), 78.7 (C-3′), 77.4 (C-1′), 75.9 (C-2′), 62.9 (C-6′), 45.0 (C-4′), 18.1 ($Si(CH(CH_3)_2)_3$), 13.1 ($Si(CH(CH_3)_2)_3$) ppm; HRMS (ESI) calcd for $C_{31}H_{43}N_2O_4Si$ $[M + H]^+$ 535.2992, found 535.2993.

*5-Methyl-2-[4-deoxy-2-O-triisopropylsilyl-4-C-(5-methylindol-2-yl)-β-D-glucopyranosyl]indole (**3bb**).* Brown foam, 354 mg, 90% yield; mp: 97−100 °C; R_f = 0.7 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −23.6° (*c* 1.61, $CHCl_3$); IR (KBr) 3405, 3165, 3018, 2942, 2864, 1665, 1623, 1458, 1400, 1314, 1258, 1129, 1063, 883, 794 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.81, 8.68 (2s, each 1H), 7.43, 7.41 (2s, each 1H), 7.21−7.18 (m, 2H), 7.05−7.02 (m, 2H), 6.46 (s, 1H), 6.25 (s, 1H), 4.36 (d, 1H, *J* = 8.6 Hz, 4.05 (t, 1H, *J* = 8.6 Hz), 3.88 (br t, 1H, *J* = 9.2 Hz), 3.56−3.48 (m, 2H), 3.24 (br d, 1H, *J* = 9.6 Hz), 3.11 (t, 1H, *J* = 10.4 Hz), 2.49, 2.48 (2s, each 3H), 0.91−0.83 (m, 21H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 135.7, 135.5, 134.5, 134.1, 129.4, 128.89, 128.88, 128.3, 123.8, 123.5, 120.4, 119.8, 110.8, 110.7, 102.4, 98.8, 79.6, 78.8, 77.4, 75.6, 62.7, 45.0, 21.64, 21.57, 18.1, 13.0 ppm; HRMS (ESI) calcd for $C_{33}H_{46}N_2O_4Si$ $[M + H]^+$ 562.3227, found 562.3228.

*5-Fluoro-2-[4-deoxy-2-O-triisopropylsilyl-4-C-(5-fluorolindol-2-yl)-β-D-glucopyranosyl]indole (**3bc**).* Brown foam, 335 mg, 84% yield; mp: 95−97 °C; R_f = 0.7 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −21.9° (*c* 1.48, $CHCl_3$); IR (KBr) 3405, 3165, 3018, 2942, 2864, 1665, 1623, 1458, 1400, 1314, 1258, 1129, 1063, 883, 794 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 9.10, 8.95 (2s, each 1H), 7.25−7.22 (m, 2H), 7.15−7.11 (m, 2H), 6.93−6.88 (m, 2H), 6.48 (s, 1H), 6.29 (s, 1H), 4.46 (d, 1H, *J* = 8.8 Hz), 4.05 (t, 1H, *J* = 8.8 Hz), 3.95 (br t, 1H, *J* = 8.8 Hz), 3.73−3.64 (m, 2H), 3.37 (br d, 1H, *J* = 9.6 Hz), 3.28 (t, 1H, *J* = 10.4 Hz), 2.65 (s, 1H), 0.88−0.84 (m, 21H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.2 (2d, $^1J_{C\text{-}F}$ = 232.0 Hz), 158.0 (2d, $^1J_{C\text{-}F}$ = 232.0 Hz), 137.25, 137.19, 132.7, 132.3, 129.0 (2d, $^3J_{C\text{-}F}$ = 10.0 Hz), 128.2 (2d, $^3J_{C\text{-}F}$ = 10.0 Hz), 111.65 (2d, $^3J_{C\text{-}F}$ = 9.0 Hz), 111.56 (2d, $^3J_{C\text{-}F}$ = 10.0 Hz), 110.8(2d, $^2J_{C\text{-}F}$ = 26.0 Hz), 110.3 (2d, $^2J_{C\text{-}F}$ = 26.0 Hz), 105.4 (2d, $^2J_{C\text{-}F}$ = 23.0 Hz), 105.1 (2d, $^2J_{C\text{-}F}$ = 23.0 Hz), 103.3, 103.2, 99.43, 99.39, 79.5, 78.8, 77.4, 75.9, 62.8, 44.8, 18.1, 13.1 ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −124.1 (dt, J_1 = 9.0 Hz, J_2 = 4.9 Hz); −124.5 (dt, J_1 = 9.4 Hz, J_2 = 4.5 Hz) ppm; HRMS (ESI) calcd for $C_{31}H_{41}F_2N_2O_4Si$ $[M + H]^+$ 571.2804, found 571.2803.

*5-Chloro-2-[4-deoxy-2-O-triisopropylsilyl-4-C-(5-chloroindol-2-yl)-β-D-glucopyranosyl]indole (**3bd**).* Brown foam, 367 mg, 87% yield; mp: 49−50 °C; R_f = 0.7 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −16.5° (*c* 0.51, $CHCl_3$); IR (KBr) 3405, 3165, 3018, 2942, 2864, 1665, 1623, 1458, 1400, 1314, 1258, 1129, 1063, 883, 794 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.94, 8.86 (2s, each 1H), 7.55, 7.54 (2s, each 1H), 7.18−7.09 (m, 4H), 6.46 (s, 1H), 6.31 (s, 1H), 4.51 (d, 1H, *J* = 8.4 Hz), 4.04−3.96 (m, 2H), 3.78−3.72 (m, 2H), 3.40 (dd, 1H, *J*= 2.8 Hz, *J* = 9.2 Hz), 3.29 (t, 1H, *J* = 10.0 Hz), 0.87−0.84 (m, 21H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.9, 136.8, 134.5, 134.2, 129.7, 129.0, 126.0, 125.5, 122.7, 122.4, 120.1, 119.8, 112.0, 111.9, 102.6, 99.1, 79.7, 78.5, 77.4, 76.2, 63.0, 44.8, 18.1, 13.1 ppm; HRMS (ESI) calcd for $C_{31}H_{41}Cl_2N_2O_4Si$ $[M + H]^+$ 603.2213, found 603.2215.

*5-Bromo-2-[4-deoxy-2-O-triisopropylsilyl-4-C-(5-bromoindol-2-yl)-β-D-glucopyranosyl]indole (**3be**).* Brown foam, 412 mg, 85% yield; mp: 95−97 °C; R_f = 0.7 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −25.8° (*c* 1.04, $CHCl_3$); IR (KBr) 3405, 3165, 3018, 2942, 2864, 1665, 1623, 1457, 1400, 1314, 1258, 1129, 1063, 883, 794 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 9.11, 8.98 (2s, each 1H), 7.71, 7.70 (2s, each 1H), 7.25−7.21 (m, 2H), 7.11−7.08 (m, 2H), 6.43 (s, 1H), 6.26 (s, 1H), 4.43 (d, 1H, *J* = 8.8 Hz), 4.03 (t, 1H, *J* = 8.8 Hz), 3.96−3.91 (m, 1H), 3.69−3.62 (m, 2H), 3.32 (br d, 1H, *J* = 12.0 Hz), 3.26 (t, 1H, *J* = 10.4 Hz), 2.64 (br s, 1H), 0.86−0.83 (m, 21H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.74, 136.69, 134.7, 134.4, 130.3, 129.6, 125.2, 124.9, 123.2, 122.8, 113.4, 113.1, 112.5, 112.4, 102.6, 98.9, 79.5, 78.8, 77.3, 75.8, 62.8, 44.7, 18.1, 13.1 ppm; HRMS (ESI) calcd for $C_{31}H_{40}Br_2N_2O_4Si$ $[M]^+$ 690.1124, found 690.1123.

*Methyl 4S-4-C-(5-Chloroindol-2-yl)-2,3-O-isopropylidene-β-D-erythrofuranoside (**3ca**).* Brown oil, 188 mg, 83% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −45.1° (*c* 0.56, $CHCl_3$); IR (KBr) 3389, 3046, 2960, 1629, 1599, 1556, 1489, 1459, 1377, 1209, 1096, 799 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 9.03 (s, 1H), 7.56 (s, 1H), 7.27 (d, 1H, $J_{7,6}$ = 8.4 Hz), 7.15 (d, 1H, $J_{6,7}$ = 8.4 Hz), 6.42 (s, 1H), 5.48 (s, 1H), 5.20 (s, 1H), 4.87 (d, 1H, $J_{3',2'}$ = 4.8 Hz), 4.28 (br s, 1H), 3.47 (s, 3H), 1.60, 1.37 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.0, 135.2, 129.3, 125.6, 122.6, 120.2, 113.0, 112.1, 110.5, 101.0, 85.6, 85.2, 84.00, 55.8, 26.6, 25.1 ppm; HRMS (ESI) calcd for $C_{16}H_{19}$ $ClNO_4$ $[M + H]^+$ 324. 1003, found: 324.1006.

*Methyl 4S-4-C-(Indol-2-yl)-2,3-O-isopropylidene-β-D-erythrofuranoside (**3cb**).* Brown oil, 172 mg, 85% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −45.1° (*c* 1.25, $CHCl_3$); IR (KBr) 3444, 3062, 2939, 1625, 1589, 1550, 1491, 1455, 1377, 1207, 1097, 799 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.95 (s, 1H), 7.60 (d, 1H, *J* = 8.0 Hz), 7.35 (d, 1H, *J* = 8.0 Hz), 7.20 (t, 1H, *J* = 7.6 Hz), 7.11 (t, 1H, *J* = 7.6 Hz), 6.47 (s, 1H), 5.50 (s, 1H), 5.19 (s, 1H), 4.88 (d, 1H, *J* = 5.8 Hz), 4.82 (d, 1H, *J* = 5.8 Hz), 3.46 (s, 3H), 1.59, 1.36 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.9, 136.5, 128.3, 122.4, 120.9, 120.0, 112.9, 115.2, 110.5, 101.6, 85.8, 85.3, 84.2, 55.7, 26.6, 25.1 ppm; HRMS (ESI) calcd for $C_{16}H_{20}NO_4$ $[M + H]^+$ 290.1392, found 290.1390.

*Methyl 4S-4-C-(5-Methylindol-2-yl)-2,3-O-isopropylidene-β-D-erythrofuranoside (**3cc**).* Brown oil, 191 mg, 90% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −46.8° (*c* 1.23, $CHCl_3$); IR (KBr) 3387, 3029, 2939, 1627, 1596, 1555, 1492, 1458, 1377, 1212, 1097, 795 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.82 (s, 1H), 7.37 (s, 1H), 7.23 (d, 1H, *J* = 8.2 Hz), 7.01 (d, 1H, *J* = 8.2 Hz), 6.37 (s, 1H), 5.46 (s, 1H), 5.16 (s, 1H), 4.86 (d, 1H, *J* = 6.0 Hz), 4.80 (d, 1H, *J* = 6.0 Hz), 3.44 (s, 3H), 2.44 (s, 3H), 1.57, 1.34 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.5, 135.2, 129.1, 128.5, 123.9, 120.5, 112.8, 110.8, 110.4, 101.0, 85.7, 85.2, 84.2, 55.5, 26.6, 25.1, 21.5 ppm; HRMS (ESI) calcd for $C_{17}H_{22}NO_4$ $[M + H]^+$ 304.1549, found 304.1550.

*Methyl 4S-4-C-(5-Fluoroindol-2-yl)-2,3-O-isopropylidene-β-D-erythrofuranoside (**3cd**).* Brown oil, 172 mg, 80% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −38.2° (*c* 1.52, $CHCl_3$); IR (KBr) 3413, 3045, 2957, 1629, 1588, 1553, 1489, 1452, 1377, 1212, 1095, 797 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.96 (s, 1H), 7.25−7.21 (m, 2H), 6.96−6.91 (m, 1H), 6.42 (s, 1H), 5.47 (s, 1H), 5.18 (s, 1H), 4.86 (d, 1H, *J* = 6.0 Hz), 4.80 (d, 1H, *J* = 6.0 Hz), 3.46 (s, 3H), 1.58, 1.35 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.0 (d, $^1J_{C\text{-}F}$ = 233.0 Hz), 138.3, 133.4, 128.6 (d, $^3J_{C\text{-}F}$ = 10.0 Hz), 113.0, 111.7 (d, $^3J_{C\text{-}F}$ = 9.0 Hz), 110.7 (d, $^2J_{C\text{-}F}$ = 26.0 Hz), 110.5, 105.6 (d, $^2J_{C\text{-}F}$ = 24.0 Hz), 101.5 (d, $^4J_{C\text{-}F}$ = 4.0 Hz), 85.7, 85.2, 84.0, 55.7, 26.6, 25.0 ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −124.9 (dt, J_1 = 9.3 Hz, J_2 = 4.1 Hz) ppm; HRMS (ESI) calcd for $C_{16}H_{19}FNO_4$ $[M + H]^+$ 308.1294, found 308.1296.

*Methyl 4S-4-C-(5-Bromoindol-2-yl)-2,3-O-isopropylidene-β-D-erythrofuranoside (**3ce**).* Brown oil, 213 mg, 83% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −39.3° (*c* 1.15, $CHCl_3$); IR (KBr) 3406, 3056, 2958, 1624, 1598, 1579, 1485, 1456, 1378, 1096, 1055, 795 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.99 (s, 1H), 7.70 (s, 1H), 7.27−7.20 (m, 2H), 6.39 (s, 1H), 5.45 (s, 1H), 5.17 (s, 1H), 4.84 (d, 1H, *J* = 5.8 Hz), 4.79 (d, 1H, *J* = 5.8 Hz), 3.45 (s, 3H), 1.56, 1.34 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.8, 135.4, 130.0, 125.1, 123.3, 113.1, 113.0, 112.6, 110.5, 100.9,

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85.6, 85.2, 83.9, 55.7, 26.6, 25.0 ppm; HRMS (ESI) calcd for $C_{16}H_{19}BrNO_4$ $[M + H]^+$ 368.0497, found 368. 0499.

*Methyl 4S-4-C-(5-Fluoroindol-2-yl)-2,3-O-isopropylidene-α-L-erythrofuranoside (**3da**).* Pale yellow oil, 165 mg, 78% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −23° (*c* 0.50, $CHCl_3$); IR (KBr) 3337, 3048, 2926, 1626, 1586, 1542, 1485, 1457, 1380, 1090, 1026, 800 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.74 (s, 1H, NH), 7.30−7.22 (m, 2H, H-4, H-7), 6.96−6.91 (m, 1H, H-6), 6.52 (s, 1H, H-3), 5.15 (d, 1H, $J_{4',3'}$ = 3.2 Hz, H-4′), 5.00 (s, 1H, H-1′), 4.86 (dd, 1H, $J_{3',4'}$ = 3.2 Hz, $J_{3',2'}$ = 5.6 Hz, H-3′), 4.69 (d, 1H, $J_{2',3'}$ = 5.6 Hz, H-2′), 3.40 (s, 3H, OCH_3), 1.60, 1.34 (2s, each 3H, $2CH_3$) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.0 (C-5, d, $^1J_{C\text{-}F}$ = 232.0 Hz), 134.2 (C-2), 133.2 (C-7a), 127.9 (C-3a, d, $^3J_{C\text{-}F}$ = 10.0 Hz), 113.0 (isopropylidene-C), 111.9 (C-7, d, $^3J_{C\text{-}F}$ = 9.6 Hz), 110.9 (C-6, d, $^2J_{C\text{-}F}$ = 26.3 Hz), 107.1 (C-1′), 105.5 (C-4, d, $^2J_{C\text{-}F}$ = 23.3 Hz), 103.3 (C-3, d, $^4J_{C\text{-}F}$ = 4.5 Hz), 85.5 (C-2′), 81.7 (C-3′), 75.2 (C-4′), 55.2 (OCH_3), 26.4, 24.6 ($2CH_3$) ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −124.9 (dt, J_1 = 9.3 Hz, J_2 = 4.1 Hz) ppm; HRMS (ESI) calcd for $C_{16}H_{19}FNO_4$ $[M + H]^+$ 308.1294, found 308.1292.

*Methyl 4S-4-C-(Indol-2-yl)-2,3-O-isopropylidene-α-L-erythrofuranoside (**3db**).* Brown oil, 157 mg, 73% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −25.0° (*c* 0.5, $CHCl_3$); IR (KBr) 3447, 3032, 2926, 1624, 1591, 1557, 1491, 1450, 1378, 1231, 1096, 802 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.74 (s, 1H), 7.60 (d, 1H, *J* = 7.6 Hz), 7.37 (dd, 1H, *J* = 8.0 Hz, *J* = 0.8 Hz), 7.18 (dt, 1H, *J* = 8.0 Hz, *J* = 0.9 Hz), 7.08 (dt, 1H, *J* = 8.0 Hz, *J* = 0.8 Hz), 6.56 (s, 1H), 5.18 (d, 1H, *J* = 3.4 Hz), 5.00 (s, 1H), 4.86 (dd, 1H, *J* = 3.4 Hz, *J* = 5.6 Hz), 4.69 (d, 1H, *J* = 5.6 Hz), 3.40 (s, 3H), 1.60, 1.34 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.7, 132.4, 127.6, 122.4, 120.9, 119.8, 112.9, 111.3, 107.1, 103.3, 85.5, 81.8, 75.4, 55.1, 26.4, 24.6 ppm; HRMS (ESI) calcd for $C_{16}H_{20}NO_4$ $[M + H]^+$ 290.1392, found 290.1391.

*Methyl 4S-4-C-(5-methylindol-2-yl)-2,3-O-isopropylidene-α-L-erythrofuranoside (**3dc**).* Yellow oil, 151 mg, 75% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −9.0° (*c* 0.50, $CHCl_3$); IR (KBr) 3457, 3048, 2925, 1627, 1589, 1556, 1483, 1459, 1379, 1163, 1100, 1020, 801 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.65 (s, 1H), 7.37 (s, 1H), 7.25 (d, *J* = 8.0 Hz), 7.00 (d, 1H, *J* = 8.0 Hz), 6.47 (s, 1H), 5.15 (d, 1H, *J* = 3.2 Hz), 4.99 (s, 1H), 4.85 (dd, 1H, *J* = 3.2 Hz, *J* = 5.6 Hz), 4.68 (d, 1H, *J* = 5.6 Hz), 3.40 (s, 3H), 2.43 (s, 3H), 1.60, 1.33 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 135.1, 132.4, 128.9, 127.9, 124.1, 120.5, 112.7, 110.9, 107.1, 102.8, 85.5, 81.8, 75.4, 55.1, 26.4, 24.6, 21.6 ppm; HRMS (ESI) calcd for $C_{17}H_{22}NO_4$ $[M + H]^+$ 304.1549, found 304.1548.

*4S-4-C-(5-Fluoroindol-2-yl)-3-O-benzyl-1,2-O-isopropylidene-α-L-threofuranoside (**3ea**).* Pale yellow oil, 195 mg, 73% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −55.0° (*c* 0.48, $CHCl_3$); IR (KBr) 3442, 3058, 2926, 1625, 1589, 1549, 1488, 1456, 1378, 1261, 1081, 801 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.72 (s, 1H, NH), 7.36−7.18 (m, 5H, H-4, H-7, 3ArH), 7.01 (d, 2H, *J* = 6.8 Hz, 2ArH), 6.93 (t, 1H, *J* = 9.2 Hz, H-7), 6.48 (s, 1H, H-3), 6.06 (d, 1H, $J_{1',2'}$ = 3.4 Hz, H-1′), 5.39 (s, 1H, H-4′), 4.75 (d, 1H, $J_{2',1'}$ = 3.4 Hz, H-2′), 4.44 (d, B of AB, 1H, *J* = 11.2 Hz, Ph-CH_B), 4.18 (d, A of AB, 1H, *J* = 11.2 Hz, Ph-CH_A), 4.08 (s, 1H, H-3′), 1.59, 1.38 (2s, each 3H, $2CH_3$) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.0 (C-5, d, $^1J_{C\text{-}F}$ = 232.0 Hz), 137.0 (aromatic-C), 134.2 (C-2), 133.0 (C-7a), 128.6, 128.3, 128.01 (5 aromatic-CH), 127.95 (C-3a, d, $^3J_{C\text{-}F}$ = 11.2 Hz), 112.1 (isopropylidene-C), 111.7 (C-7, d, $^3J_{C\text{-}F}$ = 10.0 Hz), 110.7 (C-6, d, $^2J_{C\text{-}F}$ = 26.0 Hz), 105.5 (C-4, d, $^2J_{C\text{-}F}$ = 23.0 Hz), 104.8 (C-1′), 102.3 (C-3, d, $^4J_{C\text{-}F}$ = 5.0 Hz), 84.2 (C-3′), 83.1 (C-2′), 76.2 (C-4′), 72.9 ($PhCH_2O$), 27.0, 26.3 ($2CH_3$) ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −125.0 (dt, J_1 = 9.2 Hz, J_2 = 4.1 Hz) ppm; HRMS (ESI) calcd for $C_{21}H_{21}FNO_4$ $[M + H]^+$ 370.1455, found 370.1452.

*4S-4-C-(Indol-2-yl)-3-O-benzyl-1,2-O-isopropylidene-α-L-threofuranoside (**3eb**).* Pale yellow oil, 196 mg, 77% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −31.0° (*c* 0.52, $CHCl_3$); IR (KBr) 3395, 3055, 2940, 1646, 1597, 1561, 1523, 1492, 1374, 1214, 1086, 803 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.76 (s, 1H), 7.62 (d, 1H, *J* = 7.6 Hz), 7.31−6.39 (m, 8H), 6.54 (s, 1H), 6.08 (d, 1H, *J* = 3.2 Hz), 5.42 (br s, 1H), 4.76 (s, 1H, *J* = 3.2 Hz), 4.42 (d, 1H, *J* = 11.2 Hz), 4.20 (d, 1H, *J* = 11.2 Hz), 4.08 (d, 1H, *J* = 2.0 Hz), 1.60, 1.38 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.0, 136.5, 132.4, 128.6, 128.2, 128.0, 127.7, 122.2, 120.8, 119.7, 112.0, 115.2, 104.7, 102.4, 84.3, 83.2, 76.4, 72.9, 27.0, 26.3 ppm; HRMS (ESI) calcd for $C_{21}H_{22}NO_4$ $[M + H]^+$ 352.1549, found 352.1547.

*5R-5-C-(Indol-2-yl)-1,2:3,4-di-O-isopropylidene-β-L-arabinopyranose (**3fa**).* Pale yellow oil, 198 mg, 82% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −123.0° (*c* 0.50, $CHCl_3$); IR (KBr) 3473, 3030, 2927, 1619, 1601, 1558, 1498, 1458, 1381, 1260, 1093, 800 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.79 (s, 1H,NH), 7.58 (d, 1H, $J_{4,5}$ = 7.6 Hz, H-4), 7.37 (d, 1H, $J_{7,6}$ = 7.6 Hz, H-7), 7.17 (t, 1H, $J_{6,5}$ = $J_{6,7}$ = 7.6 Hz, H-6), 7.08 (t, 1H, $J_{5,4}$ = $J_{5,6}$ = 7.6 Hz, H-5), 6.48 (s, 1H, H-3), 5.66 (d, 1H, $J_{1',2'}$ = 4.8 Hz, H-1′), 5.11 (s, 1H, H-5′), 4.73 (d, 1H, $J_{3',4'}$ = 7.6 Hz, H-3′), 4.52 (d, 1H, $J_{4',3'}$ = 7.6 Hz, H-4′), 4.39 (br d, 1H, H-2′), 1.63, 1.59, 1.39, 1.38 (4s, each 3H, 4 CH_3) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.2 (C-7a), 134.6 (C-2), 127.8 (C-3a), 122.1 (C-6), 120.8 (C-4), 119.7 (C-5), 111.3 (C-7), 109.6, 108.9 (2 isopropylidene-C), 101.7 (C-3), 96.8 (C-1′), 73.8 (C-4′), 71.1 (C-3′), 70.9 (C-2′), 64.4 (C-5′), 26.4, 26.2, 25.1, 24.1 (4 CH_3) ppm; HRMS (ESI) calcd for $C_{19}H_{24}NO_5$ $[M + H]^+$ 346.1654, found 346.1652.

*5R-5-C-(5-Methylindol-2-yl)-1,2:3,4-di-O-isopropylidene-β-L-arabinopyranose (**3fb**).* Pale yellow oil, 213 mg, 85% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −168.0° (*c* 0.46, $CHCl_3$); IR (KBr) 3454, 3024, 2926, 1613, 1588, 1568, 1464, 1456, 1380, 1212, 1068, 800 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.69 (s, 1H), 7.36 (d, 1H), 7.25 (d, 1H, *J* = 8.8 Hz), 6.99 (d, 1H, *J* = 8.8 Hz), 6.39 (s, 1H), 5.65 (d, 1H, *J* = 4.8 Hz), 5.08 (s, 1H), 4.72 (d, 1H, *J* = 8.0 Hz), 4.50 (d, 1H, *J* = 8.0 Hz), 4.38 (d, 1H, *J* = 4.8 Hz), 2.43 (s, 3H), 1.63, 1.58, 1.39, 1.37 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 134.7, 134.6, 128.8, 128.0, 123.8, 120.4, 110.9, 109.5, 108,9, 101.3, 96.8, 73.8, 71.1, 70.9, 64.4, 26.5, 26.2, 25.1, 24.1, 21.6 ppm; HRMS (ESI) calcd for $C_{20}H_{26}NO_5$ $[M + H]^+$ 360.1811, found 360.1814.

*5R-5-C-(5-Fluoroindol-2-yl)-1,2:3,4-di-O-isopropylidene-β-L-arabinopyranose (**3fc**).* Pale yellow oil, 203 mg, 80% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −131.2° (*c* 1.39, $CHCl_3$); IR (KBr) 3472, 3032, 2929, 1623, 1589, 1548, 1487, 1456, 1380, 1212, 1070, 800 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.82 (s, 1H), 7.29−7.22 (m, 2H), 6.95−6.90 (m, 1H), 6.45 (s, 1H), 5.67 (d, 1H, *J* = 4.8 Hz), 5.10 (br s, 1H), 4.74 (dd, 1H, *J* = 2.2 Hz, *J* = 8.0 Hz), 4.51 (dd, 1H, *J* = 1.2 Hz, *J* = 8.0 Hz), 4.41 (dd, 1H, *J* = 4.8 Hz, *J* = 2.2 Hz), 1.63, 1.58, 1.40, 1.38 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.9 (d, $^1J_{C\text{-}F}$ = 233.0 Hz), 136.4, 133.0, 128.0 (d, $^3J_{C\text{-}F}$ = 10.0 Hz), 111.8 (d, $^3J_{C\text{-}F}$ = 9.0 Hz), 110.5 (d, $^2J_{C\text{-}F}$ = 26.0 Hz), 109.6, 109.0, 105.4 (d, $^2J_{C\text{-}F}$ = 23.0 Hz), 101.6 (d, $^4J_{C\text{-}F}$ = 5.0 Hz), 96.8, 73.6, 71.0, 70.8, 64.3, 26.4, 26.1, 25.0, 24.0 ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −125.0 (dt, J_1 = 9.3 Hz, J_2 = 4.1 Hz) ppm; HRMS (ESI) calcd for $C_{19}H_{23}FNO_5$ $[M + H]^+$ 364.1560, found 364.1563.

*5R-5-C-(5-Chloroindol-2-yl)-1,2:3,4-di-O-isopropylidene-β-L-arabinopyranose (**3fd**).* Brown oil, 223 mg, 84% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −174.4° (*c* 0.83, $CHCl_3$); IR (KBr) 3458, 3054, 2929, 1613, 1580, 1553, 1482, 1463, 1381, 1212, 1069, 801 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.82 (s, 1H), 7.52 (d, 1H, *J* = 1.4 Hz), 7.25 (d, 1H, *J* = 8.8 Hz), 7.09 (dd, 1H, *J* = 2.0 Hz, *J* = 8.8 Hz), 6.40 (s, 1H), 5.63 (d, 1H, *J* = 4.8 Hz), 5.06 (s, 1H), 4.70 (dd, 1H, *J* = 2.1 Hz, *J* = 8.0 Hz), 4.48 (dd, 1H, *J* = 8.0 Hz, *J* = 1.6 Hz), 4.38 (dd, 1H, *J* = 4.8 Hz, *J* = 2.1 Hz), 1.60, 1.55, 1.36, 1.35 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.1, 134.5, 128.8, 125.3, 122.4, 120.0, 112.2, 109.6, 109.0, 101.2, 96.8, 73.5, 71.0, 70.8, 64.3, 26.4, 26.2, 25.0, 24.0 ppm; HRMS (ESI) calcd for $C_{19}H_{23}ClNO_5$ $[M + H]^+$ 380.1265, found 380.1268.

*5R-5-C-(5-Bromoindol-2-yl)-1,2:3,4-di-O-isopropylidene-β-L-arabinopyranose (**3fe**).* Yellow oil, 258 mg, 87% yield; R_f = 0.6 (silica gel F_{254}, 3:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −137.8° (*c* 0.54, $CHCl_3$); IR (KBr) 3452, 3058, 2928, 1649, 1577, 1542, 1486, 1460, 1380, 1211, 1070, 804 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.83 (s, 1H), 7.69 (s, 1H), 7.31−7.24 (m, 2H), 6.41 (s, 1H), 5.65 (d, 1H, *J* = 4.8 Hz), 5.08 (s, 1H), 4.72 (d, 1H, *J* = 7.8 Hz), 4.50 (d, 1H, *J* = 7.8 Hz), 4.40 (d, 1H, *J* = 4.8 Hz), 1.62, 1.57, 1.38, 1.37 (4s, each 3H) ppm; ^{13}C NMR (100

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MHz, $CDCl_3$) δ 136.0, 134.8, 129.6, 125.0, 123.2, 112.9, 112.7, 109.7, 109.0, 101.1, 96.8, 73.6, 71.0, 70.9, 64.3, 26.4, 26.2, 25.0, 24.1 ppm; HRMS (ESI) calcd for $C_{19}H_{23}BrNO_5$ $[M + H]^+$ 424.0760, found 424.0763.

*1-C-(Indol-2-yl)-1,2:3,4-di-O-isopropylidene-β-D-arabinopyranose (**3ga**).* Brown oil, 198 mg, 82% yield; R_f = 0.6 (silica gel F_{254}, 2:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −26.2° (*c* 1.74, $CHCl_3$); IR (KBr) 3433, 3061, 2925, 1625, 1598, 1561, 1494, 1456, 1379, 1079, 1026, 801 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.82 (s, 1H, NH), 7.62 (d, 1H, J = 7.6 Hz, H-4), 7.33 (d, 1H, $J_{7,6}$ = 7.8 Hz, H-7), 7.19 (dt, 1H, $J_{6,4}$ = 1.0 Hz, $J_{6,5}$ = $J_{6,7}$ = 7.8 Hz, H-6), 7.10 (t, 1H, J = 7.8 Hz, H-5), 6.67 (s, 1H, H-3), 4.73 (dd, 1H, $J_{3',2'}$ = 2.7 Hz, $J_{3',4'}$ = 8.0 Hz, H-3′), 4.54 (d, 1H, $J_{2',3'}$ = 2.7 Hz, H-2′), 4.35 (dd, 1H, $J_{4',5'a}$ = 1.8 Hz , $J_{4',3'}$ = 8.0 Hz, H-4′), 4.05 (dd, 1H, $J_{5'a,4'}$ = 1.8 Hz, $J_{5'a,5'b}$ = 13.2 Hz, H-5′a), 3.87 (d, 1H, $J_{5'b,5'a}$ = 13.2 Hz, H-5′b), 1.69, 1.67, 1.45, 1.44 (4s, each 3H, 4CH_3) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.3 (C-2), 136.0 (C-7a), 127.7 (C-3a), 122.3 (C-6), 121.1 (C-4), 119.8 (C-5), 111.1 (C-7), 109.4 (2 isopropylidene-C), 100.9 (C-1′), 100.3 (C-3), 74.5 (C-2′), 70.7 (C-4′), 70.4 (C-3′), 61.7 (C-5′), 26.1, 26.0, 24.8, 24.3 (4CH_3) ppm; HRMS (ESI) calcd for $C_{19}H_{24}NO_5$ $[M + H]^+$ 346.1654, found 346.1653.

*1-C-(5-Methylindol-2-yl)-1,2:3,4-di-O-isopropylidene-β-D-arabinopyranose (**3gb**).* Brown oil, 221 mg, 88% yield; R_f = 0.6 (silica gel F_{254}, 2:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −18.6° (*c* 0.53, $CHCl_3$); IR (KBr) 3414, 3021, 2926, 1621, 1585, 1564, 1487, 1458, 1379, 1211, 1067, 799 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.68 (s, 1H), 7.39 (s, 1H), 7.20 (d, 1H, J = 7.8 Hz), 7.50 (d, 1H, J = 7.8 Hz), 6.56 (s, 1H), 4.71 (d, 1H, J = 7.8 Hz), 4.51 (s, 1H), 4.33 (d, 1H, J = 7.8 Hz), 4.03 (d, 1H, J = 13.4 Hz), 3.85 (d, 1H, J = 13.4 Hz), 2.43 (s, 3H), 1.67, 1.65, 1.44, 1.42 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 138.4, 134.4, 129.0, 128.0, 124.0, 120.8, 110.8, 109.5, 109.4, 101.0, 100.0, 74.6, 70.8, 70.5, 61.7, 26.1, 24.8, 24.3, 21.5 ppm; HRMS (ESI) calcd for $C_{20}H_{26}NO_5$ $[M + H]^+$ 360.1811, found 360.1810.

*1-C-(5-Fluoroindol-2-yl)-1,2:3,4-di-O-isopropylidene-β-D-arabinopyranose (**3gc**).* Pale yellow oil, 203 mg, 80% yield; R_f = 0.6 (silica gel F_{254}, 2:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −30.1° (*c* 0.56, $CHCl_3$); IR (KBr) 3391, 3068, 2926, 1619, 1589, 1592, 1548, 1454, 1209, 1069, 801 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.81 (s, 1H), 7.24−7.21 (m, 2H), 6.95−6.90 (m, 1H), 6.62 (s, 1H), 4.73 (dd, 1H, J = 2.8 Hz, J = 8.0 Hz), 4.51 (d, 1H, J = 2.8 Hz), 4.34 (br d, J = 7.6 Hz), 4.04 (dd, 1H, J = 1.6 Hz, J = 13.2 Hz), 3.86 (d, 1H, J = 13.2 Hz), 1.67, 1.66, 1.44. 1.43 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.0 (d, $^1J_{C\text{-}F}$ = 232.6 Hz), 140.1, 132.6, 128.1 (d, $^3J_{C\text{-}F}$ = 10.2 Hz), 111.7 (d, $^3J_{C\text{-}F}$ = 9.5 Hz), 110.8 (d, $^2J_{C\text{-}F}$ = 26.2 Hz), 109.6, 109.5, 105.9 (d, $^2J_{C\text{-}F}$ = 23.2 Hz), 100.8, 100.5 ($^4J_{C\text{-}F}$ = 4.7 Hz), 74.6, 70.8, 70.4, 61.8, 26.1, 24.9, 24.3 ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −124.8 (dt, J_1 = 9.3 Hz, J_2 = 4.5 Hz) ppm; HRMS (ESI) calcd for $C_{19}H_{23}FNO_5$ $[M + H]^+$ 364.1560, found 364.1559.

*1-C-(5-Chloroindol-2-yl)-1,2:3,4-di-O-isopropylidene-β-D-arabinopyranose (**3gd**).* Brown oil, 225 mg, 85% yield; R_f = 0.6 (silica gel F_{254}, 2:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −26.6° (*c* 0.45, $CHCl_3$); IR (KBr) 3383, 3067, 2927, 1628, 1599, 1549, 1515, 1463, 1379, 1212, 1067, 798 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.88 (s, 1H), 7.61 (s, 1H), 7.29 (d, 1H, J = 8.7 Hz), 7.17 (dd, 1H, J = 1.6 Hz, J = 8.7 Hz), 6.64 (s, 1H), 4.77 (dd, 1H, J = 2.4 Hz, J = 7.4 Hz), 4.55 (d, 1H, J = 2.4 Hz), 4.38 (d, 1H, J = 7.4 Hz), 4.08 (dd, 1H, J = 0.9 Hz, J = 12.8 Hz), 3.90 (d, 1H, J = 12.8 Hz), 1.71, 1.70, 1.49, 1.47 (4 s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.8, 134.4, 128.8, 125.5, 122.8, 120.6, 112.2, 109.7, 109.5, 100.8, 100.1, 74.6, 70.8, 70.4, 61.8, 26.1, 24.9, 24.3 ppm; HRMS (ESI) calcd for $C_{19}H_{23}ClNO_5$ $[M + H]^+$ 380.1265, found 380.1264.

*1-C-(5-Bromoindol-2-yl)-1,2:3,4-di-O-isopropylidene-β-D-arabinopyranose (**3ge**).* Brown oil, 252 mg, 85% yield; R_f = 0.6 (silica gel F_{254}, 2:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −21.5° (*c* 0.66, $CHCl_3$); IR (KBr) 3396, 3061, 2927, 1629, 1586, 1564, 1496, 1462, 1379, 1212, 1068, 798 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.84 (s, 1H), 7.72 (s, 1H), 7.25 (dd, 1H, J = 1.6 Hz, J = 8.6 Hz), 7.18 (d, 1H, J = 8.6 Hz), 6.59 (s, 1H), 4.72 (dd, 1H, J = 2.7 Hz, J = 7.6 Hz), 4.50 (d, 1H, J = 2.7 Hz), 4.34 (dd, 1H, J = 1.8 Hz, J = 7.6 Hz), 4.03 (dd, 1H, J = 1.8 Hz, J = 13.2 Hz), 3.85 (d, 1H, J = 13.2 Hz), 1.66, 1.65, 1.44, 1.42 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.6, 134.7, 129.5, 125.3, 123.7, 113.0, 112.6, 109.7, 109.5, 100.7, 99.9, 74.5, 70.7, 70.4, 61.8, 26.1, 24.8, 24.3 ppm; HRMS (ESI) calcd for $C_{19}H_{23}BrNO_5$ $[M + H]^+$ 424.0760, found 424.0761.

*1R-1-C-(Indol-2-yl)-1,2-O-isopropylidene-4-O-trityl-D-erythritol (**3ha**).* Yellow oil, 316 mg, 87% yield; R_f = 0.6 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = +9.1° (*c* 0.48, $CHCl_3$); IR (KBr) 3460, 3046, 2926, 1624, 1605, 1572, 1490, 1449, 1377, 1210, 1023, 801 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.68 (s, 1H, NH), 7.55 (d, 1H, J = 8.0 Hz, H-4), 7.45−7.20 (m, 16H, Ar*H*, H-7), 7.14 (t, 1H, J = 7.2 Hz, H-6), 7.07 (t, 1H, J = 7.2 Hz, H-5), 6.42 (s, 1H, H-3), 5.20 (d, 1H, $J_{1',2'}$ = 7.2 Hz, H-1′), 4.05 (t, 1H, $J_{2',3'}$ = $J_{2',1'}$ = 7.2 Hz, H-2′), 3.98−3.94 (m, 1H, H-3′), 3.40 (dd, 1H, $J_{4'a,3'}$ = 3.6 Hz, $J_{4'a\ 4'b}$ = 10.0 Hz, H-4′a), 3.30 (dd, 1H, $J_{4'b,3'}$ = 7.2 Hz, $J_{4'b,\ 4'a}$ = 9.6 Hz, H-4′b), 1.46, 1.44 (2s, each 3H, 2CH_3) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.7 (ArC), 137.4 (C-2), 136.2 (C-7a), 128.7, 128.1, 127.4 (ArC), 127.0 (C-3a), 121.8 (C-6), 120.6 (C-4), 119.8 (C-5), 111.0 (C-7), 110.2 (isopropylidene-C), 99.7 (C-3), 87.4 (ph_3C−O), 81.0 (C-2′), 75.9 (C-1′), 72.4 (C-3′), 65.2 (C-4′), 27.0, 26.6 (2CH_3) ppm; HRMS (ESI) calcd for $C_{34}H_{34}NO_4$ $[M + H]^+$ 520.2488, found 520.2487.

*1R-1-C-(5-Methylindol-2-yl)-1,2-O-isopropylidene-4-O-trityl-D-erythritol (**3hb**).* Pale yellow oil, 336 mg, 90% yield; R_f = 0.5 (silica gel F_{254}, 2:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −2.0° (*c* 0.50, $CHCl_3$); IR (KBr) 3422, 3012, 2924, 1628, 1598, 1542, 1489, 1453, 1380, 1095, 1025, 802 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.69 (s, 1H), 7.42−7.06 (m, 18H), 6.43 (s, 1H), 5.21 (d, 1H, J = 7.2 Hz), 4.05 (t, 1H, J = 7.2 Hz), 3.98−3.94 (m, 1H), 3.40 (dd, 1H, J = 3.6 Hz, J = 10.0 Hz), 3.30 (dd, 1H, J = 6.8 Hz, J = 10.0 Hz), 2.45 (s, 3H), 1.46, 1.45 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.5, 137.3, 134.4, 128.7, 128.5, 127.9, 127.2, 127.8, 123.2, 120.1, 110.4, 109.9, 99.0 (C-3), 87.2, 80.8, 75.7, 72.2, 65.0, 26.8, 26.4, 21.4 ppm; HRMS (ESI) calcd for $C_{35}H_{36}NO_4$ $[M + H]^+$ 534.2644, found 534.2643.

*1R-1-C-(5-fluoroindol-2-yl)-1,2-O-isopropylidene-4-O-trityl-D-erythritol (**3hc**).* Pale yellow oil, 312 mg, 83% yield; R_f = 0.5 (silica gel F_{254}, 2:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −5.0° (*c* 0.50, $CHCl_3$); IR (KBr) 3398, 3021, 2924, 1627, 1593, 1548, 1489, 1449, 1260, 1095, 801 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.70 (s, 1H), 7.41−6.85 (m, 18H), 6.38 (s, 1H), 5.18 (d, 1H, J = 7.2 Hz), 4.02 (t, 1H, J = 7.2 Hz), 3.95 (d, 1H, J = 3.4 Hz), 3.41 (dd, 1H, J = 3.4 Hz, J = 9.6 Hz), 3.29 (dd, 1H, J = 7.0 Hz, J = 9.6 Hz), 1.46, 1.44 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.0 (d, $^1J_{C\text{-}F}$ = 232.4 Hz), 143.6, 139.4, 132.7, 128.7, 128.1, 128.0 (d, $^3J_{C\text{-}F}$ = 7.8 Hz), 127.4, 111.5 (d, $^3J_{C\text{-}F}$ = 9.5 Hz), 110.3, 110.0 (d, $^2J_{C\text{-}F}$ = 26.2 Hz), 105.4 (d, $^2J_{C\text{-}F}$ = 23.2 Hz), 99.8 (d, $^4J_{C\text{-}F}$ = 4.4 Hz), 87.4, 81.0, 75.9, 72.4, 65.3, 26.9, 26.6 ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −125.0 (dt, J_1 = 9.3 Hz, J_2 = 4.1 Hz) ppm; HRMS (ESI) calcd for $C_{34}H_{33}FNO_4$ $[M + H]^+$ 538.2394, found 538.2396.

*1R-1-C-(5-Chloroindol-2-yl)-1,2-O-isopropylidene-4-O-trityl-D-erythritol (**3hd**).* Pale yellow oil, 345 mg, 89% yield; R_f = 0.5 (silica gel F_{254}, 2:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −8.5° (*c* 0.50, $CHCl_3$); IR (KBr) 3396, 3020, 2923, 1626, 1591, 1546, 1484, 1447, 1262, 1097, 800 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.77 (s, 1H), 7.33−6.97 (m, 18H), 6.28 (s, 1H), 5.09(d, 1H, J = 7.2 Hz), 3.94 (t, 1H, J = 7.2 Hz), 3.87−3.82 (m, 1H), 3.29 (dd, 1H, J = 3.6 Hz, J = 10.0 Hz), 3.18 (dd, 1H, J = 7.2 Hz, J = 9.6 Hz), 1.35, 1.33 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.6, 139.1, 134.3, 129.4, 128.7, 128.1, 127.9, 127.4, 122.0, 119.9, 112.0, 110.3, 99.2, 87.4, 80.9, 75.9, 72.4, 65.3, 26.9, 26.5 ppm; HRMS (ESI) calcd for $C_{34}H_{33}ClNO_4$ $[M + H]^+$ 554.2098, found 554.2099.

*1R-1-C-(5-Bromoindol-2-yl)-1,2-O-isopropylidene-4-O-trityl-D-erythritol (**3he**).* Pale yellow oil, 364 mg, 87% yield; R_f = 0.5 (silica gel F_{254}, 2:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −10.8° (*c* 0.50, $CHCl_3$); IR (KBr) 3392, 3018, 2921, 1623, 1590, 1543, 1482, 1448, 1260, 1090, 800 cm^{-1}; ^1H NMR (400 MHz, DMSO) δ 11.29 (s, 1H), 7.64 (s, 1H), 7.33−7.18 (m, 17H), 6.35 (s, 1H), 5.36 (d, 1H, J = 6.0 Hz), 4.25 (t, 1H, J = 6.0 Hz), 3.91−3.88 (m, 1H), 2.98 (dd, 1H, J = 8.0 Hz, J = 16.0 Hz), 2.89 (dd, 1H, J = 4.4 Hz, J = 4.8 Hz), 1.39, 1.34 (2s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.8, 138.3, 135.2, 129.4, 128.3, 127.7, 126.9, 123.6, 122.2, 113.3, 111.4, 108.9, 100.1, 86.0, 80.9,

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73.2, 69.8, 65.4, 27.0, 26.9 ppm; HRMS (ESI) calcd for $C_{34}H_{33}BrNO_4$ $[M + H]^+$ 598.1593, found 598.1595.

*1R-1-C-(Indol-2-yl)-1,2:4,5-di-O-isopropylidene-D-arabinitol (**3ia**).* Pale yellow oil, 213 mg, 88% yield; R_f = 0.6 (silica gel F_{254}, 1:1, petroleum ether/EtOAc). $[\alpha]^{20}_D$ = −6° (*c* 0.50, $CHCl_3$); IR (KBr) 3420, 3058, 2925, 1627, 1582, 1553, 1501, 1460, 1380, 1217, 1095, 801 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.48 (s, 1H, NH), 7.58 (d, 1H, $J_{4,5}$ = 7.6 Hz, H-4), 7.38 (d, $J_{7,6}$ = 8.0 Hz, H-7), 7.19 (t, 1H, $J_{5,4}$ = $J_{5,6}$ = 7.6 Hz, H-6), 7.10 (t, 1H, $J_{6,5}$ = $J_{6,7}$ = 7.6 Hz, H-5), 6.48 (s, 1H, H-3), 5.26 (d, 1H, $J_{1',2'}$ = 8.0 Hz, H-1′), 4.24 (dd, 1H, $J_{2',3'}$ = 1.6 Hz, $J_{2',1'}$ = 8.0 Hz, H-2′), 4.12−4.02 (m, 3H, H-4′, H-5′), 3.62−3.60 (m, 1H, H-3′), 1.56, 1.54, 1.34, 1.31 (4s, each 3H, 4 CH_3) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.2 (C-7a), 135.0 (C-2), 128.4 (C-3a), 122.3 (C-6), 120.8 (C-4), 120.1 (C-5), 111.1 (C-7), 110.2, 109.7 (2 isopropylidene-C), 100.6 (C-3), 80.6 (C-2′), 76.5 (C-4′), 73.7 (C-1′), 70.0 (C-3′), 67.1 (C-5′), 27.3, 27.1, 26.8, 25.4 (4 CH_3) ppm; HRMS (ESI) calcd for $C_{19}H_{25}NO_5$ $[M + H]^+$ 347.1733, found 347.1734.

*1R-1-C-(5-Methylindol-2-yl)-1,2:4,5-di-O-isopropylidene-D-arabinitol (**3ib**).* Brown oil, 227 mg, 90% yield; R_f = 0.5 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −5.6° (*c* 0.48, $CHCl_3$); IR (KBr) 3420, 3064, 2987, 1625, 1597, 1558, 1482, 1456, 1372, 1260, 1060, 800 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.42 (s, 1H), 7.36 (s, 1H), 7.23 (d, 1H, *J* = 8.8 Hz), 7.01 (dd, 1H, *J* = 8.4 Hz, *J* = 1.2 Hz), 6.40 (s, 1H), 5.24 (d, 1H, *J* = 8.4 Hz), 4.24 (dd, 1H, *J* = 2.0 Hz, *J* = 8.4 Hz), 4.07−4.04 (m, 3H), 3.60 (dd, 1H, *J* = 2.0 Hz, *J* = 7.6 Hz), 2.44 (s, 3H), 1.56, 1.54, 1.34, 1.32 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 135.0, 134.6, 129.3, 128.7, 123.9, 120.4, 110.7, 110.1, 109.7, 100.2, 80.5, 76.5, 73.7, 70.0, 67.0, 27.3, 27.0, 26.8, 25.4, 21.5 ppm; HRMS (ESI) calcd for $C_{20}H_{27}NO_5$[M + H]$^+$ 361.1889, found 361.1888.

*1R-1-C-(5-Fluoroindol-2-yl)-1,2:4,5-di-O-isopropylidene-D-arabinitol (**3ic**).* Pale yellow oil, 219 mg, 86% yield; R_f = 0.5 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −1.5° (*c* 0.50, $CHCl_3$); IR (KBr) 3418, 3015, 2925, 1615, 1582, 1553, 1487, 1457, 1378, 1217, 1086, 803 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.51 (s, 1H), 7.22−7.20 (m, 2H), 6.95−6.90 (m, 1H), 6.43 (s, 1H), 5.23 (d, 1H, *J* = 8.0 Hz), 4.21 (dd, 1H, *J* = 2.0 Hz, *J* = 8.0 Hz), 4.11−4.05 (m, 3H), 3.59 (dd, 1H, *J* = 2.0 Hz, *J* = 6.8), 1.56, 1.54, 1.34, 1.31 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.1 (d, $^1J_{C\text{-}F}$ = 233.0 Hz), 137.0, 132.7, 128.8 (d, $^3J_{C\text{-}F}$ = 10.2 Hz), 111.6 (d, $^3J_{C\text{-}F}$ = 9.6 Hz), 110.7 ($^2J_{C\text{-}F}$ = 26.3 Hz), 110.3, 109.7, 105.5 (d, $^2J_{C\text{-}F}$ = 23.5 Hz), 100.6 (d, $^4J_{C\text{-}F}$ = 4.6 Hz,), 80.7, 76.5, 73.6, 70.1, 67.1, 27.3, 27.1, 26.9, 25.5 ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −125.1 (dt, J_1 = 9.3 Hz, J_2 = 4.5 Hz) ppm; HRMS (ESI) calcd for $C_{19}H_{24}FNO_5$ $[M + H]^+$ 365.1639, found 365.1640.

*1R-1-C-(6-Fluoroindol-2-yl)-1,2:4,5-di-O-isopropylidene-D-arabinitol (**3id**).* Pale yellow oil, 214 mg, 84% yield; R_f = 0.6 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −17.6° (*c* 0.42, $CHCl_3$); IR (KBr) 3362, 3061, 2926, 1627, 1599, 1560, 1499, 1457, 1377, 1221, 1063, 809 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.59 (s, 1H), 7.49 (dd, 1H, *J* = 5.6 Hz, *J* = 8.4 Hz), 7.05 (dd, 1H, *J* = 2.0 Hz, $J_{H,F}$ = 9.5 Hz), 6.91−6.86 (m, 1H), 6.47 (s, 1H), 5.24 (d, 1H, *J* = 8.0 Hz), 4.25 (dd, 1H, *J* = 2.0 Hz, *J* = 8.0 Hz), 4.14−4.05 (m, 3H), 3.61 (br d, 1H, *J* = 6.4 Hz), 1.58, 1.56, 1.36, 1.32 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.0 ($^1J_{C\text{-}F}$ = 236.4 Hz), 136.2 (d, $^3J_{C\text{-}F}$ = 12.4 Hz), 135.3, 124.8, 121.4 (d, $^3J_{C\text{-}F}$ = 10.1 Hz), 110.2, 109.7, 108.8 (d, $^2J_{C\text{-}F}$ = 24.2 Hz), 100.7, 97.5 (d, $^2J_{C\text{-}F}$ = 26.0 Hz), 80.4, 76.5, 73.5, 69.9, 67.1, 27.3, 27.0, 26.8, 25.4 ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −120.6 (dt, J_1 = 9.5 Hz, J_2 = 5.6 Hz) ppm; HRMS (ESI) calcd for $C_{19}H_{24}FNO_5$ $[M + H]^+$ 365.1639, found 365.1638.

*1R-1-C-(5-Chloroindol-2-yl)-1,2:4,5-di-O-isopropylidene-D-arabinitol (**3ie**).* Brown oil, 227 mg, 85% yield; R_f = 0.6 (silica gel F_{254}, 1:1, petroleum ether/EtOAc). $[\alpha]^{20}_D$ = −12.7° (*c* 0.50, $CHCl_3$); IR (KBr) 3420, 3053, 2959, 1624, 1581, 1510, 1462, 1378, 1217, 1061, 799 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.57 (s, 1H), 7.53 (s, 1H), 7.29 (d, 1H, *J* = 8.0 Hz), 7.13 (d, 1H, *J* = 8.0 Hz), 6.41 (s, 1H), 5.24 (d, 1H, *J* = 8.4 Hz), 4.21 (dd, 1H, *J* = 1.6 Hz, *J* = 8.4 Hz), 4.08−4.04 (m, 3H), 3.60−3.57 (m, 1H), 1.55, 1.54, 1.34, 1.30 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.0, 134.8, 129.8, 126.1, 123.0, 120.5, 112.4, 110.7, 110.1, 110.4, 81.0, 76.8, 73.8, 70.4, 67.4, 27.6, 27.3, 27.2, 25.8 ppm; HRMS (ESI) calcd for $C_{19}H_{24}ClNO_5$ $[M + H]^+$ 381.1343, found 381.1345.

*1R-1-C-(6-Choroindol-2-yl)-1,2:4,5-di-O-isopropylidene-D-arabinitol (**3if**).* Pale yellow oil, 240 mg, 90% yield; R_f = 0.6 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −25.3° (*c* 0.52, $CHCl_3$); IR (KBr) 3362, 3063, 2928, 1616, 1598, 1576, 1506, 1456, 1377, 1217, 1061, 814 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.66 (s, 1H), 7.46 (d, 1H, *J* = 8.4 Hz), 7.33 (s, 1H), 7.06 (dd, 1H, *J* = 8.4 Hz, *J* = 1.6 Hz), 6.44 (s, 1H), 5.23 (d, 1H, *J* = 8.4 Hz), 4.22 (dd, 1H, *J* = 2.4 Hz, *J* = 8.4 Hz), 4.10−4.05 (m, 3H), 3.59 (br s, lH), 1.55, 1.53, 1.34, 1.30 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.5, 135.9, 128.0, 126.9, 121.5, 120.8, 111.0, 110.3, 109.7, 100.6, 80.6, 76.4, 73.5, 70.0, 67.0, 27.2, 27.0, 26.8, 25.4 ppm; HRMS (ESI) calcd for $C_{19}H_{24}ClNO_5$ $[M + H]^+$ 381.1343, found 381.1344.

*1R-1-C-(5-Bromoindol-2-yl)-1,2:4,5-di-O-isopropylidene-D-arabinitol (**3ig**).* Brown oil, 262 mg, 88% yield; R_f = 0.6 (silica gel F_{254}, 1:1, petroleum ether/EtOAc); $[\alpha]^{20}_D$ = −30.5° (*c* 0.54, $CHCl_3$); IR (KBr) 3360, 3061, 2925, 1612, 1596, 1573, 1501, 1451, 1378, 1213, 1060, 810 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.58 (s, 1H), 7.70 (s, 1H), 7.28−7.20 (m, 2H), 6.41 (s, 1H), 5.23 (d, 1H, *J* = 8.4 Hz), 4.21 (dd, 1H, *J* = 2.0 Hz, *J* = 8.4 Hz), 4.15−4.02 (m, 3H), 3.59 (dd, 1H, *J* = 2.0 Hz, *J* = 7.6 Hz), 1.56, 1.54, 1.35, 1.31 (4s, each 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 136.5, 134.7, 130.2, 125.2, 123.2, 113.3, 112.5, 110.4, 109.8, 100.0, 80.7, 76.4, 73.4, 70.1, 67.1, 27.3, 27.0, 26.9, 25.4 ppm; HRMS (ESI) calcd for $C_{19}H_{24}BrNO_5$ $[M + H]^+$ 425.0838, found 425. 0839.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Copies of ^1H NMR, ^{13}C NMR, ^{19}F NMR, DEPT-135, and 2D NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Selected examples: (a) Guckian, K. M.; Krugh, T. R.; Kool, E. T. *J. Am. Chem. Soc.* **2000**, *122*, 6841. (b) Wu, Y. Q.; Ogawa, A. K.; Berger, M.; Mcminn, D. L.; Schultz, P. G.; Romesberg, F. E. *J. Am. Chem. Soc.* **2000**, *122*, 7621. (c) Ogawa, A. K.; Abou-Zied, O. K.; Tsui, V.; Jimenez, R.; Case, D. A.; Romesberg, F. E. *J. Am. Chem. Soc.* **2000**, *122*, 9917. (d) Kool, E. T. *Acc. Chem. Res.* **2002**, *35*, 936. (e) Lai, J. S.; Qu, J.; Kool, E. T. *Angew. Chem., Int. Ed.* **2003**, *42*, 5973. (f) Henry, A. A.; Yu, C. Z.; Romesberg, F. E. *J. Am. Chem. Soc.* **2003**, *125*, 9638. (g) Lai, J. S.; Kool, E. T. *J. Am. Chem. Soc.* **2004**, *126*, 3040. (h) Kim, Y.; Leconte, A. M.; Hari, Y.; Romesberg, F. E. *Angew. Chem., Int. Ed.* **2006**, *45*, 7809. (i) Matsuda, S.; Leconte, A. M.; Romesberg, F. E. *J. Am. Chem. Soc.* **2007**, *129*, 5551.

(2) (a) Yokoyama, M.; Toyoshima, H.; Shimizu, M.; Togo, H. *J. Chem. Soc., Perkin Trans. 1* **1997**, 29. (b) Girgis, N. S.; Cottam, H. B.; Robins, R. L. *J. Heterocycl. Chem.* **1988**, *25*, 361. (c) Matsuda, S.; Henry, A. A.; Schultz, P. G.; Romesberg, F. E. *J. Am. Chem. Soc.* **2003**, *125*, 6134. (d) Zhang, X.; Lee, I.; Berdis, A. J. *Org. Biomol. Chem.* **2004**, *2*, 1703.

(3) (a) Rajski, S. R.; Kumar, S.; Roberts, R. J.; Barton, J. K. *J. Am. Chem. Soc.* **1999**, *121*, 5615. (b) Wagenknecht, H. A.; Stemp, E. D. A.;

Barton, J. K. *J. Am. Chem. Soc.* **2000**, *122*, 1. (c) Wagenknecht, H. A.; Stemp, E. D. A.; Barton, J. K. *Biochemistry* **2000**, *39*, 5483. (d) Wagenknecht, H. A.; Rajski, S. R.; Pascaly, M.; Stemp, E. D. A.; Barton, J. K. *J. Am. Chem. Soc.* **2001**, *123*, 4400. (e) Mayer-Enthart, E.; Kaden, P.; Wagenknecht, H. A. *Biochemistry* **2005**, *44*, 11749. (f) Valis, L.; Mayer-Enthart, E.; Wagenknecht, H. A. *Bioorg. Med. Chem. Lett.* **2006**, *16*, 3184.

(4) (a) Hofsteenge, J.; Müller, D. R.; Beer, T.; Löffler, A.; Richter, W. J.; Vliegenthart, J. *Biochemistry* **1994**, *33*, 13524. (b) Beer, T.; Vliegenthart, J.; Löffler, A.; Hofsteenge, J. *Biochemistry* **1995**, *34*, 11785.

(5) Wu, Y.; Zhang, Z. X.; Hu, H.; Li, D.; Qiu, G.; Hu, X.; He, X. *Fitoterapia* **2011**, *82*, 288.

(6) Selected examples: (a) Rudisillt, D. E.; Stille, J. K. *J. Org. Chem.* **1989**, *54*, 5856. (b) Cacchi, F. S.; Fabrizi, G.; Parisi, L. M. *Org. Lett.* **2003**, *5*, 3843. (c) Esseveldt, B. C. J.; Delft, F. L.; Gelder, R.; Rutjes, F. P. J. T. *Org. Lett.* **2003**, *5*, 1717. (d) Okuma, K.; Seto, J.-i.; Sakaguchi, K.-i.; Ozaki, S.; Nagahora, N.; Shioji, K. *Tetrahedron Lett.* **2009**, *50*, 2943. (e) Tyrrell, E.; Whiteman, L.; Williams, N. *Synthesis* **2009**, *5*, 829. (f) Lu, B. Z.; Zhao, W.; Wei, H.-X.; Dufour, M.; Farina, V.; Senanayake, C. H. *Org. Lett.* **2006**, *8*, 3271. (g) Hiroya, K.; Itoh, S.; Sakamoto, T. *J. Org. Chem.* **2004**, *69*, 1126. (h) Sakai, N.; Annaka, K.; Konakahara, T. *Org. Lett.* **2004**, *6*, 1527. (i) Sanz, R.; Guilarte, V.; Garcia, N. *Org. Biomol. Chem.* **2010**, *8*, 3860. (j) Sakai, N.; Annaka, K.; Fujita, A.; Sato, A.; Konakahara, T. *J. Org. Chem.* **2008**, *73*, 4160. (k) Yin, Y.; Ma, W.; Chai, Z.; Zhao, G. *J. Org. Chem.* **2007**, *72*, 5731. (l) Liu, F.; Ma, D. *J. Org. Chem.* **2007**, *72*, 4844. (m) Chen, Y.; Xie, X.; Ma, D. *J. Org. Chem.* **2007**, *72*, 9329. (n) Majumdar, K. C.; Samanta, S.; Chattopadhyay, B. *Tetrahedron Lett.* **2008**, *49*, 7213. (o) Sakai, H.; Tsutsumi, K.; Morimoto, T.; Kakiuchi, K. *Adv. Synth. Catal.* **2008**, *350*, 2498. (p) Zhang, Y.; Donahue, J. P.; Li, C.-J. *Org. Lett.* **2007**, *9*, 627. (q) Ragaini, F.; Ventriglia, F.; Hagar, M.; Fantauzzi, S.; Cenini, S. *Eur. J. Org. Chem.* **2009**, 2185. (r) Willis, M. C.; Brace, G. N.; Holmes, I. P. *Angew. Chem.* **2005**, *117*, 407; *Angew. Chem., Int. Ed.* **2005**, *44*, 403. (s) Zhou, L.; Doyle, M. P. *J. Org. Chem.* **2009**, *74*, 9222. (t) Kamijo, S.; Yamamoto, Y. *Angew. Chem.* **2002**, *114*, 3364; *Angew. Chem., Int. Ed.* **2002**, *41*, 3230. (u) Korakas, P.; Chaffee, S.; Shotwell, J. B.; Duque, P.; Wood, J. L. *Proc. Natl. Acad. Sci. U. S. A.* **2004**, *101*, 12054. (v) Hirano, K.; Inaba, Y.; Takahashi, N.; Shimano, M.; Fujii, S. O.; Ohno, H. *J. Org. Chem.* **2011**, *76*, 1212. (w) Zhou, L.; Shi, Y.; Xiao, Q.; Liu, Y.; Ye, F.; Zhang, Y.; Wang, J. *Org. Lett.* **2011**, *13*, 968. (x) Vicente, R. *Org. Biomol. Chem.* **2011**, *9*, 6469. (y) Wei, Y.; Deb, I.; Yoshikai, N. *J. Am. Chem. Soc.* **2012**, *134*, 9098. (z) Subramanian, P.; Kaliappan, K. P. *Eur. J. Org. Chem.* **2013**, 595.

(7) (a) Arcadi, A.; Cacchi, S.; Marinelli, F. *Tetrahedron Lett.* **1989**, *30*, 2581. (b) Ezquerra, J.; Pedregal, C.; Lamas, C.; Barluenga, J.; Pérez, M.; García-Martín, M. A.; González, J. M. *J. Org. Chem.* **1996**, *61*, 5804. (c) Kondo, Y.; Kojima, S.; Sakamoto, T. *J. Org. Chem.* **1997**, *62*, 6507.

(8) (a) Takeda, A.; Kamijo, S.; Yamamoto, Y. *J. Am. Chem. Soc.* **2000**, *122*, 5662. (b) Kamijo, S.; Yammamoto, Y. *J. Org. Chem.* **2003**, *68*, 4764. (c) Kirsch, G.; Hesse, S.; Comel, A. *Curr. Org. Synth.* **2004**, *1*, 47.

(9) (a) Dohle, W.; Knochel, P. *Angew. Chem., Int. Ed.* **2000**, *39*, 2488. (b) Yasuhara, A.; Suzuki, N.; Yoshino, T.; Takeda, Y.; Sakamoto, T. *Tetrahedron Lett.* **2002**, *43*, 6579. (c) Koradin, C.; Dohle, W.; Rodriguez, A. L.; Schmid, B.; Knochel, P. *Tetrahedron* **2003**, *59*, 1571.

(10) (a) Barluenga, J.; Trincado, M.; Rubio, E.; Gonzáles, J. M. *Angew. Chem., Int. Ed.* **2003**, *42*, 2406. (b) Huang, Q.; Larock, C. R. *J. Org. Chem.* **2003**, *68*, 7342. (c) Yue, D.; Larock, C. R. *Org. Lett.* **2004**, *6*, 1037. (d) Amjad, M.; Knight, D. W. *Tetrahedron Lett.* **2004**, *45*, 539.

(11) (a) Cornia, M.; Casiraghi, G.; Zetta, L. *J. Org. Chem.* **1991**, *56*, 5466. (b) He, W.; Togo, H.; Yokoyama, M. *Tetrahedron Lett.* **1997**, *38*, 5541. (c) He, W.; Togo, H.; Waki, Y.; Yokoyama, M. *J. Chem. Soc. Perkin Trans. 1* **1998**, 2425. (d) Steinhuebel, D. P.; Fleming, J. J.; Du Bois, J. *Org. Lett.* **2001**, *3*, 293. (e) Guianvarc'h, D.; Benhida, R.; Fourrey, J.-L. *Tetrahedron Lett.* **2001**, *42*, 647. (f) Guianvarc'h, D.; Fourrey, J.-L.; Tran Huu Dau, M.-E.; Guérineau, V.; Benhida, R. *J. Org. Chem.* **2002**, *67*, 3724.

(12) (a) Barbaric, J.; Wanninger-Wei, C.; Wagenknecht, H.-A. *Eur. J. Org. Chem.* **2009**, *13*, 364. (b) Wiebe, C.; Sotilla, S. F.; Opatz, T. *Synthesis* **2012**, *44*, 1385.

(13) Lee, Y. J.; Baek, J. Y.; Lee, B.-Y.; Kang, S. S.; Park, H.-S.; Jeon, H. B.; Kim, K. S. *Carbohydr. Res.* **2006**, *341*, 1708.

(14) Yepremyan, A.; Minehan, T. G. *Org. Biomol. Chem.* **2012**, *10*, 5194.

(15) Nečas, D.; Hidasová, D.; Hocek, M.; Kotora, M. *Org. Biomol. Chem.* **2011**, *9*, 5934.

(16) (a) Nishikawa, T.; Ishikawa, M.; Isobe, M. *Synlett.* **1999**, *1*, 123. (b) Nishikawa, T.; Koide, Y.; Kajii, S.; Wada, K.; Ishikawa, M.; Isobe, M. *Org. Biomol. Chem.* **2005**, *3*, 687.

(17) (a) Ma, D. L.; Shum, T. Y. T.; Zhang, F.; Che, C.-M.; Yang, M. *Chem. Commun.* **2005**, 4675. (b) Zhang, Q.; Sun, J.; Zhu, Y.; Zhang, F.; Yu, B. *Angew. Chem., Int. Ed.* **2011**, *50*, 4933. (c) Yu, J.; Sun, J.; Niu, Y.; Li, R.; Liao, J.; Zhang, F.; Yu, B. *Chem. Sci.* **2013**, *4*, 3899.

(18) (a) Liu, H.-M.; Zhang, F.; Zhang, J.; Li, S. *Carbohydr. Res.* **2003**, *338*, 1737. (b) Liu, H.-M.; Zhang, F.; Wang, S. *Org. Biomol. Chem.* **2003**, *1*, 1641. (c) Liu, H.-M.; Zhang, F.; Zou, D.-P. *Chem. Commun.* **2003**, 2044. (d) Zhang, F.; Liu, H.; Li, Y.-F.; Liu, H.-M. *Carbohydr. Res.* **2010**, *345*, 839. (e) Zhang, Q.; Sun, J.; Zhang, F.; Yu, B. *Eur. J. Org. Chem.* **2010**, 3579. (f) Liu, H.; Zhang, F.; Li, J.-P.; Yan, X.; Liu, H.-M.; Zhao, Y. *J. Chem. Crystallogr.* **2011**, *41*, 1228. (g) Zhang, F.; Liu, H.; Sheng, Y.; Liu, H.-M. *Chin. J. Chem.* **2012**, *30*, 195. (h) Zhang, F.; Wang, L.; Zhang, C.; Zhao, Y. *Chem. Commun.* **2014**, 2046. (i) Zhang, F.; Xi, Y.; Lu, Y.; Wang, L.; Liu, L.; Li, J.; Zhao, Y. *Chem. Commun.* **2014**, 5771.

(19) Alzeer, J.; Vasella, A. *Helv. Chim. Acta* **1995**, *78*, 177. (b) Bohner, T. V.; Beaudegnies, R.; Vasella, A. *Helv. Chim. Acta* **1999**, *82*, 143.

(20) (a) Cory, E. J.; Fuchs, P. L. *Tetrahedron Lett.* **1972**, *36*, 3769. (b) Huang, S. L.; Omura, K.; Swern, D. *J. Org. Chem.* **1976**, *41*, 3329. (c) Krishna, P. K.; Ayyagari, V. S. *Org. Lett.* **2007**, *9*, 1121. (d) Kalanidhi, V. S. A. P.; Krishna, P. K. *Chem.—Eur. J.* **2010**, *16*, 8545. (e) Jarosz, S. *Tetrahedron Lett.* **1988**, *29*, 1193. (f) Ramana, C. V.; Giri, A. G.; Suryawanshi, S. B.; Gonnade, R. G. *Tetrahedron Lett.* **2007**, *48*, 265. (g) Lee, H. H.; Hodgson, P.; Bernacki, R. J.; Korytnyk, W.; Sharm, M. *Carbohydr. Res.* **1988**, *176*, 59. (h) Roldan, F.; Gonzalez, A.; Palomo, C. *Carbohydr. Res.* **1986**, *149*, l. (i) Walton, D. J.; Mcpherson, J. D. *Carbohydr. Res.* **1987**, *167*, 123.

(21) Tronchet, J. M. J.; Gonzalez, A.; Zumwald, J.-B.; Perret, F. *Helv. Chim. Acta* **1974**, *57*, 1505.

(22) (a) Thiéry, J.-C.; Fréchou, C.; Demailly, G. *Tetrahedron Lett.* **2000**, *41*, 6337. (b) Ohira, S. *Synth. Commun.* **1989**, *10*, 561. (c) Pietruszka, J.; Witt, A. *Synthesis* **2006**, *24*, 4266.

(23) Dolhem, F.; Lièvre, C.; Demailly, G. *Tetrahedron* **2003**, *59*, 155.

(24) Norsikian, S.; Soulé, J.-F.; Cannillo, A.; Guillot, R.; Dau, M.-E. T. H.; Beau, J.-M. *Org. Lett.* **2012**, *14*, 544.

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